First Edition
First Printing, December, 1907

Second Edition
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Second Printing, March, 1910

Third Edition
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Fourth Edition
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information on each subject might be presented in reasonably compact form, and at the same time be easily located.

Thus each numbered paragraph opens with a descriptive title or phrase in bold-faced type, while in other respects the use of such type has been limited to subheads and important key words which should catch the eye upon a casual glance over the pages. An entirely new feature is the consistent use of subheads throughout each section and the grouping of these on each section title page, for the double purpose of describing the contents in some detail and serving as a ready guide to any particular subdivision or minor subject. This general scheme of presentation is not intended to relieve the necessity for a thorough and complete index, but rather to supplement the latter and make the book of maximum usefulness. Another new feature is the addition of bibliographies at the end of each section or subsection, and the insertion of numerous references throughout the text to more extended or specialized literature.

In retaining the sectional or unit system of arranging a reference work of this character, both the Editor and the Publishers are convinced from past results that there is no other form of arrangement which is so well suited to the production of a useful and convenient handbook, or which makes possible the segregation of all the material relating to each subject, presented in logical sequence and so displayed as to give it the desired prominence.

Sections 1 to 5 inclusive cover the same general ground as in the third edition, but have been almost completely rewritten and considerably extended.

Sections 6 to 9 inclusive embrace the same subjects as Sections 6 to 8 in the third edition, but conform to a revised classification which is believed to be preferable to the former arrangement. These sections have also been entirely rewritten and substantially enlarged.

Section 10 covers the same general subject matter as the corresponding section in the last edition, but is entirely rewritten and greatly enlarged.

Sections 11 and 12 cover the same ground as Section 11 in the third edition, but are entirely new and much more comprehensive.

Section 13 replaces Section 18 in the old edition, being entirely

PREFACE TO THE THIRD EDITION

The preface to the first edition of the STANDARD HANDBOOK which appears on another page, describes the "unit" system o which the work was developed. The present edition, th publishers believe, is somewhat of a triumph for this system The thorough revision of a book of this size, when manufac tured according to the usual plan, is commercially impossibl except at long intervals when the changes in the art become s great as to demand an entirely new book. The "unit" systen employed in the STANDARD HANDBOOK permits thorough revisior in part or as a whole without any of the usual limitations.

In the present revision the authors of the various section were allowed a free hand in so far as mechanical details were concerned. They were not restricted in space or compelled to cut and prune material to fit pages. The result is a book that has been thoroughly revised from cover to cover so that it could be fairly called a new STANDARD HANDBOOK.

The following synopsis gives a brief outline of the changes and additions that have been made to the various sections.

Section 1, Units, is corrected and slightly enlarged.

Section 2, Electric, Magnetic and Dielectric Circuits, is greatly enlarged. The general theory of electric and magnetic circuits is entirely rewritten and the calculation of inductance and capacity is given in greater detail than before.

Section 3, Measurements and Measuring Instruments, is greatly enlarged. Several new instruments are described, tests of self and mutual inductance have been added and a section devoted to pyrometers and high temperature measurements has been included. The design of rheostats and motor starters has been transferred to Section 5.

Section 4, Properties of Conductor, Resistor and Insulating Materials, is enlarged more than any other section. Many tables have been added giving data on the latest types of conductors and cables. An entirely new section giving the properties of a large number of commercial resistor alloys has also been added and the magnetic testing of iron has been entirely rewritten and now forms a very comprehensive treatment of the latest practice in this important subject.

Section 13, Traction, has been corrected, revised and enlarged. The locomotive section has been entirely rewritten, and more space has been given to the method of constructing speed-time curves.

Section 14, Electrochemistry, has been thoroughly revised and somewhat enlarged.

Section 15, Telephony, has been entirely rewritten. It is now a comprehensive treatise and represents a new method of presenting the subject.

Section 16, Telegraphy, is corrected.

Section 17, Miscellaneous Applications of Electricity, is corrected and somewhat enlarged.

Section 18, Wiring, is corrected and brought to date.

Section 19, Standards, is considerably enlarged. The latest changes in the A. I. E. E. Standardization Rules have been noted, and standard specifications for rubber insulation, copper conductors and transformers have been added.

Section 20, Tables and Statistics, has been corrected and enlarged by adding telephone, telegraph and central station statistics and by general revision.

first edition of a work containing such a mass of figures an data, although the greatest care has been exercised in its prepa ration. Any suggestions, criticisms, or corrections from user will be of great service in making The Standard Handbook standard in fact as well as in name.

December 12, 1907.

PREFACE TO THE SECOND EDITION

No new material has been added to this edition of the Stand ard Handbook, with the exception of directions for resus citation from electric shock, which have been inserted at the en of the book. However, every page has been most carefully rea and every possible effort made to insure the accuracy of all dat and perfection of the typographical work. Several of the ta bles, which were especially prepared for this book, have bee recalculated and others have been checked by plotting the value and recalculating those which did not fall on a smooth curve.

The success of the Standard Handbook has been phenome nal. The general interest in the work has been manifested b the many letters received from prominent men commending it general character and offering suggestions and criticisms. I has already been adopted for use as a text-book in thirt universities and colleges.

The publishers take this occasion to express their appre ciation of its reception by the profession, and to thank thos who by their kindness in pointing out typographical and othe errors, have materially assisted in the work of correction.

New York, *May*, 1908.

SECTION 7

ALTERNATING-CURRENT GENERATORS AND MOTORS
By Comfort A. Adams and Henry M. Hobart

Synchronous Machines, Armature Winding, E.M.F. Generation, The Magnetic Circuit, Characteristics of Synchronous Alternators, Synchronous Motors, Parallel Operation, Design, Insulation, Efficiency, Ventilation, Construction and Testing; Induction Machines, Theory of Polyphase Motors, Characteristics, Magnetizing Current, Leakage Reactance, Circle Diagram, Efficiency, Standard Polyphase Motors, Induction Generators, Design, Single-phase Motors and Their Speed Control; Commutator Motors, Auxiliary Commutating Machines, Phase Modifiers, Motor-generators and Frequency Changers.

SECTION 8

DIRECT-CURRENT GENERATORS AND MOTORS. By Alexander Gray, B.Sc., Whit. Sch.

Types, Windings, Armature Reactions, Commutation, Armature Design, Field Design, Construction, Insulation, Cooling, Efficiency, Characteristics, Regulation, Weights, Costs, Standard Machines, Thury System, Motor-generator Sets, Operation and Testing.

SECTION 9

CONVERTERS AND DOUBLE-CURRENT GENERATORS. By F. D. Newbury, M.E. and Alexander Gray, B.Sc., Whit. Sch.

Synchronous Converters, Theory, Design, Characteristics, Applications, Operation, Testing; Inverted Converters, Motor Converters, Direct-current Converters, Dynamotors and Double-current Generators.

SECTION 10

POWER PLANTS. By Reginald J. S. Pigott, Arthur T. Safford and George I. Rhodes

Steam Power Plants, Laws of Heat Transfer, Boilers, Furnaces, Stokers, Chimneys, Mechanical Draft, Fuel, Water Supply, Coal and Ash Handling, Engines, Turbines, Condensers, Heaters, Economizers, Pumps, Piping and Testing; Gas Power Plants, Producers, Superheaters, Condensers, Scrubbers, Purifiers, Holders, Properties of Gas, Engines, Piping and Testing; Oil Power Plants, Engines, Testing; Hydraulic Power Plants, Hydraulics, Flow Formulas, Stream Flow, Dams, Headworks, Water Wheels and Testing; Buildings and Foundations; Electrical Equipment, Generators, Excitation, Voltage Control, Switching, Station Transformers, Lightning Arresters and Wiring; Power-plant Economics.

SECTION 11

POWER TRANSMISSION. By Harry E. Clifford, S.B. and Chester L. Dawes, S.B.

Transmission Systems, Electrical Calculations, Tables of Reactance and Charging Current, Design, Corona, Insulators, System Connections, Switching, Spans and Supports, Construction, Cables, Substations, Operation, Economics and Cost Data.

SECTION 12

DISTRIBUTION SYSTEMS. By Harry Barnes Gear, A.B., M.E.

Classification, Applications, Types of Circuits, Circuit Design, Substations, Regulation, Secondary Distribution, Transformation, Protection, Construction and Economics.

SECTION 13

INTERIOR WIRING. By Terrell Croft

Fire Risk, Methods of Wiring, Wires and Cables, Fittings and Accessories, Calculations, Lay-outs, Installation, Protection and Miscellaneous.

SECTION 20

BATTERIES. By Walter E. Winship, Ph.D.

Primary Batteries, Wet Cells, Dry Cells, Storage Batteries; Lead Storage Batteries, Electrolyte, Testing, Stationary Batteries, Vehicle Batteries, Train-lighting Batteries, Miscellaneous Applications, Battery Rooms, Regulating Equipment, Operation, Depreciation and Maintenance; Alkaline Storage Batteries.

SECTION 21

TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY. By Frank F. Fowle, S.B., and Louis W. Austin, Ph.D.

Telephone Instruments, Switchboards, Intercommunicating Systems, Phantom Circuits, Manual Telegraph Systems, Simplex and Composite Sets, Dispatching and Patrol Systems, Fire and Police Alarm Systems, Cables, Protectors, Cross-talk and Inductive Disturbances, Transmission, Construction, Testing; Radiotelegraphy, Antenna, Receiving Circuits, Detectors, Wave Transmission, Undamped Oscillations, Arc-wave Generator, Continuous Oscillations, Wireless Telephones, Directive Antennas and Measuring Instruments.

SECTION 22

MISCELLANEOUS APPLICATIONS OF ELECTRICITY. By the following specialists:

W. S. Hadaway, Jr.	Otis Allen Kenyon	John C. Bogle
Harry B. Gear	H. A. Hornor	Capt. Edw. D. Ardery
John E. Newman	Frank F. Fowle	Milton W. Franklin
Edwin P. Adams	Ernst J. Berg.	Eugene W. Caldwell, M.D.

Resuscitation, Electric Heating and Cooking, Electric-Welding, Electrical Equipment for Gas Automobiles, Thawing Water Pipes, Marine Applications, Electricity in the U. S. Army, Electricity and Plant Growth, Windmill Electric Plants, Ozone Production, Radioactivity and the Electron Theory, Roentgen Rays, Lightning Rods, Electrostatic Machines, Electric Piano Players, Telegraphone, Telharmonium, Train-lighting Systems, Statistics of the Electrical Industry, Specifications and Contracts.

SECTION 23

MECHANICAL SECTION. Compiled from standard authorities.

Elements of Sections, Beams, Columns, Shafting, Gearing, Chain Drives, Belts, Rope Drives, Pipe and Screw Threads.

SECTION 24

STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. Approved edition of Dec. 1, 1914

SECTION 25

GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS. By Frank F. Fowle, S.B., and James Raley Cravath

General Engineering Economics, Definitions, Value, Price, Cost, Capital, Rent, Interest, Annual Charges, Depreciation, Social-economic Investigations, Valuation and Rate Making; Central Station Economics, Factors Relating to Utilisation of Investment, Factors Relating to Territory Served, Typical Earnings of Companies, Rate Making and Valuation.

SECTION 1

UNITS, CONVERSION FACTORS, AND TABLES

SYSTEMS OF UNITS

1. Nature of units. Engineering makes use of physical quantities in the broadest sense of that term, *i.e.*, including mechanical, chemical, physical, thermal and physiological quantities. In order adequately to compare the magnitudes of physical quantities of the same kind, unit magnitudes, or units, are necessary for each kind of physical quantity dealt with.

2. Classification of units. The subdivisions and species into which units may be divided are indicated in the scheme shown in Fig. 1, with explanations which follow in Par. 3.

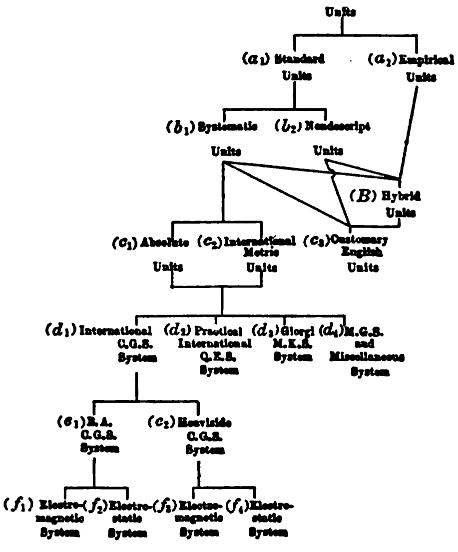

FIG. 1.

3(a_1) Standard units (see Fig. 1) may be said to include all units which have received the stamp of recognition in technical literature.

3(a_2) Empirical units, on the other hand, are units which have sprung into existence locally, ordinarily without any pretense to scientific derivation, and which have not been sanctioned by general usage. At various times during recorded history, empirical units have appeared. Thus, in the early history of electrical units, a unit of conductor resistance was used as representing the resistance of a certain length of a certain size of telegraph

3(c₃) Customary English units are the units of the English and American measures, viz., length measure, square measure, land measure, cubic measure, cord measure, dry measure, liquid measure, avoirdupois weight, troy weight, apothecaries weight and jeweler's weight. Each of these measures may be regarded as a system. The complete list may be regarded as a congeries of imperfectly connected systems. Empirical and hybrid units are mingled with the rest.

3(d_1) C.G.S. units are the units of that particular system of absolute units which is based on the **international centimeter**, the **international gram** and the **mean solar second.** That is, they are absolute units employing the metric system in a definite way. A reason for the centimeter having been selected in place of the meter as the fundamental unit of length was that the mass of the cubic centimeter of water (at the temperature of unit density) is the gram or unit mass; whereas the mass of a cubic meter of water would be a million grams.

3(d_2) Q.E.S. units are units pertaining to the quadrant-eleventh-gram-second absolute system; *i.e.*, the system in which the unit of length is 10^9 cm. or 1 theoretical quadrant of the earth as measured from a pole to the equator, the unit of mass is 10^{-11} g.,* and the unit of time the mean solar second, or the 1/86,400th part of the annual mean daily period of revolution of the earth with respect to the sun. This is the system to which the international ohm, volt, ampere, joule, watt, coulomb, farad and henry, belong. The system was not intentionally established as a Q.E.S. system; but the ohm having been arbitrarily selected, for convenience of magnitude, as 10^9 C.G.S. electromagnetic units, and the volt similarly as 10^8 C.G.S. units, the rest of the system necessarily coincides with the Q.E.S. system; or is such a system as would be produced by the selection of the quadrant, eleventh-gram and second as fundamental units, together with unity for the permeability and unity for the dielectric constant of the ether.

3(d_3) Giorgi units are units in a combined absolute and practical system devised by Prof. G. Giorgi,† in which the fundamental units are: the meter-kilogram-second-international ohm, and the further assumption that the permeability of free ether, instead of being unity as in the C.G.S. magnetic system, is $\mu_o = 4\pi \times 10^{-7}$ henry/m. On this basis the ohm-volt-ampere series of practical units become also absolute units. The electric inductivity, instead of being unity, as in the C.G.S. electric system, becomes $k_o = 1/36\pi \times 10^{-9}$ farad/m. No distinction arises in the Giorgi system between electric and magnetic units. The system is also rectified in regard to 4π factors, or is **"rationalized"** in the Heaviside sense; so that a number of fundamental equations in the system differ from those of the C.G.S. system in regard to such 4π factors.

3(d_4) M.G.S. units, etc. Units in an absolute system whose fundamental units are the meter-gram-second, the millimeter-milligram-second, the foot-grain second, etc. None of these extraneous absolute systems have come into extensive use.

3(e_1) B.A. units are the units of the C.G.S. system as established by the British Association for the Advancement of Science‡ in 1862. The electrostatic subsystem was established on the basis of the unit quantity of electricity such that it repelled its prototype at a distance of 1 cm. with a force of 1 dyne. The electromagnetic subsystem was similarly established on the basis of the unit magnetic pole such that it repelled its prototype at a distance of 1 cm. with a force of 1 dyne. This procedure led to the anomalous result that every electromagnetic quantity has a unit both in the electrostatic subsystem and in the magnetic subsystem.

3(e_2) Heaviside units are units in that form of the C.G.S. system which was first suggested by Mr. Oliver Heaviside in 1882.§ He showed that if a unit electric point charge and a unit magnetic point pole had been respectively defined such that unit total flux emanated therefrom, the strength of

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* Maxwell, J. C. "A Treatise on Electricity and Magnetism," 1881, Chapter X.

† Ascoli, M. "On the Systems of Electrical Units," Trans. Int. Electrical Congress of St. Louis, 1904, Vol. I, p. 130.

‡ "British Association Report on Electrical Standards," 1863.

§ Heaviside, O. "The Relations between Magnetic Force and Electric Current." The Electrician, London, Nov. 18, 1882.

than another. The numerical values applying to any particular case covered by the equation will vary greatly according to the unit selected. If, however, any one of the terms is expressed in a particular unit, all the other terms must adopt the same unit. In all cases, however, it is helpful to the reader to have the unit of the equation written out at the end of its line, as above, in order to assist the numerical interpretation.

HISTORICAL SKETCH OF ENGLISH UNITS

5. The English weights and measures are based upon old Roman weights and measures.* The **troy pound** is supposed to have been a weight of silver referred to as a "pound sterling." This pound would be coined into 240 silver pennies or "pennyweights," each of 24 gr. (barley grain weights). It would, therefore, contain 5,760 gr. Heavy bodies (substances in gross outside of coins or bullion) were weighed by "avoirdupois" weight, authorised by law early in the fourteenth century. Several slightly different avoirdupois pounds were in use. Since Queen Elisabeth's reign the avoirdupois pound has been fixed at 7,000 troy grains.

6. In regard to British lengths, the earliest seems to have been the **cubit** or half yard. The cubit is a very ancient measure, and corresponds to a forearm length from elbow to middle finger-tip. The royal iron standard **yard** was constructed in the thirteenth century, after which the cubit or half yard gradually fell out of use. The **foot** was standardized at one-third of the yard. The mile was a relic of the Roman "millia passuum," or thousand paces; the Roman pace was two of our paces, or counted between the lifts of one and the same foot.

7. Gallon measures of volume existed at different times in England in six different forms, such as the corn-gallon, the ale-gallon, etc. Among these, the wine-gallon of Queen Anne contained 231 cu. in. This gallon was brought to America by the early colonists and remains to-day the U. S. gallon. In 1824, the British enacted a new "**imperial gallon**" to supersede all pre-existing gallons, and defined it as the volume of 10 avoirdupois pounds of distilled water at the temperature of 62 deg. fahr. with the barometer at 30 in. It was further defined as a measure containing 277.274 cu. in. of distilled water. There is thus a **difference between British and American gallons** in the ratio 277.274 to 231 = 1.204 : 1; so that the British gallons, quarts, and pints are respectively about 20 per cent. larger than American gallons, quarts and pints, a large discrepancy that has frequently led to misunderstandings.

8. In land measure, since Anglo-Saxon times, a "**perch**" or "**pole**" was 11 **cubits** in length = 16½ ft., and such a pole was the **surveyor's unit.** A length of 40 perches was a **furlong,** and 8 furlongs the **statute mile.** An **acre** of land was the area of a rectangular strip a furlong in length and 4 perches in breadth, which breadth was known as the "**acre's breadth.**" An acre therefore included 40×4 = 160 sq. perches. Eight such strips end to end made the statute mile, and 80 such strips side by side made a statute mile breadth; so that a **square statute mile** contained 640 acres. Early in the seventeenth century, Prof. Edmund Gunter of Gresham College decimalized acre measure by inventing a 100-link "**chain**" of outstretched length equal to 4 perches or the acre's breadth (66 ft.). The acre thus became 10 sq. chains.

HISTORICAL SKETCH OF THE INTERNATIONAL METRIC SYSTEM

9. Prior to 1790, differences existed between the weights and measures of different Departments of France. Reform in the directions of simplification and unification was promised in a decree of the National Assembly under the sanction of Louis XVI in 1790. The metric system was actually developed under the authority of the French Republic in 1793, in the hands of a committee of scientists and engineers.

10. The decimal system, at the base of the metric system, was originally extended to angles and to time, the right angle being divided into 100 grades, each subdivided into 100 min. and again into 100 sec. The day was divided into 10 hr., each subdivided into 100 min. and again into 100 sec. The decimal subdivision of time never came into extended effect, and the decimal subdivision of angles has only been used to a limited extent.

* Watson, Sir C. M. "British Weights and Measures." London, 1910.

18. In 1882, an international commission met at Paris and adopted a length of 106 cm. as the length of the mercury column defining the ohm, as a closer approximation to the true ohm than the B.A. ohm. This 106-cm. ohm was called the "**legal**" **ohm**, as distinguished from the B.A. ohm. Legal ohms, volts, etc., have at the present date almost completely disappeared. They represented an intermediate stage of approximation to the present international unit values.

19. In 1889, an international electrical congress at Paris adopted the joule, the watt, and the quadrant, as the practical units of energy, power and inductance, respectively.

20. Edinburgh conference. In 1892, a conference was held in connection with the B.A. meeting at Edinburgh. It was then decided to adopt 106.3 cm. as the length of mercury column whose resistance should embody the ohm.

21. In 1893, the international electrical congress of Chicago adopted the 106.3-cm. ohm, which was called the **international ohm**. The other units of the practical system adjusted in conformity to this value were called correspondingly the **international ampere, volt, coulomb,** etc. The name of the unit of inductance was changed from the quadrant to the **henry,** in honor of the American physicist of that name.

22. In 1900, an international electrical congress at Paris, after some debate, adopted the **maxwell** as the unit of magnetic flux and the **gauss** as the unit either of magnetic intensity or of flux-density in the C.G.S. magnetic system.

23. In 1908, an international commission at London considered the **order of sequence of** resistance, current and voltage **standards,** which had been left indefinite at preceding congresses. It was decided that the **ohm** should be the **first unit**, and the **ampere the second**, as determined by the rate of electrodeposition of silver under specified conditions. The volt was to be determined from the ohm and ampere.

DEFINITIONS OF FUNDAMENTAL UNITS

24. Length. (*L.*) Linear distance between any two points. The unit of length in the metric system is the **meter**, in the C.G.S. system the **centimeter**, in the customary system it is any one of the following:—inch, foot, yard, pole, furlong, statute mile, nautical mile.

The fundamental unit of length of the United States is the international meter, the primary standard of which is deposited at the International Bureau of Weights and Measures near Paris, France. This is a platinum-iridium bar with three fine lines at each end; and the distance between the middle lines of each end when the bar is at the temperature of 0 deg. cent., and is supported at the two neutral points 28.5 cm. each side of the centre is 1 m. by definition. Two copies of this bar (prototype meters) are in the possession of the United States and are deposited at the Bureau of Standards.

The United States yard is defined by the relation

$$1 \text{ yd.} = 3600/3937 \text{ m.}$$

The legal equivalent of the meter for commercial purposes was fixed as 39.37 in. by the law of July 28, 1866, and experience having shown that this value was exact within the error of observation, the United States Office of Standard Weights and Measures was, by executive order in 1893, authorized to derive the yard from the meter by the use of this relation.

25. Mass. (*M.*) The quantity of matter in a body is estimated either by its inertia or by its weight. In the metric system, the unit of mass is the **gram**, which was originally defined as the mass of a cubic centimeter of distilled water at 0 deg. cent., although in practice it is taken as the thousandth part of a standard kilogram. In the customary system, the unit is ordinarily any one of the following: avoirdupois grain, ounce, pound, or ton (long or short); occasionally, it is one of the Troy system (ounce, pound). In the use of drugs, it is usually stated in apothecaries weight. The mass of precious stones is commonly estimated in carats.

26. Time. (*T.*) The interval elapsing between any two events. In the C.G.S. system, the unit of time is the **mean solar second**, or 86,400th part of the mean solar day. In the customary system, it is either the second, minute, hour, day, week or year of mean solar time.

a **poundal** being the force which acting on a pound mass for 1 sec., develops in it a velocity of 1 ft. per sec. A pound weight is equal to 32.2 poundals. But if we consider a pound to be a force, represented by a weight W,

$$F^{*} = \frac{W}{g} \cdot \frac{v^2}{r} \qquad (\text{* pounds force}) \qquad (8)$$

It is evident that there is no difference between the two contrasted modes of presenting the facts, provided that we distinguish carefully between a "**pound-mass**" and a "**pound-force.**" If, however, we use the same word "pound" to do duty in the two cases, contradictory and illogical results may be obtained.

It follows that the terms **gram, kilogram, pound, ton,** etc., are susceptible of either of **two distinct meanings**; namely, a **unit of mass** of matter or a **unit of force** equal to the gravitational force exerted on that mass by the earth. Confusion can be avoided in all cases, however, by using distinguishing terms, as "gram-mass," "gram force," or "gram weight."

32. Linear velocity (v). Rate of movement along a line, and ordinarily along a straight line; also, time rate of change of space. The unit in the C.G.S. system is the centimeter-per-second, in the metric system the meter-per-second, or per minute or per hour. In the customary system, it would be any of the customary English units of length per second, minute, hour or day, etc. Velocities may be either + or − with respect to a selected point on the line of motion.

33. Linear acceleration (a). Time rate of change of linear velocity. The C.G.S. unit is the **(cm. per sec.) per sec.**; or the cm. per sec.^{2}. The metric unit may be a meter per sec.^{2}, or a meter per hour^2, or any decimal derivative of the meter, per square of the second, minute, hour, etc. A useful hybrid unit is the (kilometer per hour) per second. Accelerations may be either + or −.

34. Plane angle (α, β, γ). In plane circular trigonometry, the ratio of a circular arc to its radius. The C.G.S. unit is the **radian**, or 1 cm. of arc drawn with a radius of 1 cm. The metric unit is the **grade** or one-hundredth of the quadrant with unit radius. The customary unit is either the degree—one-ninetieth of the unit-radius quadrant—or the revolution of four quadrants.

35. Angular velocity (ω). In plane circular trigonometry, the time rate of change of angle at any given instant. The C.G.S. unit is the **radian per second.** The customary unit is either the degree per second, or the revolution per second, or per minute, etc. Angular velocities may be either + or −.

36. Angular acceleration. In plane circular trigonometry, the time rate of change of angular velocity. The C.G.S. unit is the **radian per second per second.** Customary units are the degree per sec.^{2}, the revolution per sec.^{2}, or per min.^{2}, etc.

37. Energy (W). The capacity of doing work. Energy may be considered as the fundamental entity in terms of which all dynamical quantities may be defined. In the C.G.S. system, the unit is the **erg, or dyne-centimeter.** In mechanics, it may be any product of a unit weight and unit. distance such as kilogram-meter, foot-pound, etc., according to the system. An industrial unit in the meter-kilogram-second system is the **watt-hour.**

38. Power (P). Activity or the rate of working. The rate of expending energy. The C.G.S. unit is the **erg per second.** The metric gravitational unit is the gram-meter per second, or a decimal derivative, such as the kilogram-meter per second. The absolute unit in the meter-kilogram-second system is the **watt.** The customary unit is the **foot-pound per second,** or the **horse-power** of 550 ft.-lb. per sec. It may be either local or standard.

39. Momentum. The product of the mass of a body and its velocity. The C.G.S. unit is the **gram-centimeter per second.** A customary unit is the pound-mass × (foot per second).

40. Torque (τ). Twisting effort. The moment of a twisting couple ordinarily exerted about a shaft axis. The C.G.S. unit is the **dyne-perpendicular-centimeter**; *i.e.*, a dyne acting at right angles to a radius arm 1 cm.

* Prof. W. J. M. Rankine. "Applied Mechanics," 9th edition, 1877, page 491.

E.m.f. may be reckoned for a complete circuit or for any portion thereof; that is, each and every portion of a closed circuit in the steady state obeys Ohm's law.

48. Potential difference (U or V). A condition in virtue of which an electric current tends to flow from a place of higher to a place of lower potential. The numerical measure of the potential difference is the work done on a unit quantity of electricity in passing between the two points. The practical unit is the **volt**. The C.G.S. units are the abvolt and statvolt.

49. Potential gradient. The space rate of change of potential, or the change with respect to distance. An electric potential gradient is the space rate of change of electric potential, and similarly for magnetic, thermal or gravitational potential. The systematic unit in the practical system is the **volt per quadrant**, but a hybrid unit such as **volt per centimeter** is generally used. The C.G.S. unit is either the **abvolt or statvolt per cm.**

50. Electric current (I). The rate at which electricity flows through a conductor or circuit. The practical unit is the **ampere**, which is a current of one coulomb per second. The C.G.S. unit is either the **absampere or statampere.**

51. Electric current density. The ratio of the current flowing through a conductor to the cross-sectional area of that conductor. More strictly, the current density at a point in a conductor is the ratio of the current through a very small plane element of section containing the point and perpendicular to the current, to the area of the element. The systematic practical unit is the **ampere per square quadrant.** In practice, a hybrid unit is preferred such as the **ampere per square centimeter** or square inch. The C.G.S. unit is either the absampere or statampere per square centimeter.

52. Electric resistance (R). Obstruction to electric flow. The ratio of voltage to current in a conductor or closed circuit. The practical unit is the **ohm**. The C.G.S. unit is either the **absohm or statohm.**

53. Electric resistivity (ρ). The ratio of potential gradient in a conductor to the current density thereby produced. Also the specific resistance of a substance numerically equal to the resistance offered by a unit cube of the substance as measured between a pair of opposed parallel faces. The systematic practical unit is the **ohm-quadrant** or numerically equal to the resistance in a cubic earth-quadrant. A hybrid unit such as the **ohm-cm.** is usually preferred. The C.G.S. magnetic unit is the absohm-cm.

54. Electric conductance (G). The conducting power of a conductor or circuit for electricity. The inverse or reciprocal of electric resistance. The practical unit is the **mho**. The C.G.S. unit is either the **abmho** or the **statmho.**

55. Electric conductivity (γ). The specific electric conducting power of a substance. The reciprocal of resistivity. The systematic practical unit is the **mho per quadrant.** A hybrid unit, such as the **mho per cm.** is usually preferred. The C.G.S. magnetic unit is the **abmho per cm.**

56. Inductance (L). The capacity for electromagnetic induction possessed by an active circuit either on itself or on neighboring circuits. The ratio of the magnetic flux linked with and due to an active conductor (number of turns × total flux) to the current strength carried. The practical unit is the **henry.** The C.G.S. units are the **abhenry** and **stathenry.** The term "inductance" seems to have been first introduced by Heaviside* as a brief equivalent for "coefficient of self-induction." Inductance may be divided into two species; namely, **self-inductance** and **mutual inductance.** The unit is the same for both species.

57. Electric capacity (C). Sometimes called **permittance** or **capacitance.** The power of storing or holding an electric charge. The ratio of an electric charge on a conductor to the electric potential difference producing the charge. The practical unit is the **farad.** The C.G.S. unit is either the **abfarad** or the **statfarad.** The term "permittance" was introduced by Heaviside.† It should be noted that capacitance is used by a few writers as synonymous with capacity-reactance.

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* Heaviside, O. "The Electrician," 1884, May 3, p. 583; also "Electrical Papers," Macmillan Co., 1892, Vol. 1, p. 354.

† Heaviside, O. "Electrical Papers," 1892, Vol. II, pp. 302 and 327.

72. Magnetic flux-density (𝔅). The ratio of the magnetic flux in any cross-sectional element of a magnetic circuit to the area of that element. The C.G.S. magnetic unit is the **gauss**, which is also a maxwell per square centimeter.

73. Magnetomotive force (m.m.f.). That which produces magnetic flux. The analogue in the magnetic circuit of electromotive force in the electric circuit. No name has been provided for the unit of m.m.f. either in the practical or in the C.G.S. magnetic system. The name of **gilbert** has, however, been suggested for the latter. A convenient practical unit is the **ampere-turn** which is $4\pi/10$ gilberts.

74. Magnetic field intensity (ℋ) or **gradient of magnetic potential**, also termed **magnetizing force.** The rate of change of magnetic potential with respect to distance. In a region of unit permeability, the field intensity is numerically equal to the magnetic flux density. The provisional name of the C.G.S. magnetic unit is the **gilbert per centimeter.** A numerically related hybrid unit is the **ampere-turn per centimeter.**

75. Reluctance (ℛ). Obstruction to magnetic flow. In a simple magnetic circuit, the ratio of the m.m.f. to the magnetic flux. A provisional name for the C.G.S. magnetic unit is the **oersted.** One gilbert m.m.f. acting on a magnetic circuit of one oersted reluctance produces one maxwell of flux.

76. Reluctivity (ν). A specific reluctance, numerically equal to the reluctance of unit cube of a substance between any pair of opposed parallel faces. The C.G.S. magnetic unit is the **oersted-cm.**

77. Permeance. The reciprocal of reluctance. Conducting power for magnetic flux. No name has been adopted for this unit.

78. Permeability (μ). The reciprocal of reluctivity, or **specific permeance.** No name has been adopted for this unit. In the dimensional formulas of the C.G.S. system, if the electric and magnetic constants of the æther are considered as mere numerics; both permeability and reluctivity are also mere numerics. Also magnetic intensity has the same dimensions as flux density;* so that on this basis, which was at one time undisputed, there would be no difference between gilberts-per-centimeter and gausses except numerically. It is now generally admitted,† however, that the electric and magnetic constants of the æther should not be taken as mere numerics; although their dimensional formulas are not defined. On the latter basis, there is a dimensional difference of some kind between magnetic intensity in gilberts-per-centimeter and flux-density in gausses. The permeability can also be expressed $\mu = 1 + 4\pi\kappa$ where κ is the **susceptibility.**

79. Names for the units in the C.G.S. magnetic and electric subsystems. Although the practical ohm-volt-ampere series of units is universally employed in the great majority of electrical applications, yet it is sometimes desirable to use the C.G.S. parent system of units and names for such units have only been assigned authoritatively in a few instances, such as the "dyne" for the unit of force, and the erg for the unit of work. It has been suggested‡ that the C.G.S. magnetic units might be distinguished from their prototypes in the practical system by the **prefix ab- or abs-** and also that the C.G.S. electrostatic units might be similarly distinguished by the **prefix abstat- or stat-**, as indicated in the following table, Par. **80.**

It should be borne in mind that the prefixes "ab" and "stat" have never been authorized by any technical society or institution, and terms bearing these prefixes are therefore technically irregular. The excuse for this irregularity is that no proper terms exist by which to describe these units, since the phrases "C.G.S. magnetic unit," or "C.G.S. electric unit," are cumbersome and insufficiently descriptive. Moreover, there can be no ambiguity concerning the meaning of these irregular terms.

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* Maxwell, J. C. "A Treatise on Electricity and Magnetism." 1881. Vol. II, p. 244.

† Rücker. Phil. Mag., Feb., 1889.

‡ Trans. A. I. E. E., July, 1903, Vol. XXII, p. 529. Franklin, W. S. "Electric Waves," New York, Macmillan Co., 1909, p. 67. Hering, C. "Conversion Tables," New York, John Wiley & Sons, 1904.

Pender, Harold. "American Handbook for Electrical Engineers," New York, John Wiley & Sons, Inc., 1914.

DEFINITIONS OF PHOTOMETRIC UNITS

81. Luminous flux (F), (light) is the physical stimulus produced by radiation, which excites vision. It is proportional to the rate of flow of radiant energy and to a **stimulus coefficient** which depends chiefly on the spectral distribution of that energy. The stimulus coefficient for radiation of a particular wave-length is the ratio of the luminous flux to the radiant power producing it. The conventional unit of luminous flux is the **lumen** or the flux emitted by **one international candle** through one **steradian.**

82. Luminous intensity (I), or candle-power. The luminous intensity of a point source of light is the solid-angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per steradian in that direction. The conventional unit is the candle-power, or the (candle) lumen per steradian.

83. International candle. A standard of luminous intensity, conventionally equal to the **bougie decimal,** maintained between the national laboratories of England, France and America through the medium of groups of standard incandescent lamps seasoned and intercompared. The intensity given by this standard is the conventional unit or candle.

84. True specific luminous intensity (b_0) of an element of a luminous surface is the ratio of the luminous intensity of the element, taken normally, to the area of the element. The conventional unit is the **candle per square centimeter;** or the lumen per sq. cm.

85. Apparent specific luminous intensity, or brightness (b), of an element of a luminous surface, from a given position, is the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions small in comparison with the distance from the observer. The conventional unit is the **candle per square centimeter of projected area;** or the apparent lumen per sq. cm. For luminous surfaces obeying Lambert's law, or the "cosine law," the true and the apparent specific luminous intensities are equal. In practice, the apparent specific intensity is ordinarily observed. It has been proposed to call a brightness of one apparent lumen per sq. cm. one "lambert".

86. Illumination on a surface (E) is the luminous flux-density over the surface, or the flux per unit of intercepting area. The practical unit is the **lumen per square foot** or the **foot-candle.** The conventional unit is the **lumen per square centimeter** which has been termed the **"phot"** by Blondel. It is a cm-candle. The meter-candle, or 10^{-4} phot, is sometimes called the candle-lux. The milliphot (10^{-3} phot = millilumen per square centimeter) is roughly equal to a foot-candle, since 1 foot-candle = 1.0764 milliphots.

DEFINITIONS OF THERMAL UNITS

87. Temperature. The thermal condition of a body considered with reference to its capability to communicate heat to other bodies. Bodies at the same temperature do not communicate heat to one another at their bounding surfaces. The conventional unit is the **degree centigrade.** Other units in practical use are the degree **fahrenheit,** and occasionally the degree **réaumur.**

88. Quantity of heat. The amount of heat energy contained in a body or transferred from one body to another, by virtue of which temperatures are established or changed. Since heat is a form of energy, a quantity of heat may be expressed in units of energy of any kind. Two types of units are employed, one thermal, the other dynamical. As thermal units the C.G.S. unit is the **"lesser-calorie"** or **"therm"** or **"water-gram-degree centigrade,"** *i.e.*, the quantity of heat required to raise 1 g. of water 1 deg. cent.; and as this differs slightly with the temperature, the interval from 15 deg. to 16 deg. cent. is given in the definition. A larger decimal multiple of this unit, called the **"greater calorie"** or **"kilogram-calorie"** is much used and is equal to 1,000 lesser calories. A practical unit is the **"British thermal unit"** (B.t.u.), or the heat required to raise 1 lb. of water 1 deg. fahr. Dynamic units are the erg, the joule, the watt-hr., etc.

The dimensions of velocity are therefore LT^{-1}, or the first positive power of length and the first negative power of time. Since mass does not appear in this dimensional formula we may write the formal dimensions of velocity as $L^1M^0T^{-1}$. The three exponents 1, 0 and −1 completely define the nature of velocity in any absolute system whose fundamental units are length, mass and time. Moreover, the dimensional formula of a unit assigns at once the size of a unit when systems employing different fundamental units are compared. Thus if we should compare the unit of velocity in the C.G.S. system with that, say, in the meter-kilogram-day system; then in the latter the unit would be the meter per day while in the former it would be the centimeter per second.

100. Taking the more complex case of the magnetic unit of, say, current-density in a system whose fundamental units are those of both the practical and C.G.S. systems; namely, length, mass, time, magnetic æther constant μ, and dielectric æther constant k. Then the dimensional formula of current-density is $L^{-\frac{3}{2}}M^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}$. If now we compare the size of the practical unit with that of the C.G.S. unit the former has a unit length of a quadrant or 10^9 cm., and a mass unit of 10^{-11} g. Consequently, the size of the practical unit is to the size of the C.G.S. unit in the ratio $(10^9)^{-\frac{3}{2}} \times (10^{-11})^{\frac{1}{2}} = 10^{-19}$; so that the practical unit, the ampere per square quadrant, is less than the C.G.S. unit or absampere per square centimeter in the ratio 10^{-19}. For practical purposes, we should probably ignore the systematic practical unit of current density, the ampere per square quadrant, and select a hybrid unit, say the ampere per square centimeter or per square inch. By such a departure from the absolute system, however, the fundamental equations of the system involving lengths, areas, or volumes, may become erroneous unless we introduce compensating numerical coefficients.

100a. Vector units and complex quantities. As is explained in Sec. 2, at Par. 163 and elsewhere, vector alternating quantities are much used in electrical engineering, and call for corresponding vector units, as well as vector symbols, in the formulas relating to such quantities. Strictly speaking, such quantities and units are not vectors in the mathematical sense of that term, but are "complex" quantities and units, because when two such quantities are multiplied together, they do not possess both a "vector product" and a "scalar product" as is the case when two mathematical vectors are multiplied. Nevertheless, such alternating quantities may be called "plane vectors" to avoid conflict with mathematical usage, and the word "vector," which is much used in alternating-current literature, may then be interpreted, in this sense, as subject to the algebra of complex quantities in a plane.

It is not only logical but also very desirable to distinguish between simple and complex quantities, *i.e.*, between scalars and vectors in alternating-current formulas employing both. There are three ways in which this is done:

1. Distinctive symbols, or types of symbol, are used to designate vectors. Thus a scalar e.m.f. in volts might be represented by E and a vector by **E** or **F**, *i.e.*, by a black letter capital, or by a gothic capital, of the same letter. This method has the disadvantage of calling for and reserving special fonts in representing vectors.

2. The same symbol may be used, but a distinctive mark, such as an "under dot," may be applied to symbols representing vector quantities. Thus a scalar e.m.f. in volts might be represented by E, and a vector e.m.f. by $\underset{.}{E}$. In any formula or equation, if any one term is a vector, all of its terms must be vectors; so that the under dot must be applied to each and every term of a vector equation. This method has the disadvantages that it is difficult to print or to set up in type, and that a page containing many vector formulas presents a speckled appearance.

3. No special symbols or symbol marks may be used for vector quantities, but the unit at the end of the line on which the equation appears may have a distinctive sign, such as an angle mark ($\angle$), to indicate that the equation employs vectors. Thus the equation

$$E = IZ_1 + IZ_2 + IZ_3 \qquad \text{volts } \angle$$

would indicate that the e.m.f. E is a vector, and can be represented by the polygonal or vector sum of three vector elements. In this case the unit of the equation becomes a "vector volt."

101. The international metric system. There are only three units

TABULAR SUMMARY OF DEFINITIONS OF UNITS

110. Fundamental Units

Symbol	Quantity	Equation	Dimension	C.G.S. units	Abbreviation	Practical units, English	Abbreviation	Value in C.G.S.
L	Length	——	L	Centimetre	cm.	Foot Inch	ft. in.	30.48 2.54
M	Mass	——	M	Gram	g.	Pound	lb.	453.59
T	Time	——	T	Second	sec.	Minute Second	min. sec.	60. 1.
111. Auxiliary Fundamental Units								
μ	Magnetic permeability	——	μ					
k	Electric permeability	——	k					
θ	Temperature	——	θ					
112. Geometrical Units								
A	Area	$A = L_1 L_2$	L^2	Square centimeter	sq. cm.	Square foot Square inch	sq. ft. sq. in.	929.03 6.45
V	Volume	$V = L_1 L_2 L_3$	L^3	Cubic centimeter	cu. m. cu. cm.	Cubic foot Cubic inch	cu. ft. cu. in.	28,317. 16.39
α β	Plane angle	$\alpha = \frac{jL_1}{L_2}$	j number	Radian { Degree Minute Second	{ Deg. Min. Sec.	{ Degree Minute Second	{ Deg. Min. Sec.	
ψ	Solid angle	$\psi = A/L^2$	number					

115. Electric Units

Symbol	Quantity	Equation	Dimensional formula: Electro-magnetic	Dimensional formula: Electro-static	Practical units	Abbreviations	Value of practical units in electromagnetic units
I, i	Current	$I = \frac{E}{Z}$ $I = \frac{Q}{T}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Ampere	amp.	10^{-1}
	Current density	$\frac{I}{A}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Ampere per square centimeter	amp. per sq. cm.	10^{-1}
Q, q	Quantity	$Q = I\,T$	$L^{\frac{1}{2}} M^{\frac{1}{2}} \mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$	Coulomb Ampere-hour	spell out amp-hr.	10^{-1} 360
R, r	Resistance	$R = \frac{P}{I^2}$	$L\,T^{-1} \mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^9
E, e	Electromotive force	$E = \frac{d\phi}{dT}$ $E = \frac{W}{Q}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{-\frac{1}{2}}$	Volt	spell out	10^8
ρ	Resistivity	$\rho = \frac{RA}{L}$	$L^2\,T^{-1} \mu$	$T\,k^{-1}$	Ohm-centimeter	ohm-cm.	10^9

(Continued on next page)

Electric Units.—*Continued*

Symbol	Quantity	Equation	Dimensional formula		Practical Units	Abbreviations	Value of practical units in electromagnetic units
			Electro-magnetic	Electro-static			
	Electro-kinetic momentum	$I L$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$			
	Thermoelectric height or specific heat of electricity	$\frac{E}{\theta}$**	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} \theta^{-1} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \theta^{-1} k^{-\frac{1}{2}}$			
	Coefficient of Peltier effect	$\frac{H}{I T}$†	$L^{-1} M^{\frac{1}{2}} \theta \mu^{\frac{1}{2}}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} T \theta k^{-\frac{1}{2}}$			
	Coefficient of Peltier effect	$\frac{W}{I T}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{-\frac{1}{2}}$			
	Surface density	$\frac{Q}{A}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} \mu^{-\frac{1}{2}}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$	Coulomb per square centimetre	coulomb per sq. cm.	
L	Coefficient of self induction	$L = \frac{N \phi}{I}$	$L \mu$	$L^{-1} T^2 k^{-1}$	Henry	spell out	10^9
X_s	Inductive reactance	$X_s = 2 \pi f L$	$L T^{-1} \mu$	$L^{-1} T k^{-1}$	Ohm	spell out	10^9

(Concluded on next page)

117. Photometric Units ††

Symbol	Quantity	Equation	Dimensional formula	Unit	Abbreviation	
Q	Quantity of light	$Q = \phi T$	$L^2 M T^{-2}$	Lumen-hour		
ϕ	Flux of light	$\phi = \frac{Q}{T}$	$L^2 M T^{-3}$	Lumen		
I	Intensity of light	$I = \frac{\phi}{\text{solid angle}}$	$L^2 M T^{-3}$	Candle		
b	Brightness	$b = \frac{I}{A}$	$M T^{-3}$	Candle or lumen per square centimeter	c. per sq. cm.	
E	Illumination	$\frac{\phi}{A}$	$M T^{-3}$	Phot, Foot-candle, Lux		

118. Thermal Units ††

Symbol	Quantity	Equation	Dimensional Formulas‡			
			Dynamical	Thermal	Thermometric	$\theta = H + M$
H	Heat	$H = W$ $H = M\theta$ $H = V\theta$	$L^2 M T^{-2}$	$M \theta$	$L^3 \theta$	$L^2 M T^{-2}$
	Rate of heat production	$\frac{H}{T}$	$L^2 M T^{-3}$	$M T^{-1} \theta$	$L^3 T^{-1} \theta$	$L^2 M T^{-3}$

(Concluded on next page)

WEIGHTS AND MEASURES

NOTE:—In this and the following tables, the numerical values are not carried to more than four significant digits, a degree of precision sufficient for ordinary engineering purposes. For higher degrees of precision in conversion factors, reference may be made to publications of the Bureau of Standards, and to Hering's "Conversion Tables."

119. Linear Measure*

English*	U. S.	Abreviation	Metric equivalent: Meter	Metric equivalent: Reciprocal
	1 mil		0.000 0254	39,370
1 inch	1000 mils = 1 inch	in.	0.0254	39.37
4 inches = 1 hand			0.1016	9.843
7.92 inches = 1 surveyor's link	7.92 inches = 1 surveyor's link		0.2012	4.970
12 inches = 1 engineer's link = 1 foot	12 inches = 1 engineer's link = 1 foot	ft.	0.3048	3.281
3 feet = 1 yard	3 feet = 1 yard	yd.	0.9144	1.094
2 yards = 1 fathom	2 yards = 1 fathom		1.829	0.5468
5½ yards = 1 rod, pole, or perch	5½ yards = 1 rod, pole, or perch		5.029	0.1988
100 surveyor's links = 1 surveyor's chain = 66 feet.	100 surveyor's links = 1 surveyor's chain = 66 feet.	ch.	20.12	0.04970
100 engineer's links = 1 engineer's chain = 100 feet.	100 engineer's links = 1 engineer's chain = 100 feet.	ch.	30.48	0.03281
40 yards = 1 bolt (cloth)			36.58	0.02734
10 surveyor's chains = 1 furlong	40 rods = 1 furlong		201.2	0.004970
8 furlongs = 1 Statute mile	8 furlongs = 1 mile = 5280 feet		1,609	0.000 6214
1.152 statute mile = 1 nautical mile = 1 naut.	1.152 statute miles = 1 nautical mile = 6080 feet. = 1 naut.		1,853	0.000 5397
3 statute miles = 1 league			4,827	0.000 2071
60 nautical miles = 1 degree†	60 nautical miles = 1 degree†	deg.	111,100	0.9×10^{-5}

* Strictly speaking, there is a small difference between the English and United States inch, foot, yard, etc.; see Hering's "Conversion Tables;" but it is inappreciable for most engineering purposes. The units in the columns marked "English" are taken from Wightman's Arithmetical Tables, London, Old Westminster Press. The units in the columns marked "U. S." are taken from "The World Almanac," N. Y.

† 1 deg. of longitude on the equator is equal, more nearly to 60.07 nautical or 67.17 statute miles (111,300 m.).

122. Dry Measure (volume)

English	U. S.	Abbreviation	Metric equivalent	
			Liters*	Reciprocal
	1 pint	pt.	0.5506	1.816
1 pint	....	pt.	0.5682	1.760
	2 pints = 1 quart	qt.	1.101	0.9081
2 pints = 1 quart	....	qt.	1.136	0.8799
4 quarts = 1 gallon	....	gal.	4.546	0.2200
	8 quarts = 1 peck	....	8.810	0.1135
2 gallons = 1 peck	....	....	9.092	0.1100
	4 pecks = 1 bushel	....	35.24	0.02838
4 pecks = 1 bushel	....	....	36.37	0.02750
8 bushels = 1 quarter	....	....	290.9	0.003438
36 bushels = 1 chaldron	....	....	1309.	0.0007639

* A liter is 1,000 cu. cm.

123. Cord and Board Measures (volume)

English	U. S.	Abbreviation	Metric equivalent	
			Cubic meters	Reciprocal
	16 cubic ft. = 1 cord foot	cd. ft.	0.4530	2.208
	8 cord feet = 1 cord*	cd.	3.624	0.2759
	144 square in. = 1 board foot†	bd. ft.	....	....

* A cord is the volume of a rectangular parallelopiped, 8 ft. long, 4 ft. wide, and 4 ft. high = 128 cu. ft.

† The board foot is customarily 144 sq. in. with a thickness of 1 in. Less than 1 in. thick is customarily counted as 1 in.; for example, a board $\frac{3}{4}$ in. or $\frac{13}{16}$ in. thick would be counted 1 in. thick in board measure.

126. Liquid Measure; General

English	U. S.	Abbreviation	Metric equivalent: Liters	Metric equivalent: Reciprocal
	1 gill		0.1183	8.453
1 gill			0.1421	7.039
	4 gills = 1 pint	pt.	0.4732	2.113
4 gills = 1 pint		pt.	0.5682	1.760
	2 pints = 1 quart	qt.	0.9464	1.057
2 pints = 1 quart		qt.	1.1365	0.8799
	4 quarts = 1 gallon	gal.	3.785	0.2642
4 quarts = 1 gallon		gal.	4.546	0.2200
	31½ gallons = 1 barrel*	bbl.	119.2	0.008389
31½ gallons = 1 half hogshead			143.2	0.006983
	42 gallons = 1 tierce		159.0	0.006289
42 gallons = 1 tierce			190.9	0.005238
	2 barrels = 1 hogshead	hhd.	238.4	0.004195
63 gallons = 1 hogshead		hhd.	286.4	0.003492
2 tierces = 1 puncheon			381.8	0.002619
2 hogsheads = 1 pipe			572.8	0.001746
2 pipes = 1 tun			1146.0	0.0008726

* The barrel and larger units are practically confined to the measurement of oil, wine or liquor volumes.

CONVERSION TABLES

129. Density *

	Grams per cu. cm.	Reciprocal
1 lb. av. per sq. mil. ft.	2.936×10^6	0.3406×10^{-6}
1 lb. av. per circular mil-ft.	2.306×10^6	0.4337×10^{-6}
1 lb. av. per cu. in.	27.68	0.03613
1 lb. av. per cu. ft.	0.01602	62.43
1 grain per cu. in.	0.003954	252.9
1 lb. av. per cu. yd.	0.0005933	1,685

* Tables for converting **deg. Baumé** (liquid density) to specific gravity a 60 deg. Fahr., and vice versa, are given in Circular No. 19, Bureau o Standards, pp. 31–35.

130. Time Intervals

	Mean solar			
	days	hours	mins.	secs.
1 mean solar year	365.2	8,766	5.26×10^5	3.156×10^7
1 week of 7 days	7.0	168	1.008×10^4	6.048×10^5
1 mean solar day	1.0	24	1.440×10^3	8.640×10^4
1 siderial day	0.9973	23.93	1.436×10^3	8.616×10^4
1 mean solar hour	4.167×10^{-2}	1	60	3.60×10^3
1 siderial hour	4.155×10^{-2}	0.9973	59.83	3.590×10^3
1 mean solar minute	6.944×10^{-4}	1.667×10^{-2}	1	60

131. Solid Angle

	Sphere	Hemisphere	Spherical right angle	Steradian
1 sphere	1	2	8	12.57
1 hemisphere	0.5	1	4	6.283
1 spherical right angle	0.125	0.25	1	1.571
1 steradian	0.07958	0.1592	0.6366	1

132. Force

	Grams Weight	Reciprocal	Dynes	Reciprocal
1 lb., weight avoird.	453.6	0.002205	4.448×10^5	0.2248×10^{-5}
1 poundal	14.10	0.07092	1.383×10^4	0.7233×10^{-4}
1 grain, weight	0.06480	15.43	63.55	0.01573
1 gram, weight	1	1	980.665‡	0.0010197
1 short ton, weight	0.9072×10^6	1.102×10^{-6}	0.8896×10^9	1.124×10^{-9}
1 dyne	0.0010197	980.665‡	1	1

‡ The internationally accepted conventional value of gravitational ac celeration at latitude 45 deg. and sea-level. This is usually adopte although later researches have indicated a slightly different value.

134. Energy

	Ergs	Reciprocal	Gram-wt-cm. $g = 980.7$	Reciprocal	Gram-calories	Reciprocal
1 erg	1	1	1.0197×10^{-3}	980.7	0.2389×10^{-7}	4.186×10^{7}
1 joule	10^{7}	10^{-7}	1.0197×10^{4}	0.9807×10^{-4}	0.2389	4.186
1 gram-wt-cm. (g = 980.7)	980.7	1.0197×10^{-3}	1	1	0.2342×10^{-4}	4.269×10^{4}
1 gram-calorie	4.186×10^{7}	0.2389×10^{-7}	4.269×10^{4}	0.2342×10^{-4}	1	1
1 kilogram-calorie	4.186×10^{10}	0.2389×10^{-10}	4.269×10^{7}	0.2342×10^{-7}	1,000	10^{-3}
1 foot-grain (g = 980.7)	1.937×10^{3}	0.5163×10^{-3}	1.975	0.5063	0.4628×10^{-4}	2.161×10^{4}
1 foot-pound (g = 980.7)‡	1.356×10^{7}	0.7375×10^{-7}	1.383×10^{4}	0.7231×10^{-4}	0.3240	3.086
1 foot-long-ton (g = 980.7)	3.037×10^{10}	0.3293×10^{-10}	3.097×10^{7}	0.3229×10^{-7}	0.7256×10^{3}	1.378×10^{-3}
1 foot-short-ton (g = 980.7)	2.712×10^{10}	0.3687×10^{-10}	2.766×10^{7}	0.3615×10^{-7}	0.6480×10^{3}	1.543×10^{-3}
1 British thermal unit	1.054×10^{10}	0.9488×10^{-10}	1.075×10^{7}	0.9302×10^{-7}	0.2518×10^{3}	3.971×10^{-3}
1 watt-hour	3.600×10^{10}	0.2778×10^{-10}	3.671×10^{7}	0.2724×10^{-7}	0.8602×10^{3}	1.163×10^{-3}
1 kilowatt-hour	3.600×10^{13}	0.2778×10^{-13}	3.671×10^{10}	0.2724×10^{-10}	0.8602×10^{6}	1.163×10^{-6}
1 horse-power-hour* (746 watt-hrs.)	2.686×10^{13}	0.3723×10^{-13}	2.739×10^{10}	0.3651×10^{-10}	0.6418×10^{6}	1.558×10^{-6}
1 horse-power-hour (745.7 watt-hrs., g = 980.7).	2.684×10^{13}	0.3726×10^{-13}	2.737×10^{10}	0.3654×10^{-10}	0.6412×10^{6}	1.560×10^{-6}
1 metric horse-power-hour (736 watt-hrs.).**	2.650×10^{13}	0.3774×10^{-13}	2.702×10^{10}	0.3701×10^{-10}	0.6332×10^{6}	1.579×10^{-6}
1 metric horse-power-hour (735.5 watt-hrs., g = 980.7).	2.648×10^{13}	0.3776×10^{-13}	2.700×10^{10}	0.3704×10^{-10}	0.6326×10^{6}	1.581×10^{-6}

* For g = 981.2 for approximate latitude of London.

** For g = 981.3 for approximate latitude of Berlin.

‡ The local foot-pound varies between the equator and the poles, according to the local intensity of gravitation between the limits 1.352 and 1.359 joules.

136. Torque

	Grams perp. cm.	Reciprocal	Dynes perp. cm.	Reciprocal
1 lb.-perp.-ft.*	1.383×10^{4}	0.7233×10^{-4}	1.356×10^{7}	0.7375×10^{-7}
1 g.-perp.-cm	1	1	980.665	0.0010197
1 dyne-perp.-cm ..	0.0010197	980.665	1	1

137. Linear Velocity

	Metric equivalent	
	Meters per sec.	Reciprocal
1 ft.-per-sec	0.3048	3.281
1 ft.-per-min	0.005080	196.9
1 mile-per-hr........................	0.4470	2.237
1 km.-per-hr	0.2778	3.60
1 knot, or naut-per-hr...............	0.5148	1.943

138. Linear Acceleration

	Meters per sec. per sec.	Reciprocal	Km. per hr. per sec.	Reciprocal
1 ft. per sec. per sec.....	0.3048	3.281	1.097	0.9114
1 mile per hr. per sec....	0.4470	2.237	1.609	0.6214
Standard gravitation *g*..	9.80665	0.10197	35.30	0.02833
1 m. per sec. per sec.....	1	1	3.600	0.2778
1 km. per hr. per sec....	0.2778	3.600	1	1

139. Conversion of Angles (plane)

Angles	Degrees	Reciprocal	Grades	Reciprocal	Radian	Reciprocal
1 degree.........	1	1	1.1111	0.900	0.01745	57.30
1 grade..........	0.9	1.111	1	1	0.01571	63.66
1 radian.........	57.30	0.01745	63.66	0.01571	1	1
1 quadrant......	90°	0.01111	100	0.010	$\pi/2=1.571$	0.6366
1 revolution.....	360°	0.002778	400	0.00250	$2\pi=6.283$	0.1592
π radians........	180°	0.005556	200	0.005	$\pi=3.142$	0.3183
$\pi/2$ radians.....	90°	0.01111	100	0.010	$\pi/2=1.571$	0.6366
$\pi/4$ radians.....	45°	0.02222	50	0.020	$\pi/4=0.7854$	1 2730
2π radians......	360°	0.002778	400	0.0025	$2\pi=6.283$	0.1592

140. Linear Mass

	Gram per meter	Reciprocal
1 lb. per linear yard........	496.1	0.002016
1 lb. per linear foot........	1488	0.0006720

* A torque is the product of a force and a length taken perpendicularl thereto. Its dimensions are therefore those of force $\times -jL$ where $j=\sqrt{-}$ or $-jL^2M^1T^{-2}$. Any element of angle is also the ratio of an element of ar length to the length of a radius perpendicular thereto, or has dimension $jL/L=j$. The product of torque and the angle through which it advance is thus $-jL^2M^1T^{-2}\times j=L^2M^1T^{-2}$ which are the dimensions of work. I the foregoing direction symbols are neglected, a torque appears to have th same dimensions and nature as a work, which is illogical. A torque of 1 g force acting at a radius of 1 cm. is thus correctly to be expressed as a gran perpendicular centimeter rather than as a gram centimeter.

143. Storage of Water

1 acre-ft. = 325,800 U. S. gal. = 43,560 cu. ft. = 1613 cu. yd. = 1234 cu. m.
1 gal. = 0.3069×10^{-5} acre-ft.
1 cu. ft. = 0.2298×10^{-4} acre-ft.
1 cu. yd. = 0.00062 acre-ft.
1 cu. m. = 0.000811 acre-ft.

144. Temperature

Scale	Freezing point of water	Boiling point of water	Interval
Fahrenheit......	32 deg.	212 deg.	180 deg.
Centigrade.....	0 deg.	100 deg.	100 deg.
Réaumur.......	0 deg.	80 deg.	80 deg.

1 deg. fahr. = 0.5556 or (5/9) deg. cent. = 0.4444 or (4/9) deg. Réa.
1 deg. cent. = 0.8000 deg. Réa. = 1.800 deg. fahr.
1 deg. Réa. = 2.250 deg. fahr. = 1.250 deg. cent.
Absolute zero = −273.1 deg. cent. = −491.6 deg. fahr. = −218.5 deg. réaumur.

T_{abs} = 273.1 + deg. cent. (in cent. scale)
T_{abs} = 491.6 + deg. fahr. (in fahr. scale)
T_{abs} = 218.5 + deg. réaumur (in réaumur scale)

The international hydrogen scale of temperature.

145. Mechanical equivalent of heat.

1 B.t.u. = 1,054 joules = 777.5 ft-lb. = 0.2928 watt-hr. = 0.0003927 h.p-hr
1 joule = 0.7375 ft-lb. = 0.0009488 B.t.u. = 0.0002778 watt-hr.
1 ft-lb. = 1.356 joules = 0.001286 B.t.u. = 0.0003766 watt-hr.
1 watt-hr. = 3,600 joules = 2.655 ft-lb. = 3.415 B.t.u.
Also see Par. **133** on energy conversion factors.

MATHEMATICAL CONSTANTS AND TABLES

146. Useful Constants. Base of the hyperbolic system of logarithms = ϵ = 2.7183 to the nearest unit in five significant figures; it is not a commensurate quantity.

Ratio of circumference to diameter of circle = π = 3.1416 (incommensurate).

	Numeric	Reciprocal
ϵ...............	2.7183	0.36788
$\log_{10} \epsilon$...........	0.434295	2.302585
π...............	3.1416	0.31831
2π..............	6.2832	0.15915
3π..............	9.4248	0.10610
4π..............	12.566	0.079577
$\pi/2$............	1.5708	0.63662
$\pi/3$............	1.0472	0.95493
$\pi/4$............	0.7854	1.2732
π^2.............	9.8696	0.10132
$\sqrt{\pi}$............	1.7725	0.56419
$\sqrt{2}$............	1.4142	0.70711
$\sqrt{3}$............	1.7321	0.57733

1 radian = 57.296 deg. = 57 deg., 17 min. and 45 sec.
An arc of 1 deg., in terms of its radius = 0.017453.
For further conversion factors of circular measure, see Par. **134** on angles.

Natural Tangents and Cotangents—*Concluded*

Deg.	°0.0	°0.1	°0.2	°0.3	°0.4	°0.5	°0.6	°0.7	°0.8	°0.9	
45	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319	44
46	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686	43
47	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067	42
48	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463	41
49	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875	40°
50°	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305	39
51	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753	38
52	1.2799	1.2846	1.2892	1.2938	1.3985	1.3032	1.3079	1.3127	1.3175	1.3222	37
53	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713	36
54	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229	35
55	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770	34
56	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340	33
57	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941	32
58	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577	31
59	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251	30°
60°	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966	29
61	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728	28
62	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542	27
63	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413	26
64	2.0503	2.4059	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348	25
65	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355	24
66	2.2460	2.2566	2.2673	2.2781	3.2889	2.2998	2.3109	2.3220	2.3332	2.3445	23
67	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627	22
68	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916	21
69	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326	20°
70°	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878	19
71	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	2.0415	3.0595	18
72	3.0777	3.0961	3.1146	3.1334	3.1524	2.1716	3.1910	3.2106	3.2305	3.2506	17
73	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646	16
74	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062	15
75	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812	14
76	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972	13
77	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646	12
78	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970	11
79	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140	10°
80°	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432	9
81	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264	8
82	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285	7
83	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572	6
84	9.5144	9.677	9.845	10.02	10.20	10.39	10.58	10.78	10.99	11.20	5
85	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.95	4
86	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.46	3
87	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.27	2
88	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.08	1
89	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0	0°
	°1.0	°0.9	°0.8	°0.7	°0.6	°0.5	°0.4	°0.3	°0.2	°0.1	Deg.

Logarithms of Numbers.—*Concluded*

N	0	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8456	8762	8768	8774	8779	8785	8791	8797	8802
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996

SECTION 2

ELECTRIC AND MAGNETIC CIRCUITS

ELECTRIC POTENTIAL

1. The cause of an electric current in a circuit is termed the **electromotive force** or **voltage**. The latter name is derived from the practical unit of electromotive force called the volt. The current between two points in a circuit is due to a different electric state or "potential" at each point; for this reason the electromotive force or voltage is sometimes called the **difference of potential.**

2. The electric energy (W) developed or absorbed by an electric circuit may be considered due to the actual flow of an incompressible something which we call electricity. From this point of view, the quantity of electricity Q which is transferred between two points of the circuit is the quantity factor of the energy, while the difference of potential, or the voltage E between the same points, is the intensity factor of the energy; or

$$W = QE. \qquad (1)$$

When Q is in coulombs, and E in volts, W is in joules (watt-seconds). Hence, electromotive force or voltage may also be defined as electrical energy developed or work done per unit quantity of electricity.

3. Electric Power.—Dividing both sides of the preceding equation by the time which it takes for the quantity Q to flow through a cross-section of the circuit, we get

$$P = IE, \qquad (2)$$

where P is the power, and I the rate of flow or the current. The e.m.f. can thus be defined as the power developed per unit of current.

4. The principal sources of electromotive force or difference of potential are the following:

(a) Electromagnetic induction (see Par. **36**);
(b) Contact of dissimilar substances (see Par. **5**);
(c) Thermo-electric action (see Par. **5**);
(d) Chemical action (Sec. 19);
(e) Friction between dissimilar substances (see Sec. 22).

In the light of the modern electrical theory, all these phenonema, with the exception of (a), appear to be but special cases of the general contact action.

5. In a circuit made up of several substances, a difference of potential (e.m.f.) exists at each junction of two unlike substances. However, from the law of conservation of energy it follows that unless the circuit contain a source of energy, the resultant e.m.f. in the circuit must be zero and no current can be established. This phenomenon also takes place in circuits made up of a single substance whenever the substance is not physically and chemically homogeneous. The following are the principal cases of thermal and contact action:

(a) **Seebeck effect.** In a closed circuit consisting of two different metals, if the two junctions are kept at different temperatures, a permanent current will flow. Thus, if one junction of a copper-iron circuit be kept in melting ice and the other in boiling water, it will be found that a current passes from copper to iron across the hot junction. If, however, the temperature of the hot junction be raised gradually, the e.m.f. in the circuit slowly reaches a maximum, then sinks to zero, and finally is reversed.

(b) **Peltier effect.** When a current is passed across the junction between two different metals, an evolution or an absorption of heat takes place. This effect is different from the evolution of heat (i^2r), due to the resistance of the junction, and is reversible, heat being evolved when the current the current I is in amperes. When the rate of flow is non-uniform, the instantaneous current is

$$i = \frac{\partial q}{\partial t}; \tag{7}$$

for a classification of electric currents see the Standardization Rules of the American Institute of Electrical Engineers, Sec. 24.

10. **Steady and transient states.** An electric circuit may be in a steady or in a transient state. When a current is continuous, or when it varies periodically between the same limits and according to the same law, the circuit is said to be in a steady state. For instance, the circuit of an alternator is steady as long as the load, speed and field excitation are kept constant. The same circuit is in a transient state when the load is switched on or off, or when it is varied in such a way that the same conditions do not repeat themselves periodically. A transient current may be periodic, for instance in a rectifier, in which cycles follow in such rapid succession that the current is very different from the permanent value which it would gradually assume.

11. **A direct current** given out by a chemical battery is constant in value, or **continuous**, when the load is constant. A current delivered under the same conditions by an electric generator or a rectifier is **pulsating**, that is, it varies periodically due to a finite number of commutator segments.

12. **An alternating current** may vary according to the **simple sine law** (Par. **152**), or according to a **more complicated periodic law**. In the latter case the current may be resolved, for purposes of theory and analysis, into a fundamental sine wave, and sine waves of higher frequencies (Par. **209**). Sometimes a complex alternating current or voltage is replaced for practical purposes by an equivalent sine-wave.

13. **Transient currents may be oscillating or non-oscillating**, according to the conditions in the circuit. Oscillations are due to periodic transformations of the electrostatic energy stored in the dielectric into the electromagnetic energy of the magnetic flux linking with the current. During these transformations part of the energy is converted into the Joulean (i^2r) heat in the conductors and in surrounding metallic objects, including the iron of the magnetic circuit. Part of the energy is also converted into the heat caused by magnetic and dielectric hysteresis. The oscillations are thus damped out, and their amplitude decreases. When the conditions are particularly favorable for the conversion into heat (high resistance in series, or low resistance in parallel), both the electrostatic and the electromagnetic energy are directly converted into heat, instead of being partly converted into one another. This conversion into heat is an irreversible phenomenon, so that in this case the current is non-oscillating, but gradually reaches its final value. When it is desired to maintain oscillations as long as possible (wireless telegraphy) the series resistance must be kept down as low as possible. When oscillations are harmful (switching in long cables or transmission lines), extra resistance is temporarily connected in the circuit.

14. **Conductors and insulators.** For practical purposes, materials used in electrical engineering are divided into conductors and insulators. A conducting material allows a continuous current to pass through it under the action of a continuous e.m.f. An insulator (more correctly called a **dielectric**) allows only a brief transient current which charges it electrostatically. This charge or displacement of electricity produces a counter-e.m.f. equal and opposite to the applied e.m.f., and the flow of current ceases. The division into conductors and dielectrics is not strictly correct, but convenient for practical purposes. A substance may practically stop the flow of current when the applied voltage is sufficiently low, and at the same time be unsuitable as an insulator at high voltages. Some materials which are practically non-conducting at ordinary temperatures become good conductors when sufficiently heated. For numerical data and tables of conducting and insulating properties of the principal materials used in practice see Sec. 4.

15. **The electronic theory of conduction.** According to the modern electronic or corpuscular theory of electricity, there is an indivisible atom of negative electricity, called the **electron** or the **corpuscle**. Atoms of matter consist of one or more electrons and an unknown something which has the

where λ (lambda) is called the **conductivity** of the material. Since $g = 1/r$, the relation also holds, that

$$\lambda = \frac{1}{\rho}. \qquad (14)$$

For the calculation of resistance of non-cylindrical conductors see the author's "Electric Circuit," Chap. III, and the references given there.

21. Temperature coefficient. The resistance of a conductor varies with the temperature according to a rather complicated law. The resistance of all metals and of practically all alloys increases with the temperature. The resistance of carbon and of electrolytes decreases with the temperature. For numerical values see Sec. 4. For many materials the variation of resistance with the temperature can be represented by the relation

$$r_t = r_o(1 + \alpha t) \qquad (15)$$

where r_t is the resistance at t deg. cent., r_o the resistance at 0 deg. cent., and α (alpha) is called the temperature coefficient of the material. For numerical values of α for various materials see Sec. 4. When the resistance of a material increases with the temperature, α is positive; otherwise it is negative. For other formulæ see Sec. 4.

22. Resistances and conductances in series. When two or more resistances are connected in series the equivalent resistance of the combination is equal to the sum of the resistances of the individual resistors, or

$$r_{eq} = r_1 + r_2 + \text{etc.} \qquad (16)$$

When conductances are connected in series, the equivalent conductance g_{eq} is determined from the relation

$$\frac{1}{g_{eq}} = \frac{1}{g_1} + \frac{1}{g_2} + \text{etc.}, \qquad (17)$$

in other words, when two or more conductors are connected in series, the reciprocal of the equivalent conductance is equal to the sum of the reciprocals of the individual conductances.

23. When resistances are connected in parallel, the equivalent resistance r_{eq} is determined from the relation

$$\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \text{etc.} \qquad (18)$$

or simply

$$g_{eq} = g_1 + g_2 + \text{etc.} \qquad (19)$$

24. The simple rule is: Resistances are added when in series; conductances are added when in parallel. In the case often met in practice when two resistances are connected in parallel

$$r_{eq} = \frac{r_1 r_2}{r_1 + r_2}. \qquad (20)$$

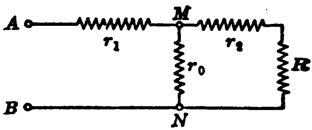

Fig. 1.—Series-parallel circuit.

25. Series-parallel circuits. In a combination like the one shown in Fig. 1, where some of the resistances are in series, some in parallel, and where it is required to find the equivalent resistance between A and B, the problem is solved step by step, by combining the resistances in series, converting them into conductances and adding them with other conductances in parallel. For instance, in the case shown in Fig. 1 begin by combining the resistances r_2 and R into one, and determine the corresponding conductance

$$\frac{1}{(R + r_2)};$$

add this conductance to the conductance $1/r_0$. This will give the total conductance between the points M and N. The reciprocal of it gives the equivalent resistance between the same points. The total resistance between the points A and B is found by adding r_1 to this resistance. When a network of conductors cannot be reduced to a series-parallel combination, the problem is solved as shown in Par. 29.

determined by solving simultaneous equations. For an example of such equations see Par. **31** below.

30. Wheatstone bridge. The combination of six resistances shown in Fig. 3 is called the Wheatstone bridge. The resistances are denoted by $a, b, c, \alpha, \beta, \gamma$, the currents by $x, y, z, \xi, \eta, \zeta$. An electric battery of e.m.f. E is connected in the branch BC, and the value of a includes the internal resistance of the battery. In practice a galvanometer is usually connected in the branch OA, and α includes its resistance. When the four resistances b, c, β, γ, are so adjusted that no current flows through OA, the bridge is said to be balanced, and the condition holds that,

$$b\beta = c\gamma. \tag{27}$$

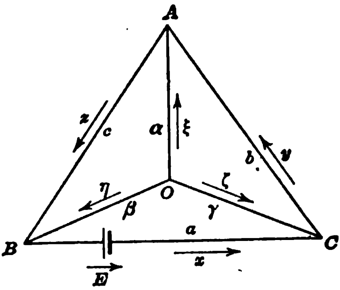

Fig. 3.—Wheatstone Bridge.

31. Unbalanced bridge. When the Wheatstone bridge is not balanced, Ohm's law and Kirchhoff's laws give the following equations:

$$\begin{aligned} ax &= C - B + E, & \alpha\xi &= A, & \xi + y - z &= O, \\ by &= A - C, & \beta\eta &= B, & \eta + z - x &= O, \\ cz &= B - A, & \gamma\zeta &= C, & \zeta + x - y &= O. \end{aligned} \tag{28}$$

Here E is the battery e.m.f., and A, B, C, denote the potentials of these points below that at O. These nine equations contain nine unknown quantities, viz., six currents and three potentials. Solving them as simultaneous equations any of the unknown quantities may be determined. For instance, the current in the galvanometer circuit is

$$\xi = \frac{E}{D}(b\beta - c\gamma), \tag{29}$$

where the "determinant" D is given by

$$D = abc + bc(\beta+\gamma) + ca(\gamma+\alpha) + ab(\alpha+\beta) + (a+b+c)\ (\beta\gamma+\gamma\alpha+\alpha\beta).^*$$

32. Networks of conductors. In a general case (Fig. 2) as many Kirchhoff equations (Par. **29**) may be written as there are conductors; the unknown quantities may be the currents, the resistances or the voltages; also any combination of these, provided that the total number of unknown quantities is equal to the number of equations. The equations are conveniently solved by the method of determinants, found in most textbooks on algebra.

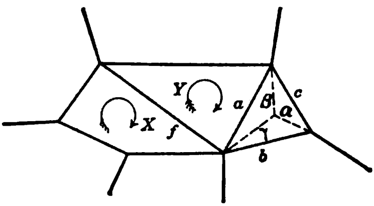

Fig. 4.—Method of simplifying networks.

33. Maxwell's solution. In some cases it is convenient to consider, instead of the actual currents, fictitious currents in each mesh (Maxwell, *ibid.*, Art. 282*b*). The actual current in each conductor is equal to the algebraic sum of the fictitious currents. For instance, in Fig. 4 the current in conductor f is the difference of the fictitious currents X and Y. The Kirchhoff equations are written for the fictitious currents.

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* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. I, Art. 347.

For practical forms of the Wheatstone bridge and its application to the measurement of resistance see Sec. 3.

the reluctance of the magnetic circuit (inductor-type alternator). If the flux is linked with N turns and varies harmonically with the time, at a frequency of f cycles per second, the **maximum induced e.m.f.** is

$$E_{max} = 2\pi f N \Phi_{max} 10^{-8} \text{ volts,} \tag{32}$$

where Φ_{max} is the maximum instantaneous value of the flux, in maxwells. The **effective value of the induced e.m.f.** is

$$E = 4.44 f N \Phi_{max} 10^{-8} \text{ volts.} \tag{33}$$

When the flux varies according to a law different from the sine law the effective voltage is

$$E = 4\chi f N \Phi_{max} 10^{-8}, \tag{34}$$

where χ is the form factor (Par. **207**).

The **average e.m.f. induced in one turn**, no matter what the law of variation of the flux with the time, is

$$E_{av} = \frac{\Phi_1 - \Phi_2}{t_2 - t_1}, \tag{35}$$

where the subscripts 1 and 2 refer to the initial and the final instants respectively.

38. Stationary flux and moving conductor. When the exciting m.m.f. which produces the flux, and the winding in which the e.m.f. is induced, move relatively to each other, as in a generator, so that the conductors cut across the lines of flux, the instantaneous induced e.m.f. in a conductor is

$$e = k\mathfrak{B}lv, \tag{36}$$

where $\mathfrak{B}$ is the flux density, l the length of the conductor, v the relative velocity between the flux and the conductor, and k a coefficient which depends upon the units selected. When e is in volts, $\mathfrak{B}$ in maxwells per square centimeter (gausses), l in centimeters and v in centimeters per second, $k = 10^{-8}$.

The three directions, $\mathfrak{B}$, l, and v, are supposed to be at right angles to each other; if not, their projections at right angles to each other are to be used in the preceding formula. For practical formulas giving the e.m.f. induced in direct-current and alternating-current machinery see Sec. 7 and Sec. 8.

39. Variable flux and moving conductor. When coils or conductors are moving through a pulsating magnetic field, as for instance in single-phase motors, the induced e.m.f. is due to a combined transformer and generator action (Par. **37** and **38**), and is equal at any instant to the sum of the e.m.f. induced by a constant flux in a moving coil and that induced by a pulsating flux in a stationary coil. Let the frequency of the pulsating field be f cycles per second; that of the rotating coil f' cycles per second. A pulsating field can be resolved into two revolving fields, one rotating clockwise, the other counter-clockwise. Therefore, the induced e.m.f. is a result of the superposition of two e.m.fs., one of the frequency $f+f'$, the other $f-f'$. In the particular case of $f=f'$ the e.m.f. induced in the rotating coil is of the frequency $2f$, the frequency $f-f'$ being equal to zero.

40. Force on a conductor carrying a current in a magnetic field. Let a conductor carry a current of i amp. and be placed in a magnetic field the density of which is $\mathfrak{B}$ maxwells per square centimeter ($\mathfrak{B}$ gausses). Then, if the length of the conductor is l cm., the force tending to move the conductor across the field is

$$F = 10.2 i\mathfrak{B}l 10^{-8} \quad \text{(kg.)} \tag{37}$$

It is presupposed in this formula that the direction of the axis of the conductor is at right angles to the direction of the field. If the directions of i and B form an angle α, the preceding expression must be multiplied by $\sin \alpha$.

The force F is perpendicular to both i and B, and its direction is determined by the right-hand screw rule (Par. **56**). Namely, the effect of the magnetic field produced by the conductor itself is to increase the original flux density ($\mathfrak{B}$) on one side of the conductor and to reduce it on the other side. The conductor tends to move away from the denser field.

41. The attraction or repulsion between two parallel straight conductors, carrying currents i_1 and i_2 (amp.) and placed in a non-magnetic medium, is calculated according to the formula

$$F = 2.04 i_1 i_2 \left(\frac{l}{b}\right) 10^{-8} \quad \text{(kg.)} \tag{38}$$

where nI is the product of the number of turns and the current in amperes. For further information about magnetic units see Sec. 1.

45. Permeability and reluctivity. The reluctance of a uniform magnetic path (Fig. 5) is proportional to its length l and inversely proportional to its cross-section A, or

$$\mathcal{R} = \nu \frac{l}{A} \tag{42}$$

and

$$\mathcal{P} = \mu \frac{A}{l}. \tag{43}$$

In these expressions ν is called the reluctivity and μ the permeability of the material of the magnetic path. For air and all non-magnetic substances, ν and μ are assumed to be equal to unity per centimeter-cube, corresponding to centimeter measure for l and A in (42) and (43), and the gilbert as the unit of m.m.f. This is the conventional assumption in the C.G.S. electromagnetic system and is the one generally employed. See also Par. **53** and **54**.

The method preferred by the author, and expounded in his "Magnetic Circuit" (see footnote reference in Par. **44**), is to take the ampere-turn as the unit of m.m.f. In such cases, with the maxwell as the unit of flux, the permeability and the reluctivity of air, respectively, are

$$\left.\begin{array}{l} \nu = 0.7955 \text{ per cm.}^3 = 0.3132 \text{ per in.}^3 \\ \mu = 1.257 \text{ per cm.}^3 = 3.193 \text{ per in.}^3 \end{array}\right\} \tag{44}$$

This method has the advantage of greater simplicity in calculations, but is not yet in general use (see Sec. 1; Giorgi system of units, Par. **3**(d_3)).

46. Magnetic field intensity $\mathcal{H}$ is defined as the m.m.f. per unit length of path. In any uniform field

$$\mathcal{H} = \frac{\mathcal{F}}{l}. \tag{45}$$

In a non-uniform magnetic circuit

$$\mathcal{H} = \frac{\partial \mathcal{F}}{\partial l}. \tag{46}$$

Inversely

$$\mathcal{F} = \mathcal{H} l \text{ or } \mathcal{F} = \int \mathcal{H} \partial l. \tag{47}$$

$\mathcal{H}$ is also known as the **magnetizing force** or as the **magnetic potential gradient.**

If $\mathcal{F}$ is in ampere-turns, $\mathcal{H}$ is in ampere-turns per centimeter (or per inch) of length. If $\mathcal{F}$ is in gilberts, $\mathcal{H}$ is in gilberts per centimeter (or per inch).

47. Flux density ($\mathcal{B}$) is defined as the flux per unit area perpendicular to the direction of the lines of force. In a uniform field

$$\mathcal{B} = \frac{\Phi}{A}. \tag{48}$$

In a non-uniform field

$$\mathcal{B} = \frac{\partial \Phi}{\partial A}. \tag{49}$$

Inversely

$$\Phi = \mathcal{B} A, \text{ or } \Phi = \int \mathcal{B} \partial A. \tag{50}$$

If the flux is measured in maxwells and areas in square centimeters, flux density is expressed in maxwells per square centimeter; one maxwell per square centimeter is sometimes called a **gauss.** In this country flux density is also expressed in maxwells, or in kilolines, per square inch.

It follows at once from (40), (43), (45) and (48) that

$$\mathcal{B} = \mu \mathcal{H} \tag{51}$$

which is the familiar relationship between flux density, permeability and magnetic field intensity.

48. Reluctances and permeances in series and in parallel. Reluctances and permeances are added like resistances and conductances (Par. **22**

intensity of induced magnetization. The coefficient κ is called the **suscepti-bility** of the material. The total flux density in iron also consists of two parts, viz., that due to $\mathcal{H}$ and to $\mathcal{I}$, or, in the C.G.S. system,

$$\mathcal{B}=\mathcal{H}+4\pi\mathcal{I}. \tag{54}$$

Dividing both sides of this equation by $\mathcal{H}$, gives

$$\mu=1+4\pi\kappa, \tag{55}$$

where μ is the permeability of the material (Par. **53**). Susceptibility is equal to zero for non-magnetic materials, is positive for paramagnetic and negative for diamagnetic substances. It is seldom used in practice.*

53. The permeability (μ) and the reluctivity (ν) of a material (Par. 45) are also defined as the ratios

$$\mu=\frac{\mathcal{B}}{\mathcal{H}} \text{ and } \nu=\frac{\mathcal{H}}{\mathcal{B}}. \tag{56}$$

Their values depend upon the units selected for $\mathcal{B}$ and $\mathcal{H}$. In the C.G.S. electromagnetic system $\mathcal{B}$ and $\mathcal{H}$ are numerically equal for non-magnetic materials, consequently $\mu=\nu=1$. When $\mathcal{B}$ is expressed in maxwells per square centimeter (or per square inch) and $\mathcal{H}$ in ampere-turns per unit length, μ and ν for air and other non-magnetic materials have values given in Par. **45**, Eq. 44.

54. Two different scales of permeability. For steel and iron the permeability $\mu=\mathcal{B}/\mathcal{H}$ is frequently calculated from the magnetization curve (Par. **49**), and is usually plotted against $\mathcal{B}$ as abscissæ (see curves in Sec. 4). One must be careful to distinguish between the **absolute permeability** and the **relative permeability**. The former is equal to $\mathcal{B}/\mathcal{H}$, the latter is the ratio of the permeability of a sample to that of the air. In the C.G.S. electromagnetic system both permeabilities are numerically the same, because μ is assumed to be unity for the air; nevertheless they have different physical dimensions in any system of units.

55. Magnetic calculations. In practice, calculations of magnetic circuits with iron are usually arranged so as to avoid the use of permeability μ altogether, using a $\mathcal{B}$–$\mathcal{H}$ curve directly (Par. **49** and **50**). In some special investigations it is convenient to use the values of permeability and also an empirical equation between μ and $\mathcal{B}$. For small and medium flux densities μ may be expressed as a parabolic curve, of the form

$$\mu=a-b(\mathcal{B}_0-\mathcal{B})^2 10^{-6} \tag{57}$$

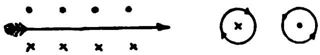

Fig. 7a.—Relation between directions of current and flux.

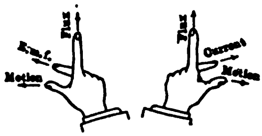

Fig. 7b.—Fleming's rules.

For numerical values of the coefficients see Sec. 4. It is also possible to represent the **relationship between $\mathcal{B}$ and $\mathcal{H}$ for a magnetic material** empirically by a hyperbola (Fröhlich's formula)

$$\mathcal{B}=\frac{\mathcal{H}}{\alpha+\beta\mathcal{H}}, \tag{58}$$

or also in the form

$$\text{reluctivity } \nu=\frac{\mathcal{H}}{\mathcal{B}}=\alpha+\beta\mathcal{H}=\frac{1}{\mu}. \tag{59}$$

The coefficients α and β must be so determined as to satisfy the saturation curve of the particular material used.

56. The right-hand screw rule. The direction of the flux produced by a given current is determined as shown in Fig. 7*a* (see also Fig. 5). If the

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II., Arts., 426 to 428.

usually a complex matter, and the results are expressed by complicated formulæ. See references in Par. 74.

62. The stored magnetic energy in a single loop of non-magnetic wire, when the dimensions of the wire are small compared to those of the loop (so that the flux inside the wire is negligible), is

$$W = \tfrac{1}{2} i\Phi = \tfrac{1}{2} i^2 \mathcal{P} = \frac{\Phi^2}{2\mathcal{P}} \qquad \text{(joules)} \qquad (66)$$

where i is the current in amperes, Φ the flux linking with the loop, in webers, and $\mathcal{P}$ the permeance of the magnetic path, in henrys.

63. Effect of leakage. When the flux linking with part of the turns of a coil C is not negligible (see Fig. 9), the **total stored energy** may be expressed in the following forms:

$$\left. \begin{aligned} W &= \tfrac{1}{2} i[n_c \Phi_c + \Sigma n_p \Delta \Phi_p], \\ W &= \tfrac{1}{2} i^2 [n^2 \mathcal{P}_c + \Sigma n_p^2 \Delta \mathcal{P}_p]. \end{aligned} \right\} \qquad (67)$$

The last expression is identical with

$$W = \tfrac{1}{2} L i^2 \qquad (68)$$

where L is the inductance of the coil (Par. 67). The subscripts c in the foregoing expressions refer to **complete linkages**, that is those which embrace

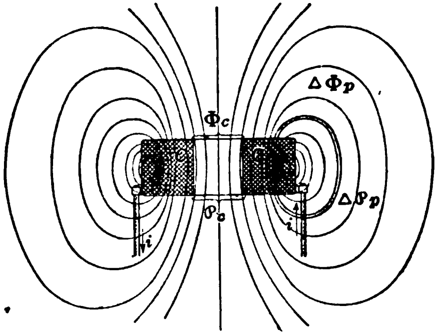

FIG. 9.—Magnetic field due to a coil.

all the turns of the coil, the subscripts p **to partial linkages.** See the author's "Magnetic Circuit," Art. 57.

64. The density of magnetic energy, or the magnetic energy stored per cubic centimeter of a magnetic field is

$$W' = \frac{\mu \mathcal{H}^2}{8\pi} = \frac{\mathcal{B}\mathcal{H}}{8\pi} = \frac{\mathcal{B}^2}{8\pi\mu} \qquad \text{(joules per cubic cm.).} \qquad (69)$$

Here $\mathcal{H}$ is the intensity in gilberts per centimeter, $\mathcal{B}$ is the flux density in webers per square centimeter and μ is the relative permeability; or if $\mathcal{H}$ is in ampere-turns per centimeter, then

$$W' = \tfrac{1}{2} \mu \mathcal{H}^2 = \tfrac{1}{2} \mathcal{B}\mathcal{H} = \frac{\mathcal{B}^2}{2\mu} \qquad \text{(joules per cubic cm.)} \qquad (70)$$

where μ is the so-called absolute permeability (see Par. 54). To find the total energy of a field the preceding expressions are multiplied by the element of the volume ∂v and integrated within the desired limits of volume. For an interesting comparison of practical possibilities as to the amount of energy stored in the magnetic form per unit volume, compared with other forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, p. 536.

permeability of the steel. If the magnetic core occupies only a part α of the cross-section bh, use the expression $bh[\alpha\mu_r + (1-\alpha)]$, in place of bh.

70. For other calculations of inductance using formula (68) see the author's "Magnetic Circuit," Chaps. X to XII.

71. Thin solenoids. For a straight coil uniformly wound with n_1 turns per centimeter length, provided that the length of the coil is large compared to its transverse dimensions, and that the winding consists of one layer of comparatively thin wire, **the inductance is**

$$L = 1.257 n_1^2 l A 10^{-8} \qquad \text{(henrys)} \qquad (77)$$

the notation being the same as in Par. 68.

72. The inductance of a long straight coil wound with several layers of wire, and with an iron core of radius a inside,

$$L = 4n_1^4 l d^2 r^2 \left[1 + (\mu_r - 1)\frac{a^2}{r^2} + \frac{d}{r} + \frac{d^2}{3r^2}\right] 10^{-9} \qquad \text{(henrys)} \qquad (78)$$

where r is the inside radius of the winding, and d its radial thickness; n_1 is the number of turns per centimeter length, and all the dimensions are in centimeters. If there is no iron core, put $a = 0$.

73. Prof. Morgan Brooks has derived a universal semi-empirical formula for the **inductance of short and long coils without iron cores.** His formula is given below in two forms, one (79) for dimensions in centimeters, the other (80) for dimensions in English units. Both give results in henrys. The notation is explained in Fig. 10.

$$L = \frac{Cm^2}{b+c+R} \times \frac{F'F''}{10^9} \qquad \text{(henrys)} \qquad (79)$$

$$L = \frac{0.366\left(\frac{Ft}{1000}\right)^2}{b+c+R} \times F'F'' \qquad \text{(henrys)} \qquad (80)$$

In Eq. (80) the conductor length is in thousands of feet, and the coil dimensions in inches; 0.366 is the conversion factor. F' and F'' are empirical coil-shape factors dependent upon the relative, and independent of the absolute dimensions of the winding. Values of F' and F'' are as follows:

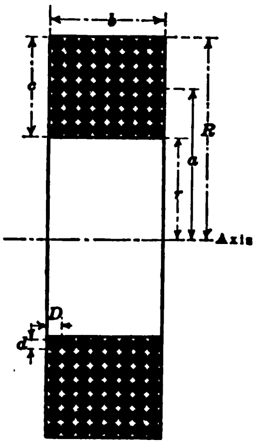

FIG. 10.—See Par. 73.

$$F' = \frac{10b + 12c + 2R}{10b + 10c + 1.4R}; \quad F'' = 0.5 \log_{10}\left(100 + \frac{14R}{2b+3c}\right). \qquad (81)$$

Cm indicates the length of the conductor in centimeters;
Ft indicates the length of the conductor in feet, and $Ft/1000$ = thousands of feet;
N is the total number of turns in the winding, whence

$$Cm = 2\pi a N, \text{ when } a \text{ is in centimeters, and} \qquad (82)$$

$$\frac{Ft}{1000} = \frac{2\pi a N}{12000} \text{ when } a \text{ is in inches.} \qquad (83)$$

Numerous tables, curves, and charts which simplify the use of this formula for practical design will be found in the Bulletin No. 53 of the University of Illinois, by Morgan Brooks and H. M. Turner, entitled "Inductance of Coils." For another empirical formula see Doggett, L. A., "The Inductance of Air-cored Solenoids," *Elec. World*, Vol. LXIII (1914), p. 259.

74. Bureau of Standards, formulas for inductance. For a thorough analysis and comparison of various formulas for the inductance of coils the reader is referred to the following excellent series of articles published in the Bulletin of the Bureau of Standards:

"Formulæ and Tables for the Calculation of Mutual and Self-inductance" (Revised), E. B. Rosa and L. Cohen, Vol. VIII, p. 1; 1912; "Calculation of

Par. 77 holds true only for the conductor situated symmetrically with respect to the other two. The inductance of the other two wires cannot be calculated in a simple manner. For practical purposes it is sufficient to take the inductance of all three wires as equal to that of a line symmetrically spaced, the equivalent spacing being equal to the geometric mean of the three actual spacings, or

$$b_{eq} = \sqrt[3]{b_1 b_2 b_3}. \tag{88}$$

82. For the equivalent resistance and reactance of a three-phase line with unequal spacings of wires see the writer's "Magnetic Circuit", Art. 63. In this case the e.m.f. induced in a conductor by the varying magnetic fluxes consists of two components, one being in quadrature, the other in phase with the current in the conductor. The first component corresponds to the inductance of the conductor, the other represents transfer of power from one phase to the others. In general, these components are different for the three conductors, and in order to equalize them for the whole line conductors are transposed after a certain number of spans. This **transposition of conductors** is used on power lines (Sec. 11) as well as on telegraph and telephone lines (Sec. 21) to reduce the unbalancing effect of mutual induction. See also Par. **87** below. The inductance of two or more parallel cylinders of any cross-section can be expressed through the so-called geometric mean distance introduced by Maxwell.* For details also see Orlich, "Kapazätit und Inductivität," pp. 63–74.

83. Mutual inductance. When two independent electric circuits, (1) and (2), are in proximity to each other, their electromagnetic energy may be said to consist of three parts: the part due to the linkages of the flux produced by the circuit (1) with the current in (1); that due to the flux produced by the circuit (2) with the current in (2); and that due to the current in each circuit linking with the flux produced by the other circuit. Employing the notation in Par. **67**, the total energy of the system is expressed by

$$W = \tfrac{1}{2} i_1^2 L_1 + \tfrac{1}{2} i_2^2 L_2 + i_1 i_2 L_m \qquad \text{(joules)} \tag{89}$$

where L_1 and L_2 are the coefficients of self-induction of the two circuits, and L_m is called the **coefficient of mutual inductance** of the two circuits. All three coefficients are measured in henrys.

84. The coefficient of mutual inductance is also defined from the relations:

$$e_1 = -L_m \frac{di_2}{dt}, \text{ or } e_2 = -L_m \frac{di_1}{dt}, \tag{90}$$

that is, L_m determines the voltage e_1 induced in the circuit (1) when the current i_2 in circuit (2) varies with the time, and *vice versa.*

85. The coefficient of mutual inductance of two long coaxial single-layer coils of the same length l and cross-section A, is

$$L_m = 1.257 n_1 n_2 l A 10^{-8}, \text{ (henrys)}, \tag{91}$$

where n_1 and n_2 are the numbers of turns per centimeter length of the two coils respectively; l and A are measured in centimeters.

86. For two long coaxial coils wound in several layers the coefficient of mutual inductance is

$$L_m = 4 n_1^2 n_2^2 l d_1 d_2 r_1^2 \left(1 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right) \qquad \text{(henrys)} \tag{92}$$

and if an iron core is present

$$L_m = 4 n_1^2 n_2^2 l d_1 d_2 r_1^2 \left[1 + (\mu_r - 1)a^2 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right] \qquad \text{(henrys)} \tag{93}$$

For explanation of notation see Par. **72** above. See also the references in Par. **74**.

87. The coefficient of mutual inductance of two parallel line circuits (Fig. 11*a*) is given by

$$L_m = 0.4605 \log_{10}\left(\frac{a_1 b_2}{b_1 a_2}\right) \qquad \text{(millihenrys per km.)} \tag{94}$$

where a_1 and b_1 are the distances from one of the wires of circuit 1 to the

* Maxwell, J. C. "Treatise on Electricity and Magnetism," Vol. II, p. 324.

wherein I is the total exciting current and θ the angle of time-phase displacement.

The **energy lost per cycle** can be represented by the area, $AfBd$, of the loop; see Par. 94 below.

93. Hysteretic angle. Without hysteresis, the current I would be in phase quadrature with E. For this reason the angle $\alpha = 90 - \theta$ is called **the angle of hysteretic advance of phase.**

$$\text{Sin}\ \alpha = \frac{I_r}{I} = \frac{I_r E}{IE} = \frac{\text{watts loss}}{\text{apparent watts}}. \qquad (95)$$

In practice, the measured loss usually includes eddy currents (Par. 98) so that the name "hysteretic" is somewhat of a misnomer.

94. The energy lost per hysteresis cycle (Fig. 12) is proportional to the area of the loop, or

$$\text{Energy} = cV \sum_{-\mathcal{B}}^{+\mathcal{B}} \mathcal{H}\Delta\mathcal{B} \qquad \text{(joules)} \qquad (96)$$

wherein V is the volume of the iron, $\mathcal{B}$ and $\mathcal{H}$ being the coordinates of the loop instead of Φ and $\mathcal{F}$ as shown in Fig. 12; and c a constant depending upon the scale used. For details see the author's "Magnetic Circuit," Art. 16.

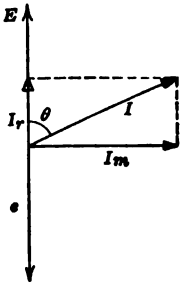

FIG. 13.—Components of exciting current; hysteretic angle.

95. Steinmetz's formula. According to exhaustive experiments by Dr. C. P. Steinmetz, the heat energy released per cycle per cubic centimeter of iron is approximately

$$W = \eta B^{1.6}_{max} \qquad \text{(ergs)} \qquad (97)$$

The exponent of $\mathcal{B}$ varies between 1.4 and 1.8 but is generally taken as 1.6. Values of η are given in Sec. 4 (see index).

96. Power loss per unit weight. The most convenient way to express the **hysteresis loss** is

$$P_h = k_h \frac{f}{100}\left(\frac{\mathcal{B}_{max}}{1000}\right)^{1.6} \qquad \text{(watts per unit weight)} \qquad (98)$$

wherein f is the frequency in cycles per second; $\mathcal{B}$ the maximum flux density in lines or maxwells per square centimeter, and k_h a constant; see Sec. 4.

97. Two-term formula. Another empirical formula for the **hysteresis loss** is

$$P_h = f(\eta' B + \eta'' B^2) \qquad \text{(watts per unit weight)} \qquad (99)$$

where η' and η'' are empirical coefficients. This formula is more accurate at medium and high flux densities than the preceding one.

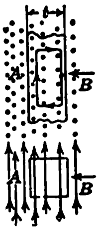

FIG. 14. Eddy currents.

98. Eddy-current losses are I^2R losses (Par. 27) due to secondary currents (Foucault currents) established in those parts of the circuit which are interlinked with alternating or pulsating flux. Referring to Fig. 14, a bar-shaped conductor is just entering a non-uniform field. The advancing side, A, is cutting more lines than the trailing side, B, so that there is a difference in potential between these two sides and electricity will flow as shown by the arrows. The value of the currents, according to Ohm's law, is directly proportional to the e.m.f. and inversely proportional to the resistance of the path. The e.m.f. is directly proportional to the thickness, t, of the bar, but the length of the path, and therefore its resistance, is but slightly altered by varying the thickness, t.

Referring to Fig. 15, which shows a cross-section of a transformer core, the primary current, I, produces the alternating flux, Φ, which by its change generates an e.m.f., e, in the core; this e.m.f. then sets up the secondary treatment of resistance to alternating currents and eddy current losses in metallic conductors see Louis Cohen, "Formulæ and Tables for the Calculation of Alternating-current Problems," Chap. I. Numerous tables and formulæ will be found there, relating to the resistance to alternating currents and eddy current losses in solid, hollow and concentric cylindrical conductors, flat conductors, coils and conductors in slots of laminated iron armatures.

102. Effective resistance and reactance. When an alternating-current circuit has appreciable hysteresis, eddy currents and skin effect, it can be replaced by an equivalent circuit, without these losses, by using **equivalent resistances** and **equivalent reactances** (Par. **154**) in place of the real ones. These equivalent or effective quantities are so chosen that the energy relations are the same in the equivalent circuit as in the actual one. In a series circuit let the true power lost in ohmic resistance, hysteresis, and eddy currents be P, and the reactive (wattless) volt-amperes P'. Then the effective resistance and reactance are determined from the relations

$$i^2r_{eff}=P; \quad i^2x_{eff}=P'. \tag{104}$$

In a parallel circuit, with a given voltage, the equivalent conductance and susceptance (Par. **162**) are calculated from the relations

$$e^2g_{eff}=P; \quad e^2b_{eff}=P'. \tag{105}$$

Such equivalent electric quantities which replace the core loss are used in the analytical theory of transformers and induction motors.

103. Core loss. In practical calculations of electrical machinery the total core loss is of interest rather than the hyteresis and the eddy currents separately. For such computations empirical curves are used, obtained from tests on various grades of steel and iron (see Sec. 4).

104. The separation of hysteresis from eddy currents. For a given sample of laminations, the total core loss P, at a constant flux density and at variable frequency f, can be represented in the form

$$P=af+bf^2 \tag{106}$$

where af represents the hysteresis loss and bf^2 the eddy or Foucault-current loss, a and b being two constants. If we write this equation for two known frequencies, two simultaneous equations are obtained from which a and b are determined.

105. Determination of constants. It is convenient to divide the foregoing equation by f, because in the form

$$\frac{P}{f}=a+bf \tag{107}$$

it represents the equation of a straight line between (P/f) and f. Having plotted the known values of (P/f) against f as abscissæ, the most probable straight line is drawn through the points thus obtained. The intersection of this line with the axis of ordinates gives a; b is calculated from the preceding equation. Knowing a and b, the separate losses are calculated at any desired frequency from the expressions af and bf^2 respectively.

THE DIELECTRIC CIRCUIT

106. Dielectric flux. When a source of continuous voltage E (Fig. 16) is applied at the terminals of a **condenser** AB, a quantity of electricity Q flows through the connecting wires and the same quantity of electricity may be said to be displaced through the dielectric between the condenser terminals, because electricity behaves like an incompressible fluid. This displaced electricity in a dielectric is called the dielectric flux and is measured in the same units as a quantity of electricity in a conducting circuit; that is, in coulombs or in microcoulombs.

107. The dielectric flux density and the potential gradient. The flux density D or the dielectric flux per unit area is $D=Q/A$ when the flux distribution is uniform, or $D=\partial Q/\partial A$ when the flux distribution is non-uniform. In these expressions Q is the dielectric flux and A is the area perpendicular to the electrostatic lines of force. Flux density is measured in microcoulombs per square centimeter or per square inch.

The voltage E applied at the terminals of the condenser acts upon the whole thickness l of the dielectric, and the **dielectric stress** G is characterized as the voltage per unit thickness (unit length) of the dielectric in the direction

112. The specific inductive capacity of a dielectric (k) is the ratio between the capacity of a condenser made entirely of this dielectric and of an identical condenser using air for dielectric. It is also termed the **dielectric constant.** Another name for specific inductive capacity is **relative permittivity.** For numerical values for various dielectrics see Sec. 4.

113. Capacity (permittance) between parallel plates. When a condenser consists of two parallel plates the distance between which is small compared to the dimensions of the plates, the lines of electrostatic displacement are nearly straight lines normal to the adjacent surfaces of the plates. The capacity of such a condenser is

$$C=\left(\frac{k}{4\pi}\right)\frac{A}{l} \qquad \text{(abstatfarads)} \qquad (115)$$

where A is the area of one of the plates in sq. cm., l the normal distance between them, in cm. and $k/4\pi$ the **permittivity** of the dielectric; k is the dielectric constant, which for air is unity. If C is to be in microfarads, then in the preceding formula in place of $k/4\pi$ use

$$\frac{k}{4\pi}\left(\frac{1}{v^2}\right)=0.08842\times k\times 10^{-6} \qquad \text{(mf. per centimeter-cube)} \qquad (116)$$

where v is the velocity of light, or the factor required to change from electrostatic to electromagnetic units.

If instead of taking $k/4\pi$ as the permittivity, a term k_a called the absolute permittivity is introduced, then

$$C=k_a\frac{A}{l} \qquad \text{(microfarads)} \qquad (117)$$

And for air, instead of unity (the relative permittivity), the absolute permittivity is

$$\kappa_a=0.08842\times 10-^6 \qquad \text{(mf. per centimeter-cube)} \qquad (118)$$

and for any other substance the absolute permittivity would be $0.08842\times 10^{-6}k$, where k is the specific inductive capacity or the relative permittivity of the dielectric; see Par. **112.** See also the author's "Electric Circuit," Article 51, for further elaboration of this theory of absolute versus relative permittivities. At present the accepted method of calculation is based on the use of formulæ (115) and (116).

114. The elastance of a dielectric between two parallel plates a short distance apart is $S=\sigma\,(l/A)$ where the coefficient σ (sigma) is called the **elastivity of the dielectric.** If S is in megadarafs (1 daraf is the reciprocal of 1 farad) and the dimensions in centimeters, σ is in megadarafs per centimeter cube. Elastance is the reciprocal of permittance, or $S=1/C$, and, likewise, elastivity is the reciprocal of permittivity, or $\sigma=4\pi/k$ Therefore

$$S=\left(\frac{4\pi}{k}\right)\frac{l}{A}=\sigma\frac{l}{A} \qquad (119)$$

For air, in practical units,

$$\sigma=11.31\times 10^6 \text{ mgd. per centimeter cube.} \qquad (120)$$

Example; to calculate the capacity of a plate condenser (Fig. 16) built according to the following specifications: The metal plates are 50 cm. by 70 cm. each, placed at a normal distance of 0.3 cm. The dielectric consists of three consecutive layers of insulation, which are 0.12 cm., 0.07 cm. and 0.11 cm. thick. The relative permittivities of the materials are 2, 3 and 5 respectively. Since elastances are added in series (Par. **110**), the total elastance of the condenser is

$$S=[11.3\times 10^6/(50\times 70)][0.12/2+0.07/3+0.11/5]$$
$$=0.34\times 10^3 \text{ mgd.}$$

Hence the capacity $C=S^{-1}=2.94\times 10^{-3}$ mf.

115. Capacity of concentric cables. For a single-conductor cable with a grounded metal sheath (Fig. 17) the capacity

$$\left.\begin{aligned} C&=\frac{0.03882k}{\log_{10}(b/a)} \quad \text{(mf. per mile) or} \\ C&=\frac{0.02413k}{\log_{10}(b/a)} \quad \text{(mf. per km.)} \end{aligned}\right\} \qquad (121)$$

of the preceding value. The transverse dimensions may be either in inches or in centimeters because only their ratio enters in the formula.

119. A three-conductor cable may be treated in a similar way (Fig. 20). The sheath is replaced by three equally spaced conductors of the same diameter and spaced according to the relation $ba = d^2$. The **capacity of a single conductor is**

$$C = \frac{0.07764k}{\log_{10}\left[\frac{3a^2(d^2-a^2)^3}{r^2(d^6-a^6)}\right]} \quad \text{(mf. per mile)} \qquad (126)$$

where the transverse dimensions are in inches or in centimeters.

120. The capacity of a single-phase transmission line per wire, or the permittance between one of the wires and the plane of symmetry is

$$C = \frac{0.03882}{\log_{10}(b/a)} \quad \text{(mf. per mile)} \qquad (127)$$

where a is the radius of the wire, and b the spacing between the centres. The capacity between the two conductors is equal to one-half of that given by the formula above. For values of charging current at standard frequencies see tables in Sec. 11.

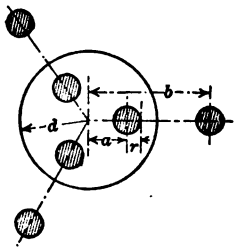

Fig. 20.—Three-conductor cable; showing electrical images due to the grounded sheath.

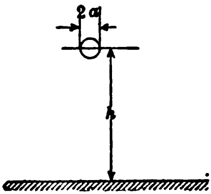

Fig. 21.—Overhead conductor.

121. The capacity of a single overhead conductor with ground return (Fig. 21) is

$$C = \frac{0.03882}{\log_{10}(2h/a)} \quad \text{(mf. per mile)} \qquad (128)$$

122. When a single-phase line with metallic return is suspended sufficiently near the ground its capacity is somewhat increased. Let the wires be suspended at the heights h_1 and h_2 above the ground; then calculate the capacity according to formula in Par. **120**, using the corrected spacing (see the author's "Electric Circuit," Art. 61)

$$b_e = \frac{b}{\sqrt{1+(0.25b)^2/h_1h_2}} \qquad (129)$$

When the heights of suspension h_1 and h_2 are greater than 3.5 times the spacing b, the difference between b and the corrected spacing b_e is less than 1 per cent. The correction in formula (117) is still smaller, because logarithms of numbers vary more slowly than the numbers themselves.

In formulæ (128) and (129) a perfectly conducting ground is assumed. With dry non-conducting earth the increase in capacity is somewhat less.

123. Capacity of a three-phase line with symmetrical spacing. The concept of the capacity of a three-phase line is not definite without further qualifications. In practice a three-phase line is calculated by reducing it to an equivalent single-phase line consisting of one of the conductors of the three-phase line and a ground return. This equivalent single-phase line carries one-third of the total power transmitted by the three-phase line an element of volume ∂v and integrating within the desired limits. For an interesting comparison of practical possibilities as to the amount of energy stored in the dielectric form per unit volume, compared with other forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, p. 536.

129. A system of charged bodies (Fig. 23). The **total charges** on the individual conductors are expressed by the equations

$$\left.\begin{aligned} q_1 &= C_1v_1 + C_{12}(v_1 - v_2) + C_{13}(v_1 - v_3) + \text{ etc.,} \\ q_2 &= C_2v_2 + C_{21}(v_2 - v_1) + C_{23}(v_2 - v_3) + \text{ etc.,} \end{aligned}\right\} \quad (135)$$

where v_1, v_2, v_3, etc., are the potentials of these conductors above the ground. The coefficients C_1, C_2, C_3, etc., are called the **partial capacities** of the conductors; C_{12}, C_{23}, etc., are called **mutual capacities.** Their computation is possible in a few simple cases only, but having determined them experimentally, it is possible to calculate from the preceding equations the resultant or equivalent capacity of the system under various operating conditions.

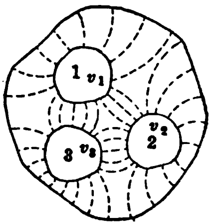

Fig. 23.—System of charged bodies.

130. Maxwell's equations of a charged system. The same equation may be written in Maxwell's form

$$\left.\begin{aligned} q_1 &= K_{11}v_1 + K_{12}v_2 + K_{13}v_3 + \text{etc.,} \\ q_2 &= K_{21}v_1 + K_{22}v_2 + K_{23}v_3 + \text{etc.,} \end{aligned}\right\} \quad (136)$$

where the coefficients K_{11}, K_{22}, etc., are called the capacities of the individual conductors, and the negative quantities K_{12}, K_{23}, etc., are called **coefficients of mutual induction.**

131. Coefficients in Maxwell's equations. The following relations hold between the coefficients K and C:

$$\left.\begin{aligned} K_{11} &= C_1 + C_{12} + C_{13} + \text{etc.} \\ K_{22} &= C_2 + C_{21} + C_{23} + \text{etc.} \\ K_{12} &= -C_{12};\ K_{21} = -C_{21}, \text{ etc.} \end{aligned}\right\} \quad (137)$$

132. The electrostatic energy stored in the field is

$$W = \tfrac{1}{2}K_{11}v_1^2 + \tfrac{1}{2}K_{22}v_2^2 + \text{etc.} + K_{12}v_1v_2 + K_{13}v_1v_3 + K_{23}v_2v_3 + \text{etc.} \quad (138)$$

W is expressed in joules (watt-seconds) if the potentials are in volts and the capacities in farads.

133. The dielectric strength of insulating materials, or the rupturing voltage gradient, is the maximum voltage per unit thickness which a dielectric can stand in a uniform field, before it breaks down electrically. The dielectric strength is usually measured in kilovolts per millimeter or per inch. The only correct way is to refer the dielectric strength to a uniform field, for instance, between large parallel plates placed at a short distance apart. If the striking voltage is determined between two spheres or electrodes of some other shape, the fact should be distinctly stated. In designing insulation a factor of safety is assumed depending upon the conditions of operation. For numerical values of the rupturing voltage gradients of various materials see Sec. 4.

134. The critical dielectric flux density is the density at which the material breaks down. It is determined from the relation

$$D_{max} = 0.08842kG_{max} \times 10^{-2}, \quad (139)$$

where D_{max} is the critical density in microcoulombs per square centimeters G_{max} is the **rupturing voltage gradient** in kilovolts per millimeter, and k is the relative permittivity of the material (Par. **112**).

135. Electrostatic corona. When the electrostatic flux density in the air exceeds a certain value, a pale violet light appears near the adjacent metal surfaces; this silent discharge is called the electrostatic corona. In the regions where the corona appears, the air is electrically broken down, and ionized so that it becomes a conductor of electricity. When the voltage is raised still higher a brush discharge takes place, until the whole thickness of the dielectric is broken down and a disruptive discharge, or spark, jumps from one electrode to the other.

The formation of corona leads to power loss which may be serious in some circuit is suddenly connected to a source of continuous voltage e, the current gradually rises to the final value $i_o = e/r$ according to the law

$$i = i_o(1 - \epsilon^{-tr/L}), \tag{140}$$

where t is time, and ϵ is the base of natural (or hyperbolic) logarithms. This expression is known as **Helmholtz's law.** When the source of e.m.f. is short-circuited the current in the remaining circuit decreases to zero according to a similar law

$$i = i_o\epsilon^{-tr/L}. \tag{141}$$

141. Periodic e.m.f. When a de-energized circuit containing r and L is suddenly connected at the instant $t = 0$, to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit varies according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha - \phi) - \frac{E_m}{z}\sin(\alpha - \phi)\epsilon^{-tr/L} \tag{142}$$

In this equation $z = \sqrt{r^2 + (2\pi fL)^2}$ is the impedance of the circuit and ϕ is the phase displacement between the current and the voltage, determined by $\tan\phi = 2\pi fL/r$. The angle α is the phase displacement between the voltage e and the reference wave which passes through zero at the time $t = 0$; f is the frequency. The first term in the expression for i is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. (See also Eq. 146.)

142. Closing a circuit containing a resistance r (ohms) and a capacity C (farads) in series. The charging current is theoretically expressed by

$$i = i_o\epsilon^{-t/(rC)}, \tag{143}$$

where i_o is the current at the first instant. This equation is not applicable to the beginning of the charge because it presupposes a sudden jump of the current from zero to i_o. In reality, the unavoidable inductance of the circuit smoothes down the initial change in current.

When a condenser, charged at a voltage e_o, is discharged through resistance r, the discharge current at the first instant is theoretically equal to $i_o = e_o/r$, and then varies according to the law

$$i = i_o\epsilon^{-t/(rC)} \tag{144}$$

The voltage across the condenser terminals decreases according to a similar law

$$e = e_o\epsilon^{-t/(rC)} \tag{145}$$

When a de-energized circuit containing r and C is suddenly connected at the instant $t = 0$ to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit will vary according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha + \phi) - \frac{E_m}{z}\sin(\alpha + \phi)\epsilon^{-t/(rC)} \tag{146}$$

In this equation $z = \sqrt{r^2 + [1/(2\pi fC)]^2}$ is the impedance of the circuit, and ϕ is the phase displacement between the current and the voltage, determined by $\cot\phi = 2\pi fCr$. The angle α is the phase displacement between the voltage e and the reference wave which passes through zero at the time $t = 0$; f is the frequency. The first term in the expression for i is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. Compare Par. **141.**

143. Single-energy and double-energy transients. The two preceding cases are examples of single-energy transients, because the energy is stored in one form only (electromagnetic or electrostatic), and the energy change consists in an increase or a decrease of the stored energy. In the case of inductance the energy is that of the magnetic field and in the case of capacity it is the energy of the electrostatic field. When both inductance and capacity are present, the energy of the circuit is stored in two forms, and there is a possibility of periodic transformation of the magnetic energy into the dielectric energy, and *vice versa*, which constitutes electric oscillations, surges, and waves. There is also a possibility of a **triple-energy transient**, when for instance a synchronous motor is hunting at the end of a long transmission line which possesses inductance and capacity. In the last successfully used for wireless telegraphy. See Poulsen, V., "System for Producing Continuous Electric Oscillations," *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, p. 963. Also Austin, L. W., "The Production of High-frequency Oscillations from the Electric Arc," *Bulletin* of the Bureau of Standards, Vol. III (1907), p. 325.

149. Stored energy. When a considerable amount of energy is liberated at some point on a transmission line, for instance due to an indirect lightning stroke, a wave starts along the line carrying this energy to the ends of the line. Part of it enters the apparatus at the ends, part is reflected and the rest is converted into heat. Generally speaking, the total energy stored in the line, or in some part of it, at an instant is

$$W = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Ce^2, \qquad \text{(joules)} \qquad (154)$$

where L is the inductance of the line in henrys, i an instantaneous current, C the capacity of the line in farads, and e an instantaneous voltage. The term $\tfrac{1}{2}Li^2$ represents the electromagnetic energy, the term $\tfrac{1}{2}Ce^2$ the electrostatic energy. At certain instants the current is equal to zero, at others the voltage is zero, so that the two energies must be equal. Therefore

$$\frac{e_{max}}{i_{max}} = \sqrt{\frac{L}{C}}. \qquad \text{(ohms)} \qquad (155)$$

Thus, knowing the maximum voltage e_{max}, the largest instantaneous current i_{max} can be calculated, and *vice versa*. For instance, in the case of a lightning stroke, the maximum voltage is limited by the disruptive strength of the insulation to instantaneous voltages, and the maximum current disturbance may be calculated from the preceding equation.

150. Surge impedance. With concentrated inductance and capacity, the frequency of oscillations is (Par. 147)

$$f_o = \frac{1}{2\pi\sqrt{LC}}. \qquad (156)$$

With **uniformly distributed inductance and capacity, the frequency is**

$$f_o{}^1 = \frac{1}{4\sqrt{LC}}. \qquad (157)$$

The expression $\sqrt{L/C}$ is called **the natural impedance or the surge impedance of the line**, and its reciprocal **the natural admittance or the surge admittance.** For further information consult the references in Par. 139 above.

ALTERNATING-CURRENT CIRCUITS

151. Sine-waves. In this treatment of alternating-current circuits, a sine-wave is arbitrarily assumed. For non-sinusoidal currents and voltages see Par. 190 and following. Beginning with non-inductive circuits, *i.e.*, circuits which contain only resistance, the current at any instant is proportional to the instantaneous value of the impressed e.m.f. Plotting the instantaneous values of the e.m.f. and the current, it is seen, Fig. 24, that the waves pass through zero and reach their maximum values at the same instant. They are said to be **in phase.**

152. Instantaneous values. Let the amplitude or the instantaneous maximum value of the voltage be E_{max}, then the instantaneous value is

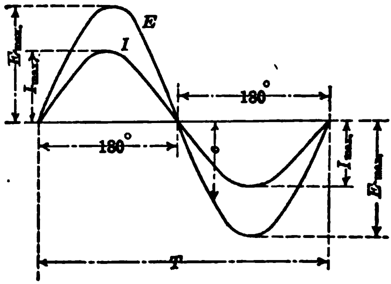

Fig. 24.—Simple sine-waves; non-inductive circuit.

$$e = E_{max} \sin 2\pi ft \qquad (158)$$

where f is the frequency in cycles per second, and t is time in seconds. The angle $2\pi ft$ is in radians. If the time of one complete cycle is T (Fig. 24), $f = 1/T$.

is called capacity reactance, or condensive reactance. When inductive reactance x (Par. 154) and condensive reactance x_c enter in the same circuit, x_c is considered negative. When C is in farads, x_c is in ohms.

159. E.m.f. components. In a circuit containing resistance and condensive reactance in series, the applied e.m.f. may be divided into two components; one consumed in resistance drop and the other in the condensive reactance. The current taken by the condensive reactance is proportional to the rate of change of the e.m.f., which is impressed across its terminals, therefore the counter-e.m.f. of the condensive reactance is in time-quadrature with the current. Referring to Fig. 26, I is the total current in phase with E_r which is the e.m.f. consumed in resistance; E_c is the voltage necessary to balance the counter-e.m.f. of the condensive reactance, and E is the total e.m.f. impressed upon the circuit. It will be seen that in this case the current is leading.

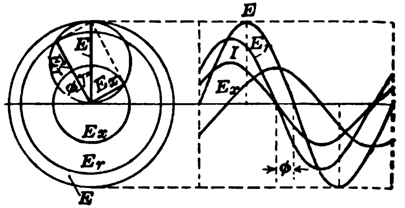

Fig. 26.—E.m.f. and current waves in a circuit containing resistance and capacity reactance in series.

If the instantaneous applied voltage is expressed as in (152), the instantaneous current is

$$i = I_{max} \sin (2\pi ft + \phi). \tag{166}$$

In this expression, the **phase angle** ϕ between the current and the voltage is determined from the relation

$$\tan \phi = \frac{1}{2\pi fCr} = \frac{x_c}{r}. \tag{167}$$

160. Terminology. The following terminology used in application of **sine-wave alternating-current circuits** is recapitulated here for the sake of convenience. An **instantaneous value** of alternating current or voltage (Fig. 24) is connected with the **maximum value** or the **amplitude** by the relation given in Par. 152. The **mean effective value**, also called the **root-mean-square value**, or simply the **effective value** of an alternating current or voltage is defined in Par. 199. For a sine-wave quantity the effective value is equal to the amplitude divided by $\sqrt{2}$; or

$$E_{eff} = \frac{E_{max}}{\sqrt{2}} = 0.7071E_{max}. \tag{168}$$

The **mean or average value** of a sinusoidal alternating current or voltage is equal to the maximum value divided by $\pi/2$, or

$$E_{ave} = \frac{2E_{max}}{\pi} = 0.6366E_{max}. \tag{169}$$

The ratio between the effective and the average value is called the **form factor** (Par. 207) and is equal to 1.11 for sine-waves.

161. Periodic time. The interval of time T in Fig. 24. corresponds to one complete cycle. The interval of time $T/2$ corresponding to one-half wave is called an **alternation**, and for every cycle there are two alternations. The **frequency** or the **periodicity** of an alternating current may be expressed either in cycles per second or in alternations per minute. However, the latter method is not common.

162. The phase displacement between two currents or two voltages, or between a current and a voltage, is commonly measured in **electrical degrees.** One electrical degree is 1/360th part of a complete cycle.

163. Vector representation. Alternating currents and voltages which vary according to the sine or cosine law can be represented graphically by directed straight lines called **vectors** (Fig. 27). The length of a vector represents, to some arbitrary scale, the effective value of the alternating

If E is the voltage across the circuit, then

$$I_r = E\left(\frac{r}{r^2+x^2}\right) = Eg \qquad \text{(amp.)} \qquad (179)$$

$$I_x = E\frac{x}{r^2+x^2} = Eb \qquad \text{(amp.)} \qquad (180)$$

$$I = \sqrt{(Eg)^2+(Eb)^2} = E\frac{1}{z} = Ey \qquad \text{(amp.)} \qquad (181)$$

In these expressions

$$g = \frac{r}{z^2} = \text{conductance} \qquad \text{(mho)} \qquad (182)$$

$$b = \frac{x}{z^2} = \text{susceptance} \qquad \text{(mho)} \qquad (183)$$

$$y = \frac{1}{z} = \text{admittance} \qquad \text{(mho)} \qquad (184)$$

$$\tan\phi = \frac{I_x}{I_r} = \frac{b}{g};\ \cos\phi = \frac{I_x}{I} = \frac{g}{y}. \qquad (185)$$

170. Resistance and condensance in parallel. In a circuit consisting of a resistance and a capacity in parallel the same relations hold except that the current is leading, and x_c is used in place of x (Par. 168). If there is any doubt whether the quadrature current is caused by an inductance or a capacity, use the expressions inductive susceptance and capacity (or condensive) susceptance. The latter is sometimes called **capacitance.** Fig. 28 also shows, in dotted lines, the resultant current when a pure resistance and a pure condensance are connected in parallel; in such case the phase angle ϕ becomes an angle of lead.

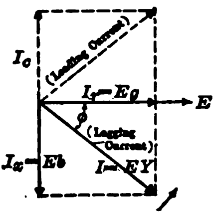

Fig. 28.—Vector diagram of currents; pure resistance in parallel with pure inductive reactance.

171. Impedances in series. In a circuit containing several resistances and reactances in series, the resistances should be added together and the reactances added together, so that

$$\left.\begin{aligned} r_{eq} &= \Sigma r; \\ x_{eq} &= \Sigma x; \end{aligned}\right\} \qquad (186)$$

$$z_{eq} = \sqrt{(\Sigma r)^2+(\Sigma x)^2}. \qquad (187)$$

The subscript *eq* stands for equivalent.

172. Impedances cannot be added algebraically, but must always be added geometrically, or vectorially. Since

$$r = z\cos\phi, \text{ and } x = z\sin\phi, \qquad (188)$$

the preceding equation gives

$$z_{eq} = \sqrt{(\Sigma z\cos\phi)^2+(\Sigma z\sin\phi)^2}. \qquad (189)$$

173. Admittances in parallel. In a circuit consisting of several parallel branches the conductances should be added together and the susceptances added together (Par. 169) so that,

$$\left.\begin{aligned} g_{eq} &= \Sigma g \\ b_{eq} &= \Sigma b \end{aligned}\right\} \qquad (190)$$

and

$$y_{eq} = \sqrt{(\Sigma g)^2+(\Sigma b)^2}. \qquad (191)$$

174. Admittances cannot be added algebraically, but must always be added geometrically, or vectorially. Since

$$g = y\cos\phi, \text{ and } b = y\sin\phi, \qquad (192)$$

the preceding equation gives

$$y_{eq} = \sqrt{(\Sigma y\cos\phi)^2+(\Sigma y\sin\phi)^2}. \qquad (193)$$

175. Equivalent series and parallel combinations. Let r_s and x_s be a resistance and a reactance connected in series and let r_p and x_p be a

Considering the series circuit shown in Fig. 30, let it be required to study the current when the resistance and reactance are varied, the e.m.f. being kept constant. With E as a diameter draw the circle. *Obc*, then *Obc* is the e.m.f. or impedance triangle and θ is the angle of phase displacement between I and E. Dividing the current, I, into imaginary components, E/r is laid off along OC in phase with E, and E/x is laid off along OA in quadrature with E. Drawing the line AC, and the circles, OBA and OBC, the line, OB, represents the current, I, both as to value and phase position. If x is constant and r variable, the point, B, will travel along the circle, OBA, while if r is constant and x variable, the point, B, will travel along the circle, OBC.

178. Circle diagram; parallel circuits. Referring to the parallel circuit in Fig. 31, let it be required to study the e.m.f. when the conductance and susceptance are varied, the current remaining constant. With I as diameter draw the circle *Obc*, then *Obc* is the current or admittance triangle and θ is the angle of phase displacement between E and I. Dividing the e.m.f. into components, I/b is laid off along OA in quadrature with I; then drawing the line, AC, and the circles, OBA and OBC, the line, OB, represents the e.m.f., E, both as to value and phase position. The circle, OBA, is the locus of the point, B, when b is constant and g variable, while the circle, OBC, is the locus of the point, B, when g is constant and b variable.

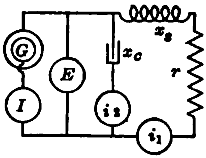

Fig. 32.—Condensance in parallel with inductive impedance.

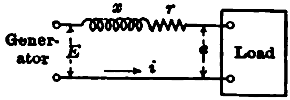

Fig. 33.—Load connected to inductive line.

179. Phase compensation. Condensive reactance connected **in shunt with an inductive impedance** can be so adjusted as to bring the total current more or less in phase with the impressed e.m.f. Referring to Fig. 32, x_c and the impedance z_s are in parallel, where

$$z_s^2 = r^2 + x_s^2. \tag{198}$$

Taking the admittances,

$$g_1 = \frac{r}{z_s^2};\; g_2 = 0;\; b_1 = \frac{x_s}{z_s^2};\text{ and } b_2 = -\frac{1}{x_c}. \tag{199}$$

In order that I be in phase with E, $b_1 + b_2$ must be equal to zero, or

$$x_c = \frac{z_s^2}{x_s}. \tag{200}$$

Thus, it is seen that the value of x_c depends upon the resistance, r, as well as upon x_s:

$$i_2 = E\frac{1}{x_c} = Eb_2;\; i_1 = E\sqrt{\left(\frac{r}{z_s^2}\right)^2 + \left(\frac{x_s}{z_s^2}\right)^2} = E\sqrt{g_1^2 + b_1^2}, \tag{201}$$

$$I = E\sqrt{\left(\frac{r}{r^2 + x_s^2}\right)^2 + \left\{\left(\frac{x_s}{r^2 + x_s^2}\right) - \frac{1}{x_c}\right\}^2} = E\sqrt{g^2 + b^2},\text{ in amp.} \tag{202}$$

180. Leading current through an inductive line will raise the e.m.f. at the receiving end of the circuit. Referring to Fig. 33, let E be the voltage at the generator end of a circuit, e the voltage at the receiver end, and i the line current. Let the load be of such a nature that the current is leading with respect to the voltage e. Adding to e the ohmic drop ir in the line (Fig. 34*a*) in phase with i, and the reactive drop ix in leading quadrature with i, the impressed voltage E is obtained. It will be seen that $E < e$; but with a lagging current, $E > e$ (Fig. 34*b*).

181. Series resonance. In a constant-potential circuit which contains inductive reactance and also condensive reactance in series, it is possible

But the total admittance y may be smaller than b_c, and in this case the total line current I is less than one of its components i_c. A similar relation may be proved for i_s. When the frequency is

$$f = \frac{1}{2\pi\sqrt{LC}}, \quad \text{(cycles per second)} \tag{212}$$

it follows that

$$b_s = b_c, \tag{213}$$

and

$$I = Eg, \quad i_s = -i_c. \tag{214}$$

The line current is comparatively small, but there is a large interchange of current between the inductance and the capacity, in parallel.

Resonance can occur at only one frequency. Sometimes, in the case of a complex wave, it occurs at the frequency of one of the component harmonics instead of the fundamental frequency. In such case, either for voltage or current (series or parallel resonance), the magnitude of the resonant harmonic component is much exaggerated, as compared with its normal magnitude in a non-resonant circuit. The condition of resonance, except in tuned circuits where it is specially desired (as in radio-telegraphy), is one to be avoided.

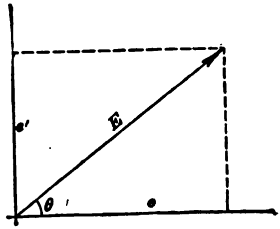

Fig. 35.—Complex quantities; axes of reals and imaginaries.

183. Consonance. Resonance in the primary circuit of a transformer, caused by the proper combination of inductance and capacity in the secondary circuit, is called consonance.

184. Alternating currents and voltages treated by means of complex (imaginary) quantities. If e and e' (Fig. 35) are the projections or the components of a vector E along two perpendicular axes, then the vector $\underset{\cdot}{E}$ may be represented symbolically as

$$\underset{\cdot}{E} = e + je', \tag{215}$$

where

$$j = \sqrt{-1}, \tag{216}$$

and the dot under E signifies that the magnitude as well as the direction of E is meant.

185. Addition and subtraction of vectors. Let two vectors of voltage be represented as

$$\underset{\cdot}{E}_1 = e_1 + je'_1, \tag{217}$$

$$\underset{\cdot}{E}_2 = e_2 + je'_2. \tag{218}$$

Then the sum or the difference of these two vectors is

$$\underset{\cdot}{E}_3 = E_1 \pm \underset{\cdot}{E}_2 = (e_1 \pm e_2) + j(e'_1 \pm e'_2). \tag{219}$$

186. Rotation of a Vector. Multiplying a vector by j turns it by 90 deg. in the positive direction (counter-clockwise). Thus,

$$j\underset{\cdot}{E} = j(e + je') = -e' + je, \tag{220}$$

because $j^2 = -1$. Multiplying a vector by $-j$ rotates the vector by 90 deg. in the negative direction—that is, clockwise.

A vector $\underset{\cdot}{E}$ may be also represented symbolically (Fig. 35) as

$$\underset{\cdot}{E} = E(\cos\theta + j\sin\theta), \tag{221}$$

where E without the dot, on the right-hand side of the equation, stands for the magnitude only.

The operator

$$\epsilon^{j\phi} = \cos\phi + j\sin\phi, \tag{222}$$

where ϵ is the base of natural logarithms, turns a vector by the angle ϕ in the positive direction. Thus,

$$\underset{\cdot}{E}(\cos\phi + j\sin\phi) = E(\cos\theta + j\sin\theta)(\cos\phi + j\sin\phi) = E[\cos(\theta + \phi) + j\sin(\theta + \phi)]. \tag{223}$$

NON-SINUSOIDAL OR COMPLEX WAVES

190. Examples of complex waves. The curves shown in Fig. 36 illustrate the effect of the inductance and the capacity in a circuit to which is applied an alternating e.m.f., differing from the simple sine-wave. The curves were taken simultaneously with an oscillograph. E is the impressed e.m.f.; I_s the current taken by an inductance coil, and I_c that taken by a condenser. Fig. 37 shows the circuit.

191. Wave of reactive e.m.f. due to inductive reactance. Assuming the reluctance of the iron core in the inductance coil to be constant, which is approximately true below the saturation point, the value of the flux is proportional to the current I_s. The instantaneous value of the e.m.f. E (see Par. 67) is

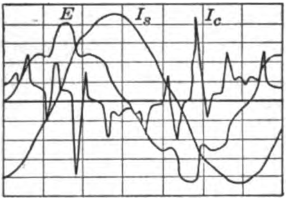

FIG. 36.—Complex alternating-current waves.

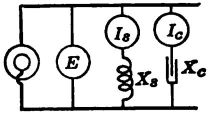

FIG. 37.—Circuit in which the waves of Fig. 36 were observed.

$$e = n\frac{d\phi}{dt} = L\frac{di}{dt} \tag{236}$$

that is, the curve E will have its maximum amplitude when the curve I_s passes through zero. This is not exactly true in this case, because of a small loss in the resistance and the iron; the current to supply this loss being in phase with the e.m.f. E.

192. Wave of current through condensive reactance. The condenser current is proportional to the rate of change of the e.m.f. (see Par. 108); the instantaneous value is

$$i_c = C\frac{de}{dt}, \tag{237}$$

that is, the curve, I_c, has its maximum when the rate of change of the curve, E, is a maximum. Were E a sine curve, I would be also a sine curve and would be in quadrature with E, but when the curve of e.m.f. is not a sine curve, as in Fig. 36, the maximum amplitude of the current will occur at the point where the slope of the e.m.f. curve is a maximum.

193. Effects of inductive and condensive reactance on wave form. These curves show the effect upon the current wave form of inductive reactance and condensive reactance. The curve, E, is the wave form produced by the generator; it contains several harmonics (see Par. 209). The inductive reactance tends to damp out the higher harmonics, while the condensive reactance emphasizes them.

194. Determination of total complex current wave. When the applied voltage contains higher harmonics (Par. 209) the total current through an impedance is found by summing the harmonic currents due to each harmonic of the voltage acting alone. Thus, the reactance at the fundamental frequency f is $x_1 = 2\pi fL$, the reactance to the nth harmonic is $x_n = 2\pi nfL$, and the impedance to the nth harmonic is

$$z_n = \sqrt{r^2 + (2\pi nfL)^2}. \tag{238}$$

195. Power and energy. The general expression for the energy delivered to an alternating-current circuit with any wave form of current and voltage is

$$W = \int_{t_1}^{t_2} eidt \text{ (joules or watt-seconds)}, \tag{239}$$

into k equal parts by $k+1$ equidistant ordinates y_0, y_1, etc., y_k, where k is an even number. Then the effective value is

$$y_{eff} = \frac{1}{\sqrt{3k}}\left[y_0^2+4(y_1^2+y_3^2+\text{etc.}+y_{k-1}^2)+2(y_2^2+y_4^2+etc+y_{k-2}^2)+y_k^2\right]^{\frac{1}{2}}. \tag{243}$$

203. Third method. If the irregular wave is given in terms of its harmonics, then the effective value is

$$y_{eff} = 0.7071\sqrt{A_1^2+A_3^2+\text{etc.}}, \tag{244}$$

where A_1, A_3, etc., are the amplitudes of the separate harmonics.

204. Fourth method. Replot the given irregular curve (Fig. 38) in polar coordinates (Fig. 39), and determine the area A_p, of the polar curve, with a planimeter, or by plotting on homogeneous paper of known area and weight, then cutting out and weighing again; the areas are then proportional

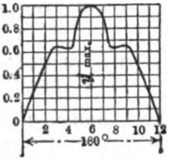

FIG. 38.—Complex wave in rectangular coordinates.

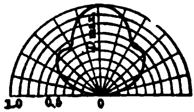

FIG. 39.—Complex wave of Fig. 38 in polar coordinates.

to the weights. This area must be expressed in units, y^2_{max}, as taken from Fig. 38. This is done by multiplying the area, A_p, of the polar curve by the ratio $\left(\frac{y_{max}}{\rho_{max}}\right)^2$; y_{max} and ρ_{max} are measured in terms of the same units.

The mean effective ordinate is

$$y_{eff} = \frac{y_{max}}{\rho_{max}}\sqrt{\frac{2A_p}{\pi}}, \qquad \text{in terms of } y_{max}. \tag{245}$$

205. Generalization of fourth method. The latter method has been generalized by Mr. C. O. Mailloux for determining the effective value of direct current taken by an electric car or a train during a run. For a detailed treatment and numerous practical applications see his paper "Methode de Determination du Courant Constant Produisant le Même Echauffement qu'un Courant Variable," in the Transactions of the International Electrical Congress held at Turin (Italy), 1911.

206. The amplitude factor is the ratio of the maximum ordinate to the mean effective ordinate, thus

$$\frac{y_{max}}{y_{eff}} = \text{amplitude factor}. \tag{246}$$

207. The form factor is the ratio of the mean effective ordinate to the mean ordinate, thus

$$\frac{y_{eff}}{y_{mean}} = \text{form factor}. \tag{247}$$

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including the two given ones, be denoted y_0, y_1, y_2, etc., y_n. Then the area of the curve is

$$A = \tfrac{1}{3}h[y_0+4(y_1+y_3+y_5+\text{etc.}+y_{n-1})+2(y_2+y_4+y_6+\text{etc.}+y_{n-2})+y_n],$$

where h is the distance between any two adjacent ordinates. The greater the number of strips (n), the more nearly the foregoing formula represents the area of the given curve.

θ_n being measured in terms of the *n*th harmonic. Assuming time measured to the right and ordinates measured up as positive, and quantities measured in opposite directions as negative, positive values of θ_n indicate that the nearest intersection of the *n*th harmonic with the axis is to the right of the intersection of the resultant wave with the axis, and positive values of B_n indicate that the *n*th harmonic is rising at its nearest intersection with the time axis. The values obtained with the above equations for the *n*th harmonic are affected by the harmonics which are multiples thereof, that is $2n$, $3n$, etc. This correction is practically negligible for all harmonics, except the first or fundamental, and a correction rarely needs to be carried beyond the ninth harmonic. Since wave forms in practice almost never contain even harmonics, they do not enter into the correction, and denoting the corrected values by prime, we have:

$$A'_n = A_n - A'_{3n} - A'_{5n} - A'_{7n} - \ \ldots \qquad (252)$$

and

$$B'_n = B_n + B'_{3n} - B'_{5n} + B'_{7n} - \ \ldots \qquad (253)$$

When applying this to the first harmonic, A_n is the ordinate of the resultant wave at y_0 (Fig. 40*b*), and B_n is the ordinate 90 time-degrees therefrom at y_3.

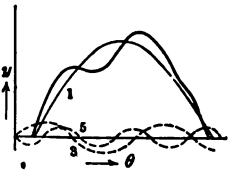

FIG. 40a.—Wave analysis, Par. 211.

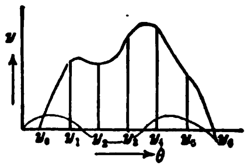

FIG. 40b. Wave analysis, Par. 211.

211. Example of wave analysis. As an example,* assume the wave given in Fig. 40*a*, which is split into three harmonics; the first or fundamental, the third and the fifth. Fig. 40*b* shows the method of determining a given harmonic, in this case the third. The base of the wave is divided into $2n$ or six equal parts and ordinates erected. Assume the ordinates to measure as follows:

$$y_1 = 676;\ y_2 = 660;\ y_3 = 940;\ y_4 = 1004;\ y_5 = 554;\ y_6 = 0. \qquad (254)$$

then,

$$A_3 = \tfrac{1}{3}(y_4 - y_2) = \frac{1004 - 660}{3} = 114.7, \qquad (255)$$

and

$$B_3 = \tfrac{1}{3}(y_1 + y_5 - y_3) = \frac{676 + 554 - 940}{3} = 96.7. \qquad (256)$$

The maximum ordinate is

$$\sqrt{(114.7)^2 + (96.7)^2} = 150 \qquad (257)$$

and the phase angle is

$$\theta_3 = \tan^{-1}\left(\frac{-114.7}{96.7}\right) = -50 \text{ deg.}\dagger \qquad (258)$$

In a similar manner it is found that $A_5 = -92.8$, and $B_5 = 37.4$. In this example the wave contains only the third and the fifth harmonics; therefore, the fundamental is determined as follows:

$$A_1 = y_0 - A'_3 - A'_5 = 0 - 114.7 + 92.8 = -21.9;$$
$$B_1 = y_3 + B'_3 - B'_5 = 940 + 96.7 - 37.4 = 999.3;$$
$$\theta_1 = \tan^{-1}(21.9/999.3) = 1 \text{ deg. } 15 \text{ min. (approx.)}$$

* *Elec. Jour.*, Vol. V, p. 386 (1908).

† Fifty deg. in the terms of the third harmonic, or 50/3 deg. in terms of the resultant

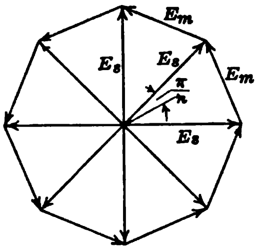

Fig. 45a.—Symmetrical star and ring e.m.fs.

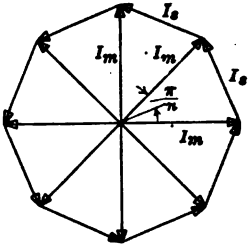

Fig. 45b.—Symmetrical star and ring currents.

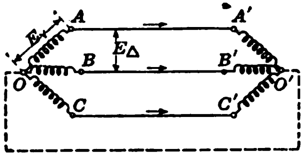

Fig. 46a.—Three-phase Y connection.

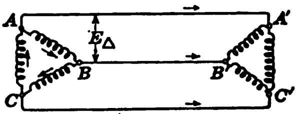

Fig. 46b.—Three-phase delta connection.

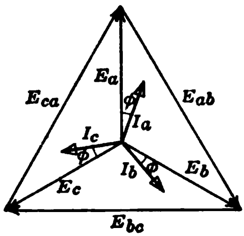

Fig. 47a.—Three-phase Y e.m.fs. and currents.

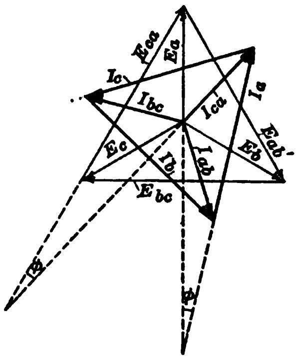

Fig. 47b.—Three-phase Δ e.m.fs. and currents.

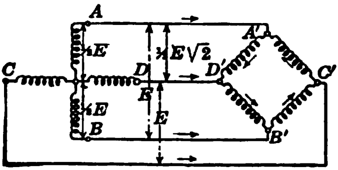

Fig. 48.—Two-phase system; star and ring connections.

221. Polyphase power. The total power in a **symmetrical** ***n*-phase system** is given by the formula

$$P = nI_sE_s \cos\phi = nI_mE_m \cos\phi. \qquad (263)$$

In an **unsymmetrical** or **unbalanced system** the **total power** is found by summing up the power in the separate phases.

222. Three-phase power. In a three-phase system (Fig. 46), the power

$$P = 3I_yE_y \cos\phi = 3I_\Delta E_\Delta \cos\phi = I_yE_\Delta\sqrt{3}\cos\phi \quad \text{(watts)} \qquad (264)$$

if the currents are in amperes and the voltages in volts.

223. Two-phase power. In a **quarter-phase system** (Fig. 47) the power

$$P = 4I_sE_s \cos\phi = 4I_mE_m \cos\phi = 2\sqrt{2}I_sE_m \cos\phi \quad \text{(watts)} \qquad (265)$$

224. An equivalent single-phase circuit is a circuit which is used in computations relating to polyphase transmission lines and machinery. For three-phase circuits some engineers use a single-phase circuit with a voltage equal to the Y-voltage of the three-phase system, and the power equal to that in one phase. Others use a single-phase circuit having a voltage equal to the delta voltage of the three-phase circuit, and transmitting the power equal to the total power in the three phases. Both methods lead to the same result, provided that the assumptions are consistently carried out.

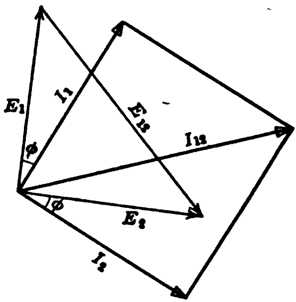

FIG. 51.—E.m.fs. and currents in two-phase three-wire system.

225. Unbalanced polyphase circuits are treated as separate single-phase circuits and then combined into one. Assuming a three-phase system with a line voltage triangle as shown in Fig. 52 and an unbalanced load, E_1, E_2 and E_3, are given. (They form the triangle *abc*.) Constructing semicircles on E_1, E_2, and E_3 as diameters, the e.m.f. triangle for each branch is constructed (Par. **155**). We have

$$\frac{E_1}{z_1} = i_1,\ \frac{E_2}{z_2} = i_2 \text{ and } \frac{E_3}{z_3} = i_3. \qquad (266)$$

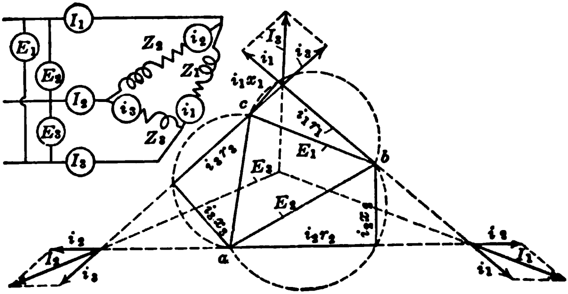

FIG. 52.—Unbalanced three-phase system.

The currents, i_1, i_2 and i_3, are in phase with the *ir* drops in their respective branches. These can be conveniently combined by prolonging the *ir* lines until they intersect, and laying off the currents, *i*, from the intersection. The main currents, I_1, I_2 and I_3, are found by taking the vector sum of the branch currents, i_2 and i_1, i_2 and i_3, i_3 and i_1, respectively.

230. Alternating impressed e.m.f. Let a sine-wave alternating voltage be applied to an equivalent single-phase line (Par. 224) with uniformly distributed characteristics. Let the resistance and the inductive reactance of the line be r ohms and x ohms per unit length, respectively, so that the series impedance is $Z = r + jx$ ohms per unit length. Let the condensive susceptance and the leakage conductance be b and g mhos, per unit length respectively, so that the shunted admittance is $Y = g - jb$ mhos per unit length. The current and the voltage relations at a distance s from the receiver end of the line are expressed by the differential equations

$$\frac{d^2I}{ds^2} = M^2I, \text{ and } \frac{d^2E}{ds^2} = M^2E \tag{273}$$

where $M = \sqrt{YZ}$. In these expressions I, E and M are complex quantities, (Par. 184), and the magnitude and the phase of the current and the voltage vary from point to point, remaining at the same time sine functions. In other words, the current and the voltage are sine functions of time t, and such functions of s as to satisfy the above-given equations. The parameter M characterizes the line and is independent of either t or s. The solution of these equations is of the form

$$I = A_1\epsilon^{-Ms} + A_2\epsilon^{Ms} \tag{274}$$

$$E = B_1\epsilon^{-Ms} + B_2\epsilon^{Ms}, \tag{275}$$

where the constants of integration A_1, A_2, B_1 and B_2 are complex quantities These constants are determined by the electrical conditions at some one point of the line, for instance, when the current and the voltage at one point are given in magnitude and in relative phase position.

231. Solution of alternating-current case. The solution of the foregoing differential equations is preferably expressed through **hyperbolic functions** (Par. 229) of the complex angle Ms. Namely,

$$I = C_1 \operatorname{Cosh} Ms + C_2 \operatorname{Sinh} Ms; \tag{276}$$

$$E = D_1 \operatorname{Cosh} Ms + D_2 \operatorname{Sinh} Ms; \tag{277}$$

where the complex quantities C_1, C_2, D_1, and D_2 are the constants of integration which depend upon the given conditions at some one point of the line.

For example, if the receiver voltage E_2 and the receiver current I_2 are given in magnitude and in phase (at $s = 0$) the constants of integration have the following values:

$$C_1 = I_2;\ C_2 = E_2\frac{Y}{M};\ D_1 = E_2;\ D_2 = I_2\frac{M}{Y}. \tag{278}$$

Thus, knowing I and E at the receiver end, their values may be calculated for the sending end or at any other point on the line.

232. References to other literature. For further details and application of the foregoing equations to power-transmission lines and to the propagation of currents in telephone and telegraph lines see C. P. Steinmetz, "Theory and Calculation of Transient Electric Phenomena and Oscillations;" J. A. Fleming, "The Propagation of Electric Currents in Telephone and Telegraph Conductors."

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SECTION 3

MEASUREMENTS AND MEASURING APPARATUS

ELECTRIC AND MAGNETIC MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

GENERAL

1. **The measurement of any given quantity** is the comparison of that quantity with another quantity of the same kind which has been chosen as a unit. The **unit** may be a purely arbitrary quantity with no rational significance, such as the foot and the pound, or it may have a very definite meaning, as the centimeter and the gram. The units used in electrical measurements belong to the latter class because they are based on the **centimeter-gram-second** or **C.G.S.** system. The C.G.S. system (Sec. 1) is the fundamental system upon which all physical measurements have been based, on the theory that all physical phenomena are the result of matter and motion, that is, space (centimeters), mass (grams) and time (seconds).

2. **Measurements classified according to precision.**—Electrical measurements may be divided, in a very general way, into three classes. (a) **High-precision measurements**, such as those made at the various national standardising laboratories in connection with the establishment and maintenance of standards. Every precaution is observed to obtain the highest possible degree of accuracy. Expense is a secondary consideration. (b) **Commercial laboratory measurements**, where the object is to secure results which are reliable and accurate, but only to the degree justified by commercial and engineering requirements. The cost must be a minimum. (c) **Commercial measurements** are those involved in the production, distribution and sale of energy. The scope of the subject in this section is limited to the last two classes.

3. **A standard** is a concrete representation of a unit. The fundamental C.G.S. units are difficult to represent and early in the development of the art the need for a system of units which could be used in electrical measurements was recognised, and resulted in the establishment of the "practical" units (see Sec. 1). These units are derived from the fundamental C.G.S. units and can be represented by definite, concrete and reproducible standards.

The distinction drawn between primary and secondary standards is largely a matter of viewpoint. In general, however, primary standards may be considered as those which represent directly by definition the unit involved, such as the mercury ohm, the silver voltameter and the saturated cadmium cell, made according to certain specifications. Secondary standards are the more practicable working standards which are standardised by comparison with primary standards and used as the basis of all ordinary measurements. They include, for example, the manganin standard resistances and the ordinary Weston-type standard cell. Primary standards are, in general, maintained only by the government custodians of the standards in the various countries; whereas secondary or working standards, based on these primary standards, serve as the fundamental basis of practical measurements in engineering and commercial fields.

4. **The precision obtainable** in an electrical measurement depends upon the various factors which enter into the determination; among these are the correctness of the principle employed and the method used, accuracy of the standards, number and magnitude of possible errors, correctness of calculations and so forth. In precision measurements, as classified above, a precision of one part in 100,000 in certain classes of measurements is regularly attained. In commercial measurements, the cost of such a high degree

from the mean value as the number of readings is increased. Where the necessary degree of reliability is not obtained in a single measurement, a number of observations are made, from which the most probable true value may be obtained, together with its probable error. These latter quantities may be derived in different degrees of precision by various mathematical methods involving the theory of probabilities and the method of least squares. In all ordinary electrical measurements it will usually be sufficiently correct to assume that the true value is equal to the average of the various values obtained (eliminating systematic errors) plus or minus the average error. The average error is the average of the differences between the average value and each individual value. It should be noted, however, that according to the theory of probability, the precision of the result does not increase directly but only as the square root of the number of observations made (see Par. 426 to 435).

7. **Certain general precautions** which should be observed in electrical measurements, and certain sources of error which should be avoided, are indicated in the following paragraphs.

(a) **The probable limit of accuracy** of the standards, instruments and methods should be known.

(b) As a general proposition, in other than rough determinations, one measurement should not be relied upon. Several readings should be taken, and the conditions should be altered, wherever possible, in order to avoid accidental errors.

(c) Indicating instruments should be of such a range that the quantity under measurement will produce a reasonably large deflection on the scale. The percentage observational error decreases in direct proportion as the magnitude of the deflection increases.

(d) The possible presence of **external or stray magnetic fields,** both direct and alternating, should always be borne in mind. Such fields may be produced by current in neighboring conductors, or by various classes of electrical machinery and apparatus, structural iron and steel in buildings, etc. These fields introduce errors by combining with the fields of portable indicating instruments, galvanometers and other instruments utilizing a magnetic field, and, in the case of alternating fields, by inducing small e.m.fs. in the loops formed in bridges, potentiometers, etc.

(e) In measurements involving high resistances and galvanometers, such as bridges and potentiometers, possible "leakage" or shunt circuits should be eliminated. This is done by providing a **"guard" circuit** the principle of which is to keep all points to which the current might flow improperly, at the same potential as the highest in the apparatus. See further discussion under potentiometers (Par. 49 to 52).

(f) **Temperature changes** in various parts of bridge, potentiometer and similar circuits should be avoided because of thermo e.m.fs. produced at the junction of dissimilar metals. Such effects are often produced if the observer's hand comes in contact with the metal parts of the galvanometer key, switches, etc.

(g) Instruments with covers made of glass and hard rubber should not be rubbed, especially with a dry dust cloth. The induced electrostatic charge on the moving element is often sufficient to change the deflection materially.

(h) At potentials of 500 volts and above, the electrostatic attraction between moving and fixed parts may become serious. This is prevented by keeping the two parts at the same electrostatic potential. When grounding is permissible, this can be done by connecting the circuit to earth at the point where the instrument is connected, care being taken that the moving-coil end of the instrument is on the ground side. In very high potential work this electrostatic attraction becomes very troublesome, so that the instruments must be connected in circuit at a grounded part of the line, or else be thoroughly insulated from ground and the moving element connected to the case or to an electrostatic shield around the instrument.

GALVANOMETERS

8. **Galvanometers** are used extensively in all classes of electrical measurements. Strictly speaking, the term applies to many other instruments for measuring current, such as voltmeters and ammeters, but it is ordinarily understood to apply to those instruments which are used to measure very small electrical quantities.

charged through it before the suspended system has moved appreciably. **The period**, or time of vibration, must therefore be long compared with the time of discharge. This is accomplished by increasing the inertia of the moving system.

16. Deflection of ballistic galvanometers. The magnitude of the first deflection is a measure of the quantity discharged into the instrument. In an instrument in which there is no damping (Par. 26) such as the moving-magnet type, the quantity may be calculated directly from the constants of the instrument. Thus

$$Q = \frac{2Ht \sin (\frac{1}{2})\alpha}{\pi G} \qquad \text{(coulomb)} \qquad (3)$$

or for small angles, 5 deg. or less,

$$Q = \frac{Ht \sin \alpha}{\pi G} \qquad \text{(coulomb)} \qquad (4)$$

where Q = quantity of electricity in coulombs, H = field strength in gausses, G = constant computed from the coils, t = period in seconds, α = angle of deflection.

17. Ballistic galvanometer constant. In practice, ballistic galvanometers are usually standardised and the formula becomes very simple: $Q = kd$ where d = deflection and k = quantity per unit deflection or galvanometer constant. The constant is determined with a standard condenser or mutual inductance. The deflection obtained upon suddenly discharging a charged condenser through the galvanometer is $d = Q = CE$; and hence $k = CE/d$, where Q = quantity of electricity in coulombs, E = potential to which the condenser had been charged in volts, and C = capacity of condenser in farads. When a mutual inductance is used, the deflection is $d = Q = MI/R$ and $k = MI/dR$, where Q = quantity of electricity in coulombs, M = coefficient of mutual inductance in henrys, I = steady or Ohm's law value of current in primary of mutual inductance in amperes, and R = resistance of secondary circuit (including the mutual inductance) in ohms.

18. A differential galvanometer is one provided with two independent coils or sets of coils by means of which two currents may be compared simultaneously. This method provides a means of measuring a current without making the circuit common with that of the comparison standard. In D'Arsonval instruments, the two coils are wound side by side on the same frame and are connected in opposition, so that when the two currents being compared are adjusted for zero deflection, their ratio is usually unity. The actual ratio can be determined experimentally.

19. Electrometers. In the electrometer, a piece of thin aluminium is suspended by a metallic suspension over four quadrants of sheet metal which are insulated from each other and from the frame or support. Opposite quadrants are connected to each other and the two sets are connected respectively to the two sides of the circuit to be measured. If a charge from a condenser is placed on the moving vane, one end will be repelled and the opposite end attracted, producing a deflection which will be a measure of the potential applied to the stationary quadrants. This instrument is extremely sensitive, and while it is one of the earliest types of electrical measuring instruments it is still used extensively in research work, especially where the available energy is extremely small, as in measurements of radiant energy.

20. Galvanometers as detectors. The majority of galvanometers are used as detectors only, that is, in zero-deflection methods where the kind of scale or proportionality of deflections does not enter into the determination. In such cases a very short, straight scale is sufficient and space may be economised by placing the galvanometer on the wall above the table, with the scale directly underneath. The beam of light is properly directed by suitable prisms and mirrors.

21. Reflecting galvanometers may be read with a telescope and scale, or with a lamp and scale. In the former, the scale is reflected from the plane mirror (attached to the moving system) to the telescope through which movements are observed. In the latter, an image of a narrow beam of light (issuing from a narrow slit in a vessel enclosing a lamp, or from a portion of an incandescent lamp filament) is thrown on to the scale by the mirror. In

29. Galvanometer shunts are combinations of resistances so arranged and so connected to the galvanometer that the constant of the latter may be quickly changed. Ordinary resistance boxes may be used as shunts for galvanometers when the resistance of the galvanometer circuit is not too small. In the latter case the box is connected as shown in Fig. 2, thus increasing the resistance R_g of the galvanometer circuit. The readings of the galvanometer must be multiplied by a factor

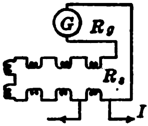


Fig. 2.—Galvanometer shunt.

$$k = \frac{R_g + R_s}{R_s} \qquad (6)$$

wherein R_g is the resistance of the galvanometer circuit and R_s is that of the shunt. In special galvanometer shunts,

$$R_s = \frac{R_g}{9}, \frac{R_g}{99}, \frac{R_g}{999}, \frac{R_g}{9999}, \ldots \ldots \text{ etc.} \qquad (7)$$

then $k = 10$, 100, 1,000, 10,000 respectively.

30. The Ayrton or universal shunt is so arranged that it can be used with any galvanometer. When, in Fig. 3, the movable contact x is at b, $I'_g = Ir_{ab}/(r_{ab} + r_g)$, where I'_g = current through galvanometer, I = current from battery, r_{ab} = resistance between a and b, and r_g = resistance of galvanometer. If the contact x is moved to c,

$$I''_g = I'_g\left(\frac{r_{ac}}{r_{ab}}\right) \quad \text{(amp.)} \qquad (8)$$

It will be noted that r_g is not in this equation; hence if the galvanometer constant is obtained with the shunt all in (x at b), the shunt ratio at any other position of x is r_{ac}/r_{ab} and is independent of the galvanometer resistance.

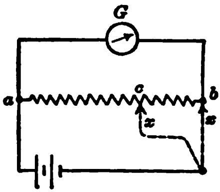


Fig. 3.—Universal galvanometer shunt.

31. Alternating-current types of galvanometers include the following: Electrodynamometers, or, as they are more commonly known, dynamometers; vibration galvanometers, thermogalvanometers, electrostatic galvanometers, alternating-current detectors, barretters and bolometers.

32. Dynamometer-type instruments are used extensively in measurements of alternating currents because they measure mean effective values and can be calibrated on direct current. They can be used for a wide range of measurements of current, e.m.f. and power, from extremely small values to very large ones.

33. The operative principle of the dynamometer is the electrodynamic action between a movable coil (or coils) suspended between two or more fixed coils, all of which are energised. **The Rowland electrodynamometer*** is typical of this class of instruments. It consists simply of two fixed coils mounted close together, between which is suspended a small coil of very fine wire. Each fixed coil consists of two separate windings of different current capacities brought out to separate terminals. For e.m.f. measurements the moving coil and the fine wire fixed coils are connected in series; for current measurements, the moving coil is connected across a non-inductive shunt in the current circuit; for power measurements, the moving coil is connected across the circuit to be measured while the proper fixed coil is connected in series with it.

34. Dynamometers are made astatic, or independent of external fields, by having two sets of moving coils, oppositely wound, one above the other, with a common suspension. There may be one or more pairs of fixed coils. In heavy-current instruments, the fixed coils are wound with cable composed of many fine strands laid up in braided form. This reduces the eddy currents which otherwise would be set up and which would influence the moving coil.

* Rowland, H. A. "Electrical Measurements by Alternating Currents;" Leeds and Northrup Catalogue No. 74, 1911; p. 294.

rings which in turn are connected through the brushes, b, b^1, to the alternating current being measured. It is apparent that the connections to the galvanometer are reversed every half cycle, so that the indication is a steady one, the value of which may be made anything from zero to a maximum by shifting the angular position of the brushes. Thus the most sensitive position can be readily found, irrespective of the phase relation between the current in the circuit being measured and the motor armature. The variation in contact resistance at high speeds, and possible presence of thermo e.m.fs., may cause trouble where the resistances or potentials are very low, as in low-resistance bridge measurements.*

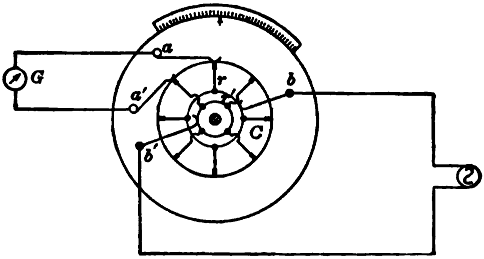


FIG. 5.—Synchronous commutator.

39. A synchronous reversing key which overcomes the latter difficulty is indicated in Fig. 6. A cam, C, mounted on the shaft of a small synchronous motor is so designed that it moves the lever, l, up and down in such a manner that the pair of contacts, a and a^1, at the end of the lever make alternate contact with the pairs of stationary contacts, c and c^1, once per cycle. The number of projections on the cam of course will correspond with the number of pairs of poles on the motor. The contacts are arranged as shown diagrammatically at the right of Fig. 6, from which it will be seen that the connections to the galvanometer are reversed every half cycle, so that a steady deflection is obtained in the direct-current galvanometer. All the contacts are supported on a solid disc which can be rotated around the shaft, and hence reversal can be made at any point on the wave as in the case of the synchronous commutator. The contacts are all made of platinum, the cam is hardened steel and the lever l is kept in contact with the cam at all times by means of a spring. The roller r is necessary to insure contact at the low portion of the cam.

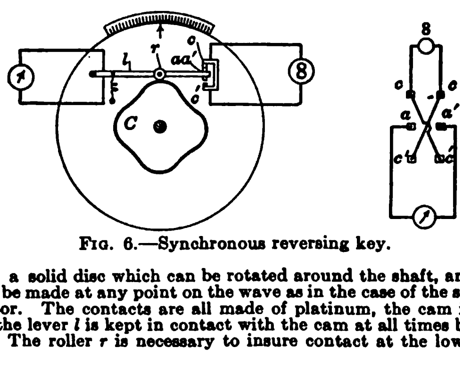


FIG. 6.—Synchronous reversing key.

* Sharp, C. H. and Crawford, W. W. "Some Recent Developments in Exact Alternating-current Measurements;" *Trans.* A. I. E. E., 1910, Vol. XXIX, p. 1518.

4 deg. cent. or above 40 deg. cent., and that no current greater than 0.0001 amp. be passed through them.

48. Comparisons of continuous electromotive forces with a standard cell. Electromotive forces may be compared with a standard cell by several methods. The more typical methods are based on the following principles.

(a) In the **substitution method,** the current flowing through a high resistance (not less than 15,000 ohms) is measured with a high-sensibility galvanometer, first with the standard cell in the circuit and then with the unknown e.m.f. substituted for the standard cell. The resistance being the same in the two cases, the deflections are proportional to the e.m.fs. $E = ed'/d$, where E = unknown e.m.f., e = standard cell e.m.f., d = deflection with standard cell and d' = deflection with unknown e.m.f.

(b) The **equal deflection method** is a modification of the above, in which the deflections are kept the same in the two cases by changing the resistance. Then $E = er'/r$, where r = total resistance of the circuit, including the galvanometer, with the standard cell in the circuit and r' = total resistance with the unknown e.m.f. This method is better than (a) because it is a constant deflection method and the result depends on the known values of two resistances, rather than observed deflections.

(c) In **Wheatstone's modification** of the equal deflection method, the galvanometer resistance does not have to be known. The deflection, d, is noted when the unknown e.m.f., E, and a known high resistance are in circuit. Additional resistance, r', is added and the deflection, d', again noted. Similarly with the standard cell of potential difference, e; the resistance is adjusted until the same deflection, d, is obtained and then an amount of resistance, r, is added until the deflection d' is again obtained. The unknown e.m.f. is $E = er'/r$.

(d) In the **condenser discharge method** a condenser is charged, first from the unknown e.m.f., then from the standard cell, and discharged in each instance through a ballistic galvanometer. The deflections will be proportional to the e.m.fs., hence $E = ed'/d$ as in (a). Obviously, if the unknown e.m.f. is much smaller or much larger than the standard cell, the deflection can be made about equal to that of the standard cell by using a larger or a smaller condenser. In that case the ratio of the capacities should be known, and then $E = ed'C'/dC$, where C = capacity of condenser used with the unknown e.m.f. and C' = capacity of condenser used with the standard cell. This method has the advantage that practically no current is required, which is advantageous in making measurements of voltaic cells of very small capacity or rapid polarization.

(e) The principle of the **opposition or potentiometer method** is that of opposing the e.m.f. of the standard cell against an equal difference of potential which bears a known proportion to the unknown e.m.f. This method is the most accurate and by far the most generally used, because it is both a zero-deflection and a zero-current method, the result depending only on the ratio of two resistances which can be very accurately determined. Potentiometers are instruments employing this principle (Par. **49**).

49. Description of Leeds and Northrup potentiometer, low resistance type. Fig. 7 shows the arrangements of the circuits. The figures for the second decimal place and beyond are obtained from a slide wire at the end of the circuit, CB, along which a contact moves. A special dial is also provided for the standard cell (at the left) and separate contacts are provided for the standard-cell e.m.f. and the unknown e.m.f., so that no settings have to be disturbed when checking the secondary current in the potentiometer circuit. The essential part of the instrument consists of 15 five-ohm coils, AC, connected in series with the extended wire, CB, the resistance of which from 0 to 1,100 scale divisions is 5.5 ohms. Thus when the current from the battery, B, is adjusted by the rheostat, R, to 0.02 amp., the fall of potential across each 5-ohm coil in AC is 0.1 volt and across CB, 0.11 volt. Since the latter is divided into 1,100 parts, the e.m.f. may be measured to 0.0001 volt. At point 5 in AC, a wire is permanently attached connecting to one point of the double switch, U. When this switch is thrown to the left, the standard cell is connected through the galvanometer to point 5 and the sliding contact T which moves over the dial at the left consisting of 19 resistance coils. Between a and A is a resistance which is adjusted to such a value that with 0.02 amp. flowing, the potential drop between 5 and a is three low dials are so arranged that a corresponding change is automatically made in the external part of the main circuit and the total resistance is kept constant. A separate dial is provided for the standard-cell adjustment, together with a separate resistance which can be altered to accommodate different cells without affecting the measuring circuits. The total range of the instrument is 1.9 volts.

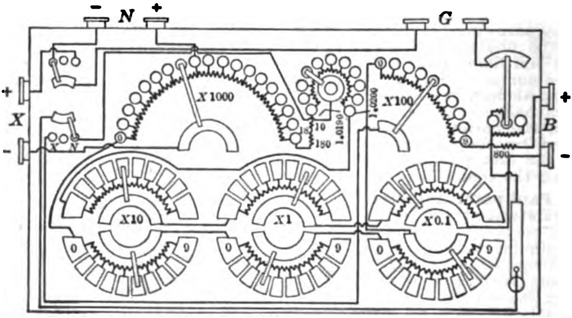


Fig. 9.—Wolff potentiometer.

52. Care and use of potentiometers. The following notes apply to the use of potentiometers in ordinary work.

(a) The accessories should be suitable for the particular type of instrument, that is, high or low resistance, and for the class of measurement to be made. The galvanometer should be sufficiently sensitive to give a perceptible deflection when there is an unbalance equal to the smallest scale division in the potentiometer curcuit. A low-resistance galvanometer, of the order of 100 ohms, should be used with a low-resistance potentiometer, and a high-resistance galvanometer of 500 to 1,000 or more ohms, with a high-resistance potentiometer. Similarly, the resistance of the volt box (Par. 53) for low-resistance potentiometers should be as low as the permissible power loss in the resistance coils will permit. This is usually about 5,000 ohms for 150 volts. For high-resistance instruments, the resistance is 1,000 ohms or more per volt.

(b) The **first trials for balance** should always be made with a resistance in series with the galvanometer. This is usually provided in the instrument, with facilities for readily cutting it out of circuit when an accurate balance is being obtained. The resistance protects the galvanometer and also the standard cell from the effects of excessive currents.

(c) Trouble is sometimes experienced, especially in damp weather, due to **current "leaking to ground"** from the potentiometer circuits in a manner which produces a false deflection. This can be obviated by providing a **"guard circuit."** In one scheme of this kind all of the apparatus is placed on small, hard-rubber pillars each of which in turn rests on a small metal plate. These are connected together and to the positive "x" binding-post by fine bare wire. Thus all points to which current might "leak" over the surface are kept at the highest external potential to which the potentiometer is connected. When the surfaces become noticeably moist, conditions can be improved by carefully wiping with a cloth moistened with grain alcohol.

(d) **Calibration and checking.** The essential requirement is that the ratio of the resistance of each step to that resistance between the standard cell terminals shall be the same as the ratio of the corresponding potentials. For example, if the standard cell e.m.f. is 1.0183 volts and the resistance between its terminals is 101.83 ohms, the resistance of the various steps should be adjusted to 10 ohms per 0.1 volt. If the standard cell resistance is 102.848 ohms the potentiometer is still accurate if the resistance throughout the circuit is adjusted to 10.1 ohms per 0.1 volt.

lines per square centimeter in the steel. A light tubular pointer attached to the coil moves over a calibrated scale. The current is introduced into the coil by two spiral springs which also provide the controlling force. Since the field strength and the gradient of the controlling forces are uniform, the deflection is strictly proportional to the current passing through the coil, and the scale divisions are uniform. A large amount of resistance is connected in series with the moving coil in order to make the current small. Thus the same instrument can be made suitable for a wide range of voltages by changing the amount of series resistance. This resistance is made of wire having a low temperature coefficient in order to neutralize as much as possible the effect of the large coefficient of the copper in the coil.

56. Voltmeter characteristics (continuous current). The usual **resistance** of portable voltmeters of this type varies from 50 to 150 ohms per volt and the **current sensibility** from 7 to 20 milliamperes at full-scale deflection. The resistance of the moving coils is about 75 ohms. The **torque** varies from 2 to 6 millimeter-grams at maximum current, with a **ratio of torque to weight** (in grams) of 1 to 5. The **temperature coefficient** is usually negligible, being of the order of 0.01 to 0.02 per cent. per deg. cent. at full scale.

57. Laboratory standard voltmeters (continuous current). So-called laboratory standard voltmeters are similar to portable instruments except that they are larger, have a longer pointer, a longer and more open scale and are made with greater care. They are only semi-portable and are intended primarily for standardising purposes.

58. Switchboard voltmeters (continuous current) are usually of the D'Arsonval type. The construction is the same as that of portable instruments, except that they are more substantial and rugged, especially as regards the moving system, in order to withstand the harder conditions of continuous service and excessive fluctuations. They are mounted in iron cases to protect them as much as possible from the normal stray fields due to the bus bars.

59. Effect of stray fields. The general effect of stray fields on the standard types of portable and switchboard instruments is shown in the table in Par. 60. These errors are usually only temporary and disappear with the stray field. When the field is very strong, as under short-circuit conditions in a neighboring conductor, **demagnetization** of the instrument magnets may result in a permanent error. Shields are likely to be of little value under such conditions because the iron becomes saturated.

60. Effect of Stray Magnetic Fields on Continuous-current Voltmeters and Millivoltmeters

Stray field, lines per sq. cm.*	Error at two-thirds full-scale deflection, per cent.	
	Shielded	Unshielded
5	0.5 to 1.0	2
10	0.75 to 1.75	3.5 to 5.5
15	1.0 to 3.0	6.0 to 7.5
20	1.25 to 3.25	7.5 to 10

61. The measurement of very small continuous potentials may be effected by some of the methods outlined in Par. 48.

A potentiometer is most convenient, high resistance for high resistance sources such as small galvanic cells and low resistance for low resistance sources such as thermocouples.

62. Ground detectors. Those of the direct-current type are usually special forms of voltmeters. In one form, there are two coils, differentially wound on the moving system. One end of each coil is connected to ground and the two free ends are connected respectively to the two sides of the

* The field produced at a distance of 30 cm. (12 in.) from a conductor carrying 3,000 amp. is about 20 lines per square centimeter.

coils as shown in Fig. 12, where *F*, *F′* are the fixed coils and *M* is the moving coil, to which a pointer *P* is attached. The deflection is approximately proportional to the square of the current. The scale is compressed at the upper end instead of extended because the coil moves beyond the uniform part of the field. The **Thomson Inclined Coil voltmeter** is similar, except that the plane of the fixed coils makes an angle of about 45 deg. with the shaft of the moving coil for the purpose of making the scale more uniform.

In the **Westinghouse** type *Q*, the **Kelvin balance** principle is used. This principle is shown in Fig. 13, where there are two coils, *MM′*, attached to opposite ends of a beam which is supported at the middle and free to move. Each coil moves between a pair of fixed coils, *F F* and *F′ F′*, and all of the coils are connected in series in such a manner that the moments of all the forces on the movable system, taken about the beam axis, are cumulative, thus tending to produce rotation. In the Kelvin balance the controlling or opposing force is a weight moved along a graduated scale attached to the beam supporting the movable coils; the moment of this weight about the beam axis, when the moving system is balanced, varies as the square of the e.m.f. In the Westinghouse instrument the coils are arranged vertically and the controlling force is a spiral spring. The amount of compression of this spring necessary to balance the electromagnetic forces, as indicated by a pointer moving over a scale, is a measure of the e.m.f. Single-coil instruments are direct reading and hence fluctuating e.m.fs. can be more easily read on them than on the torsionhead instruments, but the latter are astatic and therefore practically independent of stray fields.

68. Soft-iron-vane voltmeters (alternating current) utilise the reaction between a temporarily magnetised piece of soft iron and the magnetising field. In the **Thomson inclined coil instrument** of this type the

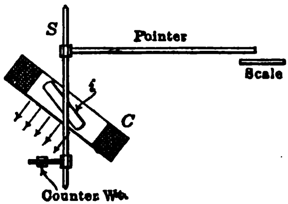


FIG. 14.—Diagram, Thomson inclined coil a.c. voltmeter.

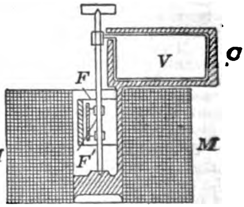


FIG. 15.—Diagram, Weston soft-iron type a.c. voltmeter.

plane of the energising coil, *C* (Fig. 14), makes an angle with the shaft, *S*, which carries a member, *i*, comprising a rectangular piece of very thin, soft iron. This piece of iron is so attached to the shaft that rotation is produced by the tendency of the iron to become parallel with the field established by the coil. In **Weston instruments** of this type (model 155), the reaction which produces the deflection takes place between two pieces of soft iron bent in the arc of a circle and placed concentrically, one of which, *F′* (Fig. 15), is movable, and the other, *F*, is stationary. When the surrounding coil, *M*, is energised, the pieces of iron become magnetised in like manner, so that the resulting force is one of repulsion. The stationary piece *F* is made triangular in shape, with the pointed end in the direction of rotation, for the purpose of making the scale more uniform. Air damping is obtained by means of a light aluminium vane, *V*, in an enclosing chamber, *C*. This type has the great advantages of low price, ruggedness, open scale and small weight.

69. Induction-type voltmeters (alternating current) utilise the principle of induction watt-hour meters (Par. 202), or the rotative tendency of a free cup of thin metal when placed within a so-called revolving magnetic field. Actual rotation of the movable element is prevented by an opposing spiral spring, so that the deflections become a measure of the current in the energising coils. The **Westinghouse** type P voltmeter is an important with scales which make them direct reading. They are made in a great variety of forms, for both portable and switchboard use, but are used commercially much more in Europe than in this country. The principle of their operation is shown in Fig. 18, in which *mm'* is a thin aluminium vane suspended or pivoted between two pairs of fixed vanes, *ff'*. The deflection through moderate ranges is proportional to the square of the potential and is controlled either by a spiral spring or by gravity. Damping is produced magnetically, by air vanes, or by immersing the elements in oil. For ordinary commercial voltages a number of sets of vanes are arranged one above the other in a vertical position, and connected in parallel, thus multiplying the effect (Fig. 19). For higher voltages, one set of vanes is sufficient and they are usually placed in a vertical plane with the moving element mounted on a horizontal shaft. In the **Westinghouse electrostatic voltmeter,** the moving system is not connected to the circuit; Fig. 20 shows the arrangement of the parts. When potential is applied to *A* and *A'*, the hollow cylinders *C* and *C'* become oppositely charged by induction. The resultant attraction produces a deflection because of the shape of the fixed plates, *P* and *P'*. The condensers *K* and *K'* are each formed by two flat plates and are connected in series with *A* and *A'* to increase the range. For lower ranges these condensers are short-circuited, so that ranges of 30,000, 60,000 and 100,000 volts are available in the same instrument and on one scale. The elements are entirely immersed

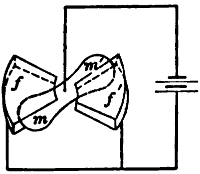


Fig. 18.—Diagram, electrostatic-type a.c. voltmeter.

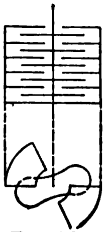


Fig. 19.—Diagram, electrostatic-type a.c. voltmeter.

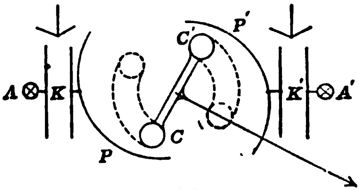


Fig. 20.—Diagram, Westinghouse high-tension voltmeter.

in oil which permits a relatively compact construction, increases the torque because of the greater specific inductive capacity of the oil and provides damping.

72. Alternating-current switchboard voltmeters are made in all of the types described above (Par. 66 to 70), although in this country the dynamometer, soft-iron vane and induction types are in most general use. They are similar in general to the portable instruments, due regard being given to the more severe requirements of switchboard service.

73. Calibration of alternating-current voltmeters. The dynamometer type of voltmeter gives the same indication on continuous current as on alternating current and may therefore be calibrated with continuous currents, direct and reversed readings being taken. The inductance in instruments of commercial ranges is so small that the readings are independent of standard frequencies.

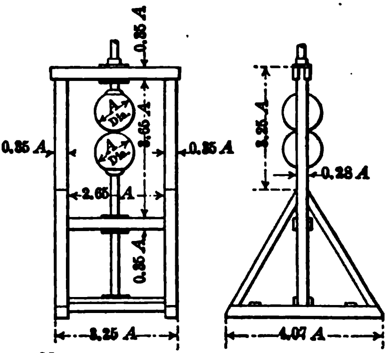
The soft-iron-vane type of voltmeter should theoretically be used only on alternating current because hysteresis occurs to some degree in the vane. Practically, however, the hysteresis is so small that there is very little difference between the respective indications with increasing and decreasing potential. Provided with a steady source of e.m.f., under suitable control, these instruments may be calibrated with continuous current by taking the average of the "up" and "down" potential readings corresponding to the various points. Care should be taken that the potential is increased or decreased only to the desired value and not beyond it. Theoretically, instruments of the soft-iron type are not independent of frequency or wave-form; practically, however, the variation is not measurable throughout commercial ranges.

load. The method is simple, convenient and accurate, but the power consumption and the cost of the transformer become prohibitive at high potentials.

(c) **Electrostatic voltmeter.** Commercial instruments are available up to about 200,000 volts. They require no appreciable power and are quite satisfactory. The principal objections are the high cost of large sizes and the lack of dead-beat qualities.

(d) **Test coil.** Where the source of the high potential to be measured is a testing transformer, an ordinary low-reading voltmeter can be connected to a few turns of the high tension winding brought out to separate terminals. These turns should be at the grounded end of the winding. The ratio, under all conditions, will be that of these turns to the total turns in the high-tension winding, if the transformer has been well designed. This method is generally sufficiently accurate and is very convenient.

(e) **Spark gaps.** The sparking distance between two terminals in atmospheric air is a standard method of measuring high potentials. The maximum length of gap which a given potential will break down depends, in this case, on the maximum value and not upon the virtual or effective value which is the value obtained in the other methods. The maximum value, however, is the important one in tests of insulators and insulating materials. When the wave form is not a sine curve the maximum value may deviate materially from the theoretical value, which is the virtual (voltmeter reading) value multiplied by $\sqrt{2}$.



Note;
A Variation of 1 Cm. in Thickness and Width of Wood Parts is Permissible

FIG. 21.—Sphere sparks gaps.

77. Needle-point and sphere spark gaps. The needle-point spark has for many years been the standard method of measuring high voltages, but it is unsatisfactory for very high potentials because of variations due to atmospheric pressure, humidity, proximity of surrounding objects and sharpness of the needle-points. It has been proposed* to use spheres instead of needle-points and the 1914 A. I. E. E. Standardization Rules recommend the use of the needle gap for voltages from 10 kv. to 50 kv. and the sphere gap for voltages above 50 kv. A gap with carefully machined and polished spheres gives very reliable and consistent results due, probably, to the fact that the gap breaks down before corona forms and perhaps also to the lesser dielectric spark lag.†

78. A. I. E. E. standard sparking distances in air, with needle-point and sphere gaps are given in Sec. 24.

79. Ratio of shunt-type instrument transformer. When a very accurate measurement (within 2 per cent.) of a high potential is to be made with an instrument transformer of the shunt type, the nominal ratio cannot be relied upon as being sufficiently correct and the true ratio should be determined by a direct measurement. In the accurate measurement of power and energy the phase angle should also be known (Par. 179). For the accurate determination of the ratio of instrument transformers of the shunt type, the following methods are typical.

(a) **Direct measurement** of the primary and the secondary voltage,

* Farnsworth, S. W. and Fortescue, C. L. "The Sphere Spark Gap," *Proc.* A. I. E. E., 1913, Vol XXXII, No. 2, p. 301. See Fig. 21.

† Minton, J. P. "Effect of Dielectric Spark Lag on Spark Gaps," *General Electric Review* (1913), Vol. XVI, p. 514.

a simple and convenient method of comparing two transformers by means of a wattmeter.

80. Alternating-current ground detectors are usually **electrostatic** instruments. Fig. 24 shows diagrammatically the principle of **Westinghouse detectors.** The stationary vanes are connected through condensers to the main lines, and the movable vane is connected to ground. In the single-phase detector, a charge will be induced on each end of the movable vane, opposite in sign to that on the corresponding stationary vane, setting up forces of attraction. When the system is free from grounds, these attractive forces are equal and opposed to each other; hence the moving system stands at zero. A ground on either phase wire produces an unbalanced condition and a deflection away from the grounded conductor. In the three-phase detector, the vanes are sectors of spheres, the movable vane being mounted on a universal bearing.

81. General Electric ground detectors operate on a principle similar to that last described. Four quadrants, or fixed, flat vanes are cross-connected and mounted between them is a moving vane connected to ground. Opposite sets of fixed vanes are connected to the two sides of the line circuit and the action is the same as described in Par. **80**. The **three-phase detector** is similar, consisting of three pairs of fixed quadrants mounted 120 deg. apart on a common base plate, and a flat moving vane with three corresponding sectors.

CONTINUOUS-CURRENT MEASUREMENTS

82. Absolute measurements of current. The fundamental unit of current, as derived from the centimeter, gram and second, is defined in terms of the dimensions of the conductor and the strength of the magnetic field produced by the current. Absolute measurements of current are therefore made with instruments so carefully constructed that the current can be calculated from their dimensions.

83. Instruments for absolute measurement of current. Absolute determinations have usually been made with two classes of instruments. In the first, the deflection of a magnetic needle at the centre of a coil is measured, and the current is calculated from the dimensions of the coil, the strength of the earth's field and the torsion of the suspension. The best known example of this class is the tangent galvanometer (Par. **11**). This method involves, of course, any error in the determination of the earth's field. In the other class of instruments, the needle is replaced with a suspended coil. When the length and the radius of both movable and fixed coils are in the ratio of $\sqrt{3}:1$, when the centres coincide and when the dimensions of the fixed coil are large compared with those of the movable coil, it has been shown by Gray that the torque exerted by the moving system is expressed by

$$T=\frac{4\pi^2 Nnr^2 I}{\sqrt{D^2+L^2}} \qquad \text{(dyne-cm.)} \qquad (12)$$

where N = number of turns in fixed coil, n = number of turns in movable coil, D = diameter of fixed coil in centimeters, L = length of fixed coil in centimeters, r = radius of movable coil in centimeters, and I = current (coils in series). Hence by measuring the torque (weighing it), the current can be determined directly in C.G.S. units.

84. Practical unit and standard of current. It would be quite impracticable to make ordinary measurements in terms of the fundamental unit, by the methods indicated above (Par. **82** and **83**). The Act of Congress of 1894 which legalised certain practical units of electrical measure defined the practical unit of current, or the **international ampere,** as one-tenth of the fundamental C.G.S. unit. This Act also defined the standard unit of current as the rate of deposition of silver at the cathode of a silver voltameter (Par. **86**) constructed and operated under certain prescribed conditions, the ampere being the current which will deposit 0.001118 g. of silver per sec. in a standard voltameter.

85. Methods of measuring continuous currents. The several methods of measuring continuous currents may be classified as follows: voltameter; potentiometer; and ammeters.

86. Voltameter method of current measurement. When a continuous current is passed through an electrolyte, the latter is decomposed at

91. D'Arsonval type of continuous-current ammeter. The principle of these instruments has been described under "e.m.f. measurements" (Par. 55). They are usually designed to have a full scale deflection with 50 to 200 millivolts (thousandths of a volt) at the terminals. The resistance of the moving coil is much lower (0.5 to 5.0 ohms) than that of voltmeters, in order to make the millivolt constant high.

92. Continuous-current ammeters of the switchboard type are intended for continuous operation and the shunt loss should therefore be low. They are designed for 50 to 75 millivolts at full scale deflection. High-grade portable ammeters are designed for 100 to 200 millivolts at full scale deflection, in order to permit the use of resistance in series with the moving coil, thus reducing the temperature error, which is more important than the larger shunt loss.

93. Shunts for continuous-current ammeters. In switchboard ammeters and the lower grade portable ammeters of 25-amp. ratings and less, the shunt is within the instrument case. Above 25-amp. ratings, the shunt is usually separate from the instrument and means of connection are provided by special flexible leads, which are included in circuit when the instrument is calibrated, since they form a part of the resistance of the entire instrument circuit. Obviously, these leads should never be altered without recalibrating the instrument. In high-grade ammeters the shunts are separate for all capacities.

94. Construction of ammeter shunts. Ammeter shunts are so constructed as to have a resistance which will be constant, as nearly as possible, under all conditions. The resistance metal has a low temperature coefficient, and the temperature is kept low either by connecting several strips in parallel and making the current density low, or by making the current density high and using short lengths of the resistance metal with heavy copper terminals designed to dissipate the heat by conduction and radiation. The former method is most generally used, the strips being silver-soldered into relatively heavy copper or brass terminals which are connected into the circuit to be measured. The resistance metal should also have a low thermo e.m.f. (Sec. 2) in junctions with copper.

95. Reduction of temperature errors in continuous-current ammeters. Because of the large temperature coefficient of copper, it is very undesirable to connect the moving coil of the instrument directly to the shunt. Temperature errors are reduced to a negligible value by connecting sufficient resistance having a low temperature coefficient (manganin or similar metal) directly in series with the moving coil as shown in Fig. 27, or by arranging a compensating circuit as shown in Fig. 28, where C = moving coil, R_m = low-coefficient resistance wire, and R_c = copper resistance wire.

FIG. 27.—Temperature compensation in millivoltmeters.

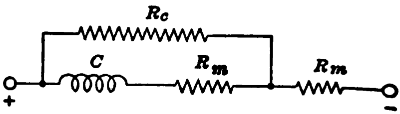


FIG. 28.—Temperature compensation in millivoltmeters.

96. The calibration of D'Arsonval type ammeters is effected by adjustment of the resistance of the shunt, the resistance of the millivoltmeter circuit, or both. Formerly each instrument and shunt were adjusted together, but it is becoming customary to adjust all of the instruments of a given type to deflect full scale with the same potential in millivolts at the terminals. The shunts for these instruments are all similarly adjusted to give the same potential drop, thus making all shunts and instruments of a given type interchangeable. The shunts should be adjusted by varying the main-line resistance between the potential taps and not by adjusting resistance wire connected in series with the instrument leads. In calibrating switchboard instruments and the lower grade portable instruments, the potential terminals are attached to the main current terminals and adjust-coarse wire instead of a large number of turns of fine wire, the ampere-turns being about the same in both cases. Hot-wire ammeters with ratings of more than 1 or 2 amp. are usually small current instruments connected to non-inductive shunts, as already described in principle (Par. 90).

102. Measurements of large alternating currents. The only type of ammeter which is generally used in the direct measurement of large alternating currents is the hot-wire ammeter, because it can be used with shunts. While shunts are made for capacities of 1,000 amp. and over, the accuracy with shunts of very large capacity depends upon the care taken in the design to eliminate the eddy-current and skin-effect errors. The most common method is to use current transformers of the series type, to step down the current to a small value, usually 5 amp., which is convenient to measure with standard instruments.

103. Series-type instrument transformers (also known as current transformers) serve two purposes; the convenient measurement of large currents, and the insulation of instruments and apparatus from high-voltage circuits. They are similar to so-called power transformers, except that the latter are connected in shunt across the line and the secondary potential remains substantially constant irrespective of the connected load. Series transformers are connected in series with the primary line, and the secondary current remains substantially constant for a wide range of loads. The load consists of instruments or other devices which are connected directly in series with the secondary winding.

104. Measurement of ratio of series transformers. The ratio of series-type instrument transformers may be determined by measuring the primary and secondary currents directly with current-measuring instruments, but obviously such a method is much less accurate than null or "zero" methods. The principle of the latter is the same as that of the potentiometer. A non-inductive resistance in the secondary circuit is adjusted until the potential drop across it is equal to that in a non-inductive resistance in the primary circuit. The ratio of the two resistances is equal to the ratio of transformation. The differences among the various null methods are largely in the manner of determining the balance and in measuring the phase angle. Fig. 29 shows the scheme of a method used at the Bureau of Standards,* where a reflecting dynamometer is used as the detecting instrument. R^1 and R^2 are the resistances in the primary and secondary circuits, respectively. The fixed coil of a dynamometer, D_1, is connected in series with the primary; then, with the switch S thrown to the right, R_2 is adjusted until zero deflection is obtained. The component of the potential drop in R_2, which is in phase with that in R_1, is thus equal in magnitude to the drop in R'. Since the phase angle is always very small, the ratio of R_2 to R_1 may be taken as the transformer ratio. The phase angle is then determined by measuring the component of the R_2 drop which is 90 deg. from the R_1 drop, by means of another dynamometer, D_2, the fixed coils of which are excited by a current displaced 90 deg. in phase from the primary current.

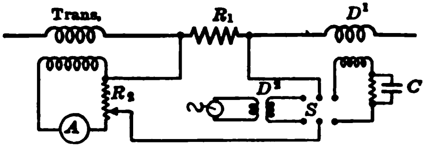


FIG. 29.—Connections for measuring ratio of series type transformers.

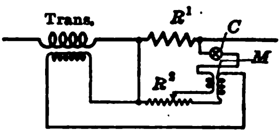


FIG. 30.—Connections for measuring ratio of series type transformers.

Fig. 30 shows the scheme of a method used at the Electrical Testing Laboratories.† R_1 and R_2 are the primary and secondary resistances,

* Bureau of Standards Bulletin, Vol. VII, 1913, No. 3, p. 423.

† Sharp, C. H. and Crawford, W. W., *Trans.* A. I. E. E., 1910, Vol. XXIX, p. 1517.

Another practical method of measuring small high-frequency currents is indicated in Fig. 32, where *a* and *a′* are two fine wires of different materials stretched between two terminals. The wires leading to the galvanometer are of the same materials, but so connected that *a′* and *b* are alike, and *a* and *b′* are alike. Thus there are two thermo-couples in series. Obviously the connections should be at the same potential, and this is adjusted on continuous current with direct and reversed readings. In a bridge method, the current is measured by the change in resistance of a carbon lamp (with a very small filament) in one arm of a bridge, Fig. 33; inductance coils, *a* and *a′* prevent the high-frequency current from flowing through the bridge.

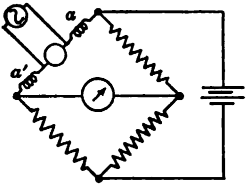


Fig. 33.—High frequency current measurements—bridge method.

108. Measurement of rectifier currents. Either of two values of the current from a rectifier may be required, the average value, or the root-mean-square value. In connection with storage-battery charging, the average value corresponds to the equivalent c.c. value and a permanent-magnet type of measuring instrument should be used. On the other hand, the power taken by incandescent lamps varies as the square of the current, and the equivalent c.c. current should be measured with instruments which indicate the mean effective value such as hot-wire or dynamometer ammeters.

109. Measurements of telephone currents. Telephone currents may be measured with a form of potentiometer* or with a barretter (Par. 40) but since telephone currents are of constantly varying amplitude and frequency, measurements made by this and the above methods are usually of little value. Telephonic intensities are usually compared by ear with a telephone, using artificial standardised cables. Where quantitative measurements are required, a high-sensibility oscillograph can be used.†

RESISTANCE MEASUREMENTS

110. Resistance standards in general. The practical unit of resistance, the **ohm**, is represented by a column of mercury having certain dimensions (Sec. 1). This standard is obviously difficult to construct, maintain and use; and, in general, will be found only in the laboratories of the national custodians of the fundamental electrical standards.

Secondary standards are therefore employed in actual measurements. These are made with metal of high specific resistance, in the form of wire or ribbon. Manganin (a copper-nickel-manganese alloy) is most used, because, when properly treated and aged, it meets the necessary requirements. These requirements are: permanent electrical and physical characteristics; low thermo e.m.f. in junctions with copper; small temperature coefficient of resistance; and relatively high specific resistance. The completed standard must, in addition, be unaffected by immersion in oil, or by changes in atmospheric conditions.

111. Classes of resistance standards. In general, resistance standards may be divided into two classes: standards of resistance, or those used primarily for the measurement of resistance; and current standards, or those intended primarily for the measurement of current.

112. General construction of standards of resistance. Standards of resistance have very small current capacity. They are made in two forms, the **Reichsanstalt** and the **N.B.S.** (National Bureau of Standards).‡ The former is shown, partially in section, in Fig. 34. The N.B.S. form is shown in Fig. 35. The distinctive features of the latter form are that it is immersed in oil and hermetically sealed. This prevents the absorption of moisture by

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* Drysdale, C. V. "Alternating-current Potentiometer for Measuring Telephone Currents," *London Electrician*, Aug. 1, 1913.

† Gati, B. Report of Second International Conference, European Telephone and Telegraph Administrations; 1910.

‡ Bureau of Standards Bulletin, Vol. V, 1908, p. 413.

very high or very low resistances and the accuracy depends upon the measurement of two unknown quantities with indicating instruments. Furthermore the current required to give a readable drop may cause overheating. The method should therefore be used with caution and only where accuracy is subordinate to simplicity and convenience. The potential should be measured, when possible, between points well within the current connections, especially when the resistance is low and the current is high. Greater accuracy can be obtained by substituting a standard resistance in place of the ammeter, and noting the drop across it, and across the unknown resistance, in succession. The latter is then equal to the ratio of the two readings multiplied by the standard resistance. The accuracy will be greatest when the two resistances are nearly equal.

117. Bridge methods are the most accurate for resistance measurements because: (a) they are zero methods; (b) comparison is made directly with standardised resistances, the accuracy of which can be made very high. The principal types of bridges are known as Wheatstone, slide-wire, Carey-Foster and Kelvin.

118. Wheatstone bridge. The Wheatstone bridge is most generally used for the measurement of all but the highest and the lowest resistances. Fig. 37 shows the theoretical arrangement of a Wheatstone bridge where r, r_1, and r_2 are accurately known resistances and r_x is the resistance to be measured. When using the bridge, the various resistances are adjusted until the galvanometer, G, shows no current flowing;

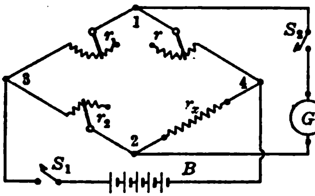

Fig. 37.—Diagram of Wheatstone bridge.

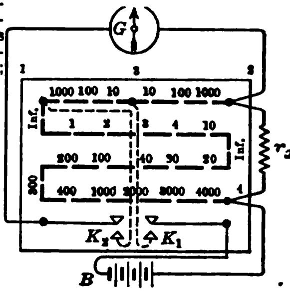

Fig. 38.—Wheatstone bridge—Postoffice form.

then, $r_x = (r_2/r_1)r$. The battery switch, S_1, should always be closed before the galvanometer switch, S_2, in order to protect the galvanometer from the momentary rush of current. The galvanometer and the battery may be interchanged without affecting the result (Sec. 2, Par. 30).

119. Forms of Wheatstone bridges. These bridges are made in a variety of forms. In most forms the resistances, r, r_1 and r_2, consist of a number of resistance coils or units carefully adjusted to various multiples of 10 and so arranged that they can be conveniently connected in and out of the circuit by means of plugs or switches. The resistances, r_1 and r_2 (Fig. 37) are commonly called the ratio arms and r the rheostat arm. A very early form, which is still in use in small portable sets, is the **Postoffice** pattern, shown diagrammatically in Fig. 38. Coils are cut out by short-circuiting them with plugs, so that there may be several plug-contact resistances of an unknown and variable amount in a given arm. In the **Anthony** form, shown diagrammatically in Fig. 39, this objection is overcome by arranging the coils of the rheostat arm on the "decade" plan in which there are nine 1-ohm coils in the "units" division, nine 10-ohm coils in the "tens" division, etc. Any number of coils in a given division can be connected in circuit by changing only one plug. In many later types, the ratio-arm coils are also connected on the decade plan, which in addition to eliminating plug-contact resistance errors, permits interchecking the coils. Furthermore, the decade arrangement permits the use of sliding-brush or dial construction instead of plugs.

In practice, r_1/r_2 is kept equal to α/β and the resistance d is made negligibly small. Then $r_x = r_2 r/r_1$, as in the Wheatstone bridge.

In the Wolff bridge, Fig. 42, the ratios r_1/r_2 and α/β are automatically adjusted simultaneously, by sliding contacts on the four dials. In the Leeds and Northrup bridge, Fig. 43, both r and the ratio r_1/r_2 are adjusted.

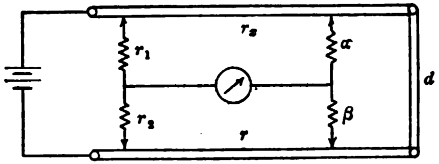

Fig. 41.—Diagram of Kelvin double bridge.

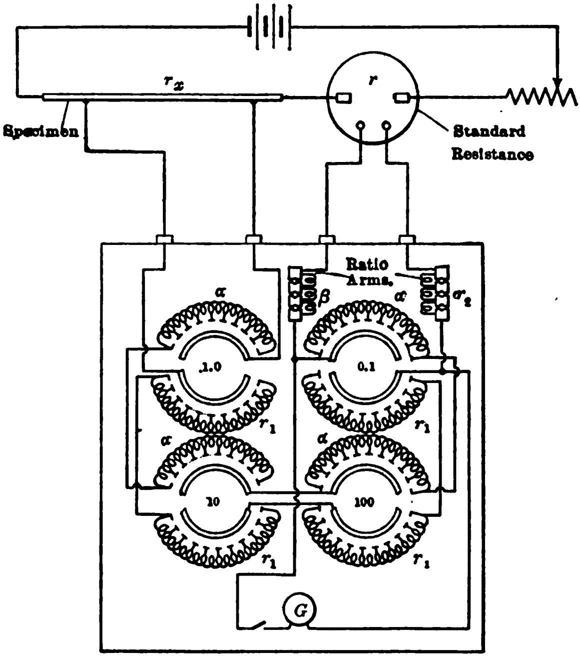

Fig. 42.—Kelvin double bridge—Wolff form.

124. Conductivity measurements. The specific conductance or conductivity of a material is the reciprocal of the specific resistance or resistivity. The relative conductivity is the ratio, expressed in per cent., of the specific conductance of the sample to that of a standard material. The relative conductivity may be based on equal masses or equal volumes. The former is in most common use because conductor metals are usually sold on a weight basis (see Sec. 4).

about 300 ohms each, in order to eliminate the effect of contact resistance at *a*, *b*, *c* and *d*. When the bridge is balanced, the resistance between *c* and *d* on r_x is equal to that between *a* and *b* on *r*. The unknown specimen r_x is cut to a certain definite length and carefully weighed. The contact, *b*, on the standard is then set at the point indicated on the carefully graduated scale *H*, which corresponds to this weight. Then the resistance, *ab*, is equal to that of a piece of wire having 100 per cent. conductivity, a length equal to 100 parts in the scale *I* and the same weight per unit length as r_x. Contact *d* is shifted until a balance is obtained and the conductivity is read directly from scale *I*, 100 scale divisions corresponding to 100 per cent. conductivity. One standard is provided for every three sizes of wire in the American (B. & S.) gage. The standards are usually of the same material as that being tested, so that the temperature does not have to be observed.

128. Resistance of rail joints. The testing of rail bonds consists in determining, either, (a) the ratio of the resistance of a given length of rail, including a bonded joint, to that of the same length of continuous rail; or (b) the length of solid rail which has the same resistance as the joint. The resistance of rail bonds is usually expressed in the latter manner, whether measured in that way or by the former method. Three methods are employed: millivoltmeter, bridge, and opposition.

129. Millivoltmeter method of measuring rail bonds. In the millivoltmeter method, simultaneous readings are taken with 2 millivoltmeters, one connected across the bond and the other across a definite length of rail. If the current fluctuations are not too rapid, only one instrument is necessary, provided there is a suitable arrangement of keys to change the connections in quick succession.

130. In the Roller bond tester the principle of the **slide wire form of Wheatstone bridge** is employed (Fig. 44). Balance is obtained by moving the contact *B* back and forth. At balance, $ab/bc = (r_1 + m)/(r_2 + n)$; where ab = resistance of bond and bc = resistance of the standard length of rail. The resistances r_1 and r_2 have the effect of extending the slide wire and providing greater accuracy (see Par. **121**). In the actual instrument, the slide wire takes the form of a circle and the scale is graduated to give the resistance directly in terms of the number of feet of the solid rail being tested.

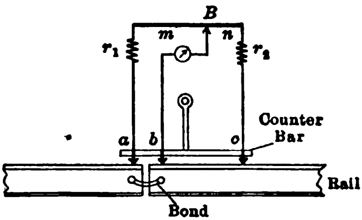

Fig. 44.—Diagram, Roller bond tester.

131. The Conant bond tester is an example of the class in which the drop across the joint is opposed to that across a length of solid rail, the outer contact on the latter (*c*, Fig. 44) being moved along until the two potentials are just equal and opposite. The detector is a telephone receiver in series with a make and break device operated by a clock.

132. Insulation resistance. The resistance of insulating materials is usually measured by deflection methods. In the case of resistances of the order of 1 megohm and less, a Wheatstone bridge may be used, but the accuracy will be low because of the extreme ratio required (Par. **121**) and the low insulation resistance of the bridge.

Two general classes of deflection methods are used: (1) direct deflection and (2) leakage. The direct-deflection methods involve a simple application of Ohm's law, the current being measured with a voltmeter used as an ammeter or with a galvanometer.

133. Direct-deflection method (insulation resistance). When the resistance is of the order of 1 megohm, an ordinary voltmeter will give results which are sufficiently accurate for most purposes. Two readings are taken, one with the voltmeter directly across the battery or generator, and the other with the resistance to be measured connected in series with the voltmeter. The resistance is $R = r_v\,(d - d_1)/d_1$; where r_v =

or graduate in which two circular, closely fitting disc electrodes are supported. One of the electrodes should be movable so that the resistance of columns of several different lengths can be measured. The first measurement should be taken as the zero or base reading and the results checked by calculation of the increase in resistance and the corresponding increase in the spacing of the electrodes at different settings.

137. Precautions in measuring insulation resistance. In the measurement of the insulation resistance of specimens having electrostatic capacity, sufficient time should be allowed for the specimen to become charged, that is, until the deflection becomes constant, at a minimum value. This usually takes place within 1 min., except in long lengths of cable. In order to eliminate uncertainties in this connection, it is customary to specify 1-minute "electrification."

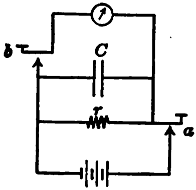

FIG. 46.—Leakage method of measuring insulation resistance.

As the apparent insulation resistance varies with the testing potential, one hundred volts is usually prescribed as the minimum pressure that should be used.

Leakage over the surface of wire or other specimens may be a source of much trouble in damp weather. In wires and cables, the lead or braid should be removed for 2 or 3 in. from the ends and the exposed insulation coated with hot, clean paraffine; or, just before measuring, these prepared ends may be carefully dried with an alcohol, Bunsen or other flame free from carbon. As a further precaution, a "*guard*" *circuit* may be arranged as shown by the dotted lines in Fig. 45. This consists of a few turns of fine copper wire twisted around the insulation close to the copper conductor and connected to the battery side of the galvanometer. In the case of solid specimens, the twisted wire is replaced with a ring of tin-foil as shown in Fig. 97.

Specimens having electrostatic capacity should be put in a neutral condition by rapidly reversing the current a number of times, beginning at a low rate of reversals and gradually increasing. Where the capacity is high it may be advisable gradually to decrease the applied voltage at the same time.

The side of the circuit which contains the galvanometer should be well insulated throughout. The battery also should be insulated as thoroughly as possible; this is a relatively easy matter when dry cells are used. The important point is to insure that all current passing through the specimen, and only that current, passes also through the galvanometer.

The galvanometer should, preferably, have a high resistance (order of 1,000 ohms) and a megohm sensibility (Par. 23 and 24) of several hundred megohms. The temperature should always be noted, because of the large coefficient which most insulating materials have.

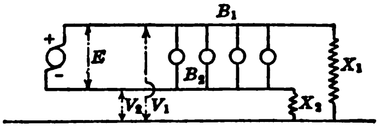

FIG. 47.—Insulation resistance of "live" circuits.

138. Measuring the insulation resistance of circuits. The insulation resistance of a "dead" circuit is conveniently made by the voltmeter method. When there is no source of e.m.f. available, various portable instruments described below are especially applicable and convenient. (Also see Sec. 21.)

When the circuit is "alive" the following method may be used.* Fig. 47 represents diagrammatically a system with lamps and motors connected. The resistances X_1 and X_2 represent the insulation resistance from the positive and negative sides respectively to ground.

$$X_1 = \frac{R(D - d_1 - d_2)}{d_2}, \text{ and } X_2 = \frac{R(D - d_1 - d_2)}{d_1} \quad \text{(ohms)} \qquad (17)$$

* Northrup, E. F. "Methods of Measuring Electrical Resistance;" McGraw-Hill Book Co. Inc., p. 210.

the electrolyte. If the slide-wire scale is divided into 1,000 parts, the resistance of the electrolyte is, at balance,

$$r_x = \left\{ \frac{a}{(1000-a)} \right\} R. \qquad \text{(ohms)} \qquad (18)$$

If the source is alternating-current power of commercial frequencies an alternating-current galvanometer (reflecting electrodynamometer) may be used, the fixed coils being connected in series between the source, S, and the bridge and the moving coil in place of D (Fig. 49). A **Vreeland oscillator** (Par. 246) is very satisfactory as a source of energy because the wave form is a pure sine curve and the frequency is sufficiently high to make the telephone sensitive.

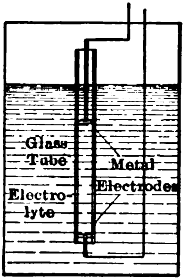

FIG. 50.—Specific resistance of electrolytes.

141. Specific resistance of electrolytes. Where the specific resistance or resistivity is required, a column of the liquid of known dimensions must be isolated. Fig. 50 shows a satisfactory method.* The glass tube is about 20 cm. long, 1 cm. internal diameter and open at both ends. The electrodes are of gold or platinum, the lower one being fixed in position and perforated, while the upper one is adjustable. The average cross-section must be carefully determined, preferably by volumetric measurement with mercury. The temperature is readily kept constant by stirring the liquid in the containing vessel.

142. Internal resistance of batteries. This measurement involves difficulties because of polarization. One simple direct-current method is as follows. The e.m.f. of the cell or battery is first measured on open circuit. The circuit is then closed through a known resistance and the e.m.f. measured again quickly before polarization begins. The resistance is

$$R_x = \frac{R(E-E_1)}{E_1} \qquad \text{(ohms)} \qquad (19)$$

where R = known resistance, E and E_1 = voltage before and after closing circuit, respectively.

This method assumes that the internal resistance will remain constant under all conditions, which is not always the case, especially in dry cells. In a modification of this method, both readings are taken with the circuit closed, but with two slightly different values of R. Then

$$r_x = \frac{(E_1-E_2)R_1R_2}{E_2R_1-E_1R_2} \qquad \text{(ohms)} \qquad (20)$$

where R_1 and E_1 are the first resistance and e.m.f., respectively, and R_2 and E_2 are the corresponding values with the second resistance.

In general, such direct-current methods should be used only with primary batteries of very low resistance and with secondary or storage batteries. Alternating-current methods are more reliable.

143. Alternating-current method of measuring internal resistance of batteries. The Kohlrausch bridge shown in Fig. 49 can be used in this method, by inserting the cell or battery in place of the electrolyte cell. Without resistance R′ connected, the resistance of the cell will be

$$r_x = \frac{a}{(1{,}000-a)} R \qquad \text{(ohms)} \qquad (21)$$

If the resistance R' is connected, the resistance of the cell with a current corresponding to R' flowing, will be

$$r_x = \frac{aR'R}{(1{,}000-a)R-Ra} \qquad \text{(ohms)} \qquad (22)$$

144. Effective resistance of alternating-current circuits. The passage of alternating current through a circuit is opposed by the ohmic resistance,

* Northrup, E. F. "Methods of Measuring Electrical Resistance," McGraw-Hill Book Co. Inc., p. 241.

151. Pulsating power. Where there are instantaneous variations in the current and the potential, the power varies from instant to instant. The average power will be the average of the products of corresponding instantaneous values of current and potential and it can be measured with *strict* accuracy only with watt-meters of the dynamometer type. In rectifier circuits, the power consumption of a storage battery or a motor can be approximately measured with a voltmeter and an ammeter of the permanent magnet type. Such instruments would give a more nearly correct result than dynamometer instruments. On the other hand, the reverse will be the case with a load of incandescent lamps or heating devices. The error will depend upon the wave shape and the character of the load. The safe method is to use a dynamometer-type wattmeter.

152. Alternating-current power. The power in an alternating-current circuit, at any instant, is the product of the current and potential at that instant. When the load consists only of resistance, the current wave, I, and the potential wave, E, are in phase as shown in Fig. 51, and the power-factor is 100 per cent. or unity. If the products of the instantaneous values of current and potential are plotted, the curve P is obtained. The average value of this curve is the power equivalent of a continuous current producing the same effect. Also, $W = EI$, where W = average watts, E = mean effective volts and I = mean effective amperes. These values of potential and current are indicated by instruments in which the deflections are proportional to the square of the current.

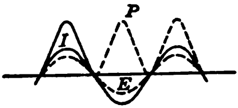

Fig. 51.—Relation of current, e.m.f. and power in a.c. circuit.

153. When the power-factor is less than unity, due to the fact that the circuit contains inductance or capacity (or the equivalent), the current and the potential will not be in phase. In the case of an inductive load, the current will lag behind the potential, as shown in Fig. 52. The power curve then will not be all on one side of the axis, but a part will be negative. If the current lags sufficiently, Fig. 53, the power curve will be positive half of the time and negative the other half; the average power will then be zero (or zero power-factor). This difference in phase, or time relation between the current and the potential, is called the phase angle and is usually expressed in degrees, an entire cycle being 360 deg. If the current and the

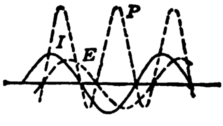

Fig. 52.

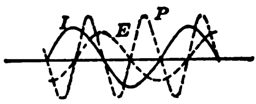

Fig. 53.

Figs. 52 and 53.—Relation of current, e.m.f. and power in a.c. circuit.

voltage are sinusoidal, the average value of the power is $W = EI \cos \theta$, where ϕ is the phase angle. Therefore if the current and the potential are not in phase, it is necessary to know the value of the phase angle if the power is to be determined from the current and the potential. Fortunately, instruments called wattmeters are available, which not only automatically integrate the power curve, but take into account the factor, $\cos \theta$.

154. Precision measurements of power must be made with an instrument which is equally accurate on continuous and alternating currents, in order that it may be calibrated on continuous current. Such measurements are most accurately made with **reflecting electrodynamometers** in which deflections are measured by means of a mirror, with a lamp and scale. (See Par. **33**, **64** and **97**.) The fixed coils are often divided into several sections, which may be connected in various series and parallel combinations to give large deflections over a wide range of power intensities. Instruments of this type made by the General Electric Company have current capacities from 5 amp. to 125 amp. and above, with corresponding sensibilities moving disc, or drum, as in the polyphase watt-hour meter. It is obvious that instruments of this type are limited to the frequency for which they are designed.

161. The Whitney wattmeter operates on the dynamometer principle (Par. 158) except that it is a torsion-head instrument, the moving element being kept in a fixed position by twisting the torsion head to which the control spring is attached. The pointer attached to this head moves over the scale. This method permits using a very long scale, extending around a full circle.

162. Wattmeters for switchboard use employ both the electrodynamic and the induction principles. Weston instruments are similar to the portable electrodynamometer instrument (Par. 158). The General Electric edgewise type "H" instruments are dynamometer types while type I is of the induction type. Westinghouse switchboard instruments are also induction type.

163. The calibration of wattmeters of the dynamometer type should be done with continuous current. It is customary to make such tests at a fixed potential, usually 100 or 200 volts and to vary the current to give the required watts. The potential is held constant at the desired value by means of one standard (standard voltmeter or potentiometer) and the current is read on another standard (standard ammeter, or potentiometer with standard resistance). It is more convenient to obtain the potential and the current from separate sources, because the process of adjustment of one circuit will not affect the other. In the case of instruments of large capacity this method economises energy, because only three or four volts are necessary for the current circuit.

164. Calibration of induction-type wattmeters. These instruments must be checked on alternating current of the frequency for which they are designed. This check is made by comparison with a secondary standard, which in turn is checked on continuous current. Polyphase instruments may be checked as single-phase instruments by connecting the current circuits in series and the potential circuits in parallel. In the case of induction-type instruments stray magnetic flux from one element may affect the other, in which case the calibration should be made on a polyphase circuit.

165. The inductance error in wattmeters may, under certain conditions, become very important. While the theory of the electrodynamometer type of wattmeter assumes that the potential circuit is non-inductive, this is not strictly true in the actual instrument because of the inherent inductance of the moving coil. Ordinarily, however, the non-inductive series resistance is sufficiently large to make the effect of this inductance negligible at ordinary frequencies and power-factors. But with low power-factors, the lag angle in the potential circuit may have to be considered. The power in an alternating-current circuit is $W = EI \cos \theta$, where W = power, I = current, E = e.m.f. and $\cos \theta$ = power-factor of circuit. When the power-factor is unity, I and E are in phase, but the potential-circuit current lags slightly behind E, thus producing the effect of a small power-factor. If, for example, the lag-angle, θ, is 2 deg., $\cos \theta = 0.9994$ and the error is ordinarily negligible. If the power-factor is 50 per cent., the lag angle in the wattmeter is $(60-2) = 58$ deg. The cosine of 60 deg. is 0.50 while the cosine of 58 deg. is 0.53, thus introducing an error of 6 per cent.

166. The stray-field error in unshielded, non-astatic, electrodynamometer wattmeters may be anything from zero to 25 per cent. with an alternating magnetic field of 5 lines per square centimeter, and from zero to 75 per cent. at 10 lines, depending upon the direction of the field and the coil deflection. A shield, properly made and placed, is extremely efficient, reducing the effect of a field of 20 lines per square centimeter to practically zero, without introducing eddy current or other errors.

Wattmeters of the Kelvin balance type, in which the coils are astatically arranged, are practically immune from these troubles except in an intense field which is not uniform throughout the space occupied by the moving system; such a condition may arise, for example, when the wattmeter is close to a conductor carrying a very large current. Induction-type instruments employ much stronger field strengths and are not appreciably affected except by very strong fields.

170. Measurement of power in a single-phase circuit. One wattmeter connected as shown in Fig. 56 will read true watts. The power may also be measured without the use of a wattmeter, by three voltmeters or three ammeters.

In the "**three-voltmeter**" method, a known non-inductive resistance, R, is connected in series with the load as shown in Fig. 58, where E, E_1 and E_2 are points where voltmeter readings are to be taken. The power in watts is

$$W = \frac{E^2 - E^2_1 - E^2_2}{2R} \qquad \text{(watts)} \qquad (24)$$

Similarly, in the "**three-ammeter**" method, Fig. 59, the power in watts is

$$W = R\left(\frac{I^2 - I^2_1 - I^2_2}{2}\right) \qquad \text{(watts)} \qquad (25)$$

171. Two-phase, four-wire circuit. Two wattmeters, connected as shown in Fig. 60, are sufficient, these conditions being equivalent to two single-phase circuits. The total power is obviously the arithmetical sum of the readings of the two instruments.

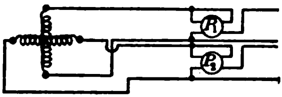

Fig. 60.—Power in two-phase, four-wire circuit.

172. Two-phase, three-wire circuit.—Two wattmeters should be connected as shown in Fig. 61, the total power being the *algebraic* sum of the two readings. This connection is correct for all conditions of load, balance and power-factor. One wattmeter may be used as in Fig. 62, provided there is no load across the outer conductors and the phases are *balanced* as to load and power-factor.

173. Two-phase, four-wire, interconnected circuit. Three wattmeters can be used, connected as in Fig. 63, the total power being the *algebraic* sum of the three readings. This connection is correct under all conditions of load, balance and power-factor. Two wattmeters, one in each phase, will give the true power only when the load is balanced.

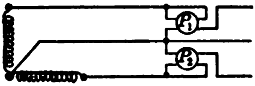

Fig. 61.—Power in two-phase, three-wire circuit.

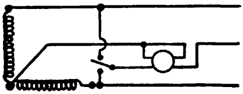

Fig. 62.—Power in two-phase, three-wire circuit.

174. Three-phase, three-wire circuits. Two wattmeters may be used, connected as in Fig. 64, the total power being the *algebraic* sum of the two readings. At unity power-factor, each instrument will indicate half the total power and at 50 per cent. power-factor one instrument will indicate the total power, the other instrument reading zero. At less than 50 per cent. power-factor, one instrument will read negative. (See Par. 209 for method of verifying power-factor.)

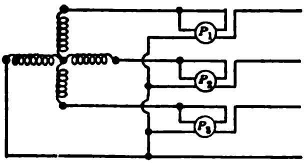

Fig. 63.—Power in two-phase, four-wire interconnected circuit.

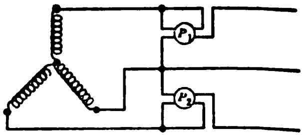

Fig. 64.—Power in three-phase, three-wire circuit, two wattmeters.

point P of the system, which may or may not be the neutral. The total power is the algebraic sum of the readings of all of the wattmeters so connected.*

178. Power measurements on high-voltage circuits should preferably be made with series-type and shunt-type instrument transformers. If the instrument wattmeter is connected directly to the circuit with series resistance in the potential circuit, the circuit should be grounded at the instrument in order to avoid errors of electrostatic attraction, and also possible injury to the instrument or the observer. The current-capacity limit of commercial wattmeters is about 200 amp. beyond which series transformers with 5-amp. instruments are used, irrespective of potential.

179. Corrections where instrument transformers are used in accurate power measurements. In every case the **true ratio** and **phase angle** should be known (Par. 79 and Par. 104, 105). The general effect of the phase changes in the instrument transformers is to make the angle between the current and the potential in the wattmeter larger or smaller than that between the current and the e.m.f. of the circuit being measured.

If $\cos\theta$ = true power-factor and $\cos\theta_2$ = apparent power-factor (*i.e.*, power-factor in the wattmeter obtained from the ratio of the watts and volt-amperes in the wattmeter), true watts = $(\cos\theta/\cos\theta_2)\times$ wattmeter reading. The apparent power-factor, $\cos\theta_2 = \cos(\theta\pm\alpha\pm\beta\pm\gamma)$, where

θ = phase angle in main circuit,
α = equivalent phase angle in wattmeter,
β = equivalent phase angle in current transformers,
γ = equivalent phase angle in voltage transformers.

The angles α, β and γ are given positive (+) signs when they tend to decrease and negative (−) signs when they tend to increase the phase angle between the current and voltage in the instrument.†

180. Power-factor. The power-factor of a circuit is the ratio of the true power in watts, as measured with a wattmeter, to the apparent power obtained from the product of the current and the potential, in amperes and volts respectively. In the ordinary continuous-current circuits, the power-factor is obviously unity but in rectifier circuits, for example, it may be slightly less than unity. In alternating-current circuits, the power-factor is usually less than unity because the current and the potential are not in phase. When the wave form is sinusoidal, the power-factor is equal to the cosine of the angle of lag.

181. The power-factor of single-phase circuits is obtained from wattmeter, voltmeter and ammeter readings, by the relation $W/EI = \cos\theta$ where W = watts, E = volts and I = amperes.

182. The power-factor of polyphase circuits which are balanced is the same as that of the individual phases. When the phases are not balanced, the true power-factor is indeterminate. For all practical purposes, however, it is sufficiently correct to assume the power-factor to be that obtained by methods which give the average of the power-factors of the separate phases. In the **wattmeter-voltmeter-ammeter method,** the power-factor is, for a two-phase, three-wire circuit $W/\sqrt{2}\ (EI)$, (I in middle wire, E between outer wires) and for a three-phase, three-wire circuit the power-factor is $W/\sqrt{3}\ (EI)$, wherein W = watts, E = volts and I = amperes. In the **two-wattmeter** method, the power-factor of a two-phase, three-wire circuit is obtained from the relation $W_2/W_1 = \tan\theta$, where W_1 is the reading of a wattmeter connected in one phase in the same manner as a single-phase circuit, and W_2 is the reading of a wattmeter connected with its current coil in the first phase, in series with the first wattmeter, and the potential coil across the second phase. Obviously, if the load is steady, one wattmeter is sufficient. If the phases are not balanced, the readings should be repeated with the instruments in the second phase, the true power-factor being taken as the average of the two results. In a **three-phase, three-wire circuit,** the power-factor can be calculated from the readings of two

* Bedell, F. "Direct and Alternating-current Testing." D. Van Nostrand Company (1912), p. 228.

† Robinson, L. T. "Electrical Measurements in Circuits Requiring Current and Potential Transformers." *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 1005.

tional to the power and the revolving element operates a registering mech anism on which the energy consumption is recorded. Meters for con tinuous current are usually of the type which utilize the electrodynami principle of direct-current motors, while those for alternating curren utilize the principle of induction motors.

188. Continuous-current watt-hour meters. Continuous-curren meters may be divided into two classes, the **commutator type** and th **mercury motor type.**

189. Commutator-type meters are similar in principle to shunt motor The essential features are shown in Fig. 71. The moving element consist of an armature, *a*, a commutator, *c*, an a light metal disc, *d*, all mounted on steel shaft which rotates in a jewe bearing. The armature is connecte to the external circuit by means of ver light silver-tipped brushes. In serie with the armature is a light-load com pensation coil, *s*, and a resistance, r The field coils are indicated at *f*, *f*.

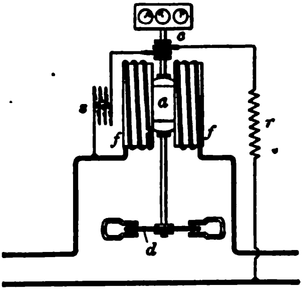

FIG. 71.—Diagram, commutator-type watt-hour meter.

190. Characteristics of commu tator-type meters. The essentia differences between this type of wat hour meter and a two-pole shunt moto are as follows: (a) entire absence o iron in the magnetic circuits; (b) th armature element is connected acro the circuit and carries a very sma current, while the field element is i series with the circuit and carries th main current; (c) the speed increase as the field strength increases which i opposite to the effect in a shunt moto

191. The principle of operation of commutator-type meters i as follows. The torque is proportional to the current in the armature coi and to the field strength. Since there is no iron in the magnetic circuit, th latter is always proportional to the field current, hence the torque is pro portional to the two currents (as in a dynamometer wattmeter). The cu rent in the armature being proportional to the line potential, and the fiel current equal or proportional to the line current, the torque is proportiona to the power. In order to make the speed proportional to the power, mechanical load must be provided, in which the counter-torque will be pro portional to the speed. This load usually takes the form of a circular dis *d* (Fig. 71) of thin copper or aluminum which revolves between the pole of one or more permanent horseshoe magnets, with poles very close togethe The eddy currents induced in the disc react with the permanent-magne field, producing a counter-torque which will always be proportional to th speed. As the load current increases, the torque of the motor element in creases and the speed increases, because there is practically no counte e.m.f. in the armature, *s*. But as the speed increases, the counter-torqu of the disc or generator element also increases and a speed is finally reache where the two torques balance each other and the speed remains constan Thus, theoretically, the speed will always be proportional to the power in th circuit. Each revolution represents a definite amount of energy, and b connecting the shaft to a suitable recording mechanism similar to that o gas and water meters, the total energy consumed is automaticall registered.

192. Effects of friction and temperature in commutator-typ meters. In practice, certain conditions prevent the speed from bein always proportional to the load, the principal factors being friction an temperature. **Bearing friction** is reduced to a minimum by using polishe sapphire or diamond jewels, with either a polished cone-shape shaft-en or a steel ball. Thus the contact surface is reduced practically to a poin The weight is reduced by using hollow shafts and very light aluminum o non-metallic frames for the armature windings. **Commutator frictio** is reduced to a minimum by making the commutator diameter small, an

198. Typical Data Applying to Modern 110-Volt, 5-amp. or 1 amp., Direct-current Watthour Meters *

	G. E. Co. C-6, 5 amps.	Westinghouse CW-6, 5 amps.	Sangamo D, 10 amps.	Duncan E, 5 amps.	Columbia D, 10 amps.
Speed, full load, r.p.m.	46	41.7	25	36.7	3
Torque, full load, mm.-grm.	170	140	55	180	9
Weight, moving element, grm.	97	80	3‡	130	9
Ratio, torque to weight	1.75	1.75	18	1.39	1.
Drop, current circuit, volts at rated current.	1.15	1.0	0.03	.....	0.5
Loss, current circuit, watts at rated current.	5.75	5.0	0.3	.....	5.
Loss, potential circuit, watts at 110 volts.	5.1	4.5	5.0	5.0	2.
Resistance, armature, ohms	825	1,185	1,850§	.....	2,66
Resistance, compensating coil, ohms	65	315	......	.....	45
Resistance, series resistance, ohms	1,540	800	450	.....	3,00
Resistance, potential circuit, total ohms	2,430	2,300	2,300	.....	6,11
Ampere-turns, field	300	600	......	910	70
Ampere-turns, armature	800	1,500	......	.....	2,10

199. Three-wire circuits are metered with two, two-wire meters o the kind described (Par. 188 to Par. 198), **or a three-wire meter.** Th latter which is usually made in the **commutator type**, is the same as th two-wire meter except that the two field coils (which should be alike) ar separated electrically, and one is connected in each outer wire in such a manne that their fields are cumulative as before. When the load is exactly balance the conditions are obviously the same as in a two-wire meter, and whe unbalanced the two field strengths add together so that the speed is pro portional to the total current.†

200. The metering of heavy-current circuits by means of standar meters becomes troublesome because of the large conductors required in th fields. While such meters have been made in capacities up to 20,000 amp they are very costly and not satisfactory at light loads. Watthour mete have been developed by some manufacturers, along standard lines, for ope ation with shunts. In order to develop sufficient torque without an exce sive shunt loss, it is necessary to employ shunts having small drop, large fie coils on the meters and relatively large leads from meter to shunt. Whe the meter has to be some distance from the shunt, the leads may have to b nearly as large as the wires in the main circuit, in order to keep down th resistance.

Another way to avoid the use of large meters is to connect seve smaller meters in parallel. Care should be taken to make the resistan of the several branches equal, if the meters are of the same capacity; or, the meters are of different capacities, inversely proportional to the capa ties of the meters. This will insure that none of the meters are overloade

201. Alternating-current watt-hour meters. Alternating-curre energy is almost always measured with induction type meters. Com mutator meters are seldom used on alternating-current circuits for the ve practical reason that induction meters are not only **more accurate**, b much **less expensive** in first cost and in maintenance.

* From Electrical Meterman's Handbook, N. E. L. A., 1912, to whi readers are referred for further data. See also Fitch, T. T. and Huber, C. "A Comparative Study of American Direct-current Watthour Mete Bureau of Standards Bulletin, 1913, Vol. X, p. 161. (Reprint No. 207.)

† The Sangamo Co. has recently developed a three-wire mercury meter (Par. 195).

practically all meters is that in which a flux is produced at the potenti pole face, slightly out of phase with the main flux. Thus eddy currents wi be produced in the disc which will be in phase with a small component of th main flux, giving rise to a slight torque which can be made sufficient to over come the friction torque. This "out-of-phase" flux is produced in variou ways in different meters. A common method is to place a short-circuite copper circuit or thin copper punching ("shading strip") in the potentia pole air-gap, in an unsymmetrical position, so that the desired unbalance flux will be obtained. In the Columbia meter, the effect is accomplishe by unbalancing the flux of the two potential poles by means of magneti shunts.

205. Adjustments of induction-type meters. Facilities are usuall provided for conveniently adjusting the meter accuracy at light and full loac The position of the light-load compensation coil can be changed wit conveniently located screws, and the light-load speed thus altered. Spee adjustment at all loads is obtained by shifting the drag magnets wit respect to the axis, as in direct-current meters, or by shunting the flu by means of a movable soft-iron **keeper** bridging the air gap. Th power-factor or lag adjustment is made at the factory and if properly don should never require readjustment.

206. Typical Data Applying to Modern 110-volt Single-phase 60 cycle, 5-amp. Induction-type Watt-hour Meters*

	G. E. Co. I–10	Westing-house 0–A	Fort Wayne K–4	San-gamo H	Duncan M	Colum-bia C
Speed, full load, r. p. m.	36	25	36.7	40	36.7	30
Torque, full load, mm.-grams	46.6	36	45	40	115	80
Weight, moving eel-ment, grams	26.3	15.	21	15.6	46	30
Ratio torque to weight	1.77	2.32	2.14	2.5	2.5	2.66
Drop, current circuit volts at 5 amp.	....	0.3	0.12	0.1	....	0.1
Loss, current circuit, watts at 5 amp.	0.98	0.75	0.59	0.5	....	0.5
Loss, potential circuit, watts at 110 volts	2.5	1.6	1.75	1.85	1.25	1.5
Power-factor, potential circuit, per cent	....	18	17	35	....	70

207. Measurement of energy in alternating-current circuits The energy consumption in alternating-current circuits is measured witl watt-hour meters connected in exactly the same manner as are wattmeter for the measurement of power. (See Figs. 60 to 68.) In **three-wire, two-phase** or **three-phase systems, polyphase meters** may be used. Sucl meters comprise merely two single-phase meters in one case, with a commo shaft, and connected to the main circuit in the same manner as two single-phase meters.

Four-wire systems, unless balanced, require **three single-phas meters.** A **three-phase system** with a **grounded neutral** should b considered a four-wire system requiring three meters, unless it is complete balanced.

208. The total energy in a three-phase circuit is the algebraic sur of the indications of two single-phase meters, just as the total power i the algebraic sum of the readings of two wattmeters (Par. 174). If a **polyphase meter** is used, the summation is automatically performed, and

* From "Electrical Meterman's Handbook," N. E. L. A., 1912, to which th reader is referred for further data.

the voltage, as indicated in Fig. 75. Resistance in the potential circuit of alternating-current meters will alter the quadrature phase relation, and therefore voltage regulation should be obtained with a variable ratio auto-transformer, an induction regulator or by field control.

213. Power-factor variation, in meter testing, can be obtained by several methods. In the **two-alternator** method, two generators are mounted on a common base, with a common shaft. The stationary members (armature or field) are made movable about the shaft with respect to the base and to each other. Thus with the potential coil of the meter connected to one machine, and the current coil to the other, any phase relation can be obtained by adjusting one movable member with respect to the other.

In the **transformer** method, a transformer with a large number of steps, or a variable-ratio auto-transformer, is connected across one phase of a polyphase circuit and the potential coil of the meter is connected in such a manner that any phase relation can be obtained. Thus, referring to Fig. 76, the current coil of the meter is connected in series with conductor *a* of a three-phase circuit, and the potential coil is connected to *o* and to *c*, the latter being a tap on a transformer connected across phase *bc*. It is apparent that **any phase angle** between the current and the potential can be obtained in a range from 0 deg. to 60 deg. by moving the connection point *c* along the transformer winding. Angles from 60 deg. to 90 deg., lead or lag, can be obtained by changing the transformer to either of the other two phases and the meter connection from *o* to *x* or *y*. These changes can be instantly made with suitable switching arrangements. A similar arrangement can be made for a two-phase circuit, Fig. 77. It is also convenient to introduce such a transformer between the taps *o*, *c* and the meter, for the purpose of compensating for the variations in the voltage between *o* and *c*, and keeping the voltage constant at the meter. Two variable-ratio auto-transformers arranged in this manner make a convenient **phase shifter.**

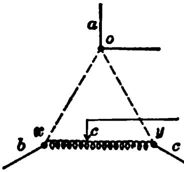

Fig. 76.—Power-factor variation—transformer method.

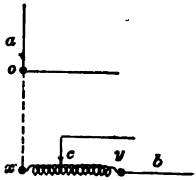

Fig. 77.—Power-factor variation—transformer method.

In the **reactance-coil** method, a reactance coil is introduced in the current circuit, the reactance being varied by moving an iron core in and out of the coil. It is difficult to obtain low power-factors with this method unless a separate low-potential current circuit is used, and then there is danger of **wave-form distortion.**

214. Measurement of meter torque. The torque is measured under normal conditions at full load by measuring the force in grams exerted at the edge of the disc, or at the end of an arm attached to the shaft. This force may be measured by means of weights, a calibrated watch spring, or by utilizing the principle of the pendulum.* By measuring the radius of the disc or the arm in millimeters, the torque is obtained in millimeter-grams, the usual unit.

215. Measurement of watt-hour meter losses. The losses in the windings of c.c. meters are calculated from the resistances, as determined with continuous current by standard methods. The losses in alternating-current meters are measured directly with wattmeters, but great care is required because of the very small amount of power and the small power-factor.

216. The standards for direct-current meter tests may be ammeters and voltmeters, in portable or special laboratory types, or potentiometers; in alternating-current meter tests, use is made of indicating wattmeters. The time in measuring the meter speed is usually determined with stop-watches, reading to tenths of seconds. Where a large number of meters

* Agnew, P. G. Bureau of Standards Bulletin, 1911, Vol. VII, No. 1. (Reprint No. 145.)

220. General precautions to be observed in testing watt-hour meters are as follows: (a) The test period should always be sufficiently long and a sufficiently large number of independent readings should be taken to insure the desired accuracy. In service tests, the period preferably should be not less than 30 sec. and the number of readings not less than three. In laboratory tests, 100-sec. periods and five readings are preferable. (b) Capacity of the standards should be so chosen that readings will be taken at reasonably high percentages of their capacity, in order to make observational or scale errors as small as possible. (c) Where indicating instruments are used on a fluctuating load, their average deflections should be estimated in such a manner as to include the time of duration of each deflection, as well as the magnitude. (d) Instruments should be so connected that neither the standards nor the meter being tested are measuring the potential-circuit loss of the other, that the same potential is impressed on both, and that the same load current passes through both. (e) When the meter under test has not been previously in circuit, sufficient time should be allowed for the temperature of the potential circuit to become constant, preferably not less than 10 min.; this is important with direct-current meters, especially in the case of rotating standards. In some types of the latter, special provision is made for rapid heating. (f) Guard against the effect of stray fields by locating the standards and arranging the temporary test wiring in a judicious manner.

221. Meter constants. The following definitions of various meters constants are taken from "Code for Electricity Meters."*

Register constant is the number by which the register readings must be multiplied to obtain the registration. They are ordinarily used only on large-capacity meters and are marked on the register.

Gear ratio is number of revolutions of the rotating element per revolution of the first dial hand.

Watt-hour constant is the registration reduced to watt-hours per revolution of the rotating element. It has a definite value for each type and rated capacity of meter.

Watt-second constant is the registration reduced to watt seconds per revolution of the rotating element. It is equal to watt-hour constant multiplied by 3,600.

Test constant is the constant assigned by the manufacturer for use in the test formula for his meter.

222. Testing formulas. The accuracy of a watt-hour meter is the percentage of the total energy passed through a meter which is registered on the dials. Accuracy in per cent. = meter watt-hours × 100/true watt-hours. The value of one revolution having been assigned by the manufacturer, the meter watt-hours $= K_h \times R$, where K_h = watt-hours per revolution or watt-hour constant and R = revolutions in S seconds. The corresponding power in watts is $P = (3{,}600 \times R \times K_h)/S$ = meter watts and 100 × meter watts/actual watts = per cent. accuracy. This is the standard formula for watt-hour meters.

223. Manufacturers' formulas for meter watts. When the test constant K differs from the watt-hour constant, K_h, the formula is changed accordingly as follows:

Manufacturer	K in terms of K_h	Manufacturers' formula for meter watts
Columbia	$K = 3{,}600\ K_h$	$W = R \times K/S$
Duncan	$K = 60\ K_h$	$W = 60 \times R \times K/S$
Fort Wayne	$K = 36\ K_h$	$W = 100 \times R \times K/S$
General Electric	$K = K_h$	$W = 3{,}600 \times R \times K/S$
Sangamo	$K = 3{,}600\ K_h$	$W = R \times K/S$
Westinghouse	$K = 3{,}600\ K_h$	$W = R \times K/S$

K_h = watt-hour constant, K = test constant (marked on meter, usually on disc), R = number of revolutions in S seconds, W = meter watts.

224. Average accuracy of watt-hour meters. The accuracy of a meter varies with the load, but it is often desirable to assign a value for the

* "Code for Electricity Meters." A. E. I. C. and N. E. L. A., 1912 ed., pp. 95 and 96.

easily emptying the mercury from the tube into the anode receptacle when the former becomes filled. This type of meter has been highly developed and inherent errors due to variation in temperature, concentration of the solution, level of mercury, effect of vibration, etc., are largely eliminated in the latest forms.

230. The principal advantages of electrolytic-type ampere-hour instruments are their low first cost and their simplicity, which results in low maintenance cost. These are important items to power companies serving very small customers, especially where the rates are low; and may outweigh the disadvantages, the principal among which are elimination of the potential element and relatively low accuracy.

231. Electromotor ampere-hour meters are similar to watt-hour meters, except that the field is produced by permanent magnets instead of electromagnets. The rotating element is geared to a register which is calibrated in watt-hours for a given assumed voltage. There are two general types, the electromagnetic and the mercury flotation. The former is not made or used very much in this country.

The **Chamberlain and Hookum meter** is an example of the electromagnetic type. It employs a flat (pan-cake) armature winding mounted on an aluminum disc which also serves as the drag element. Connection is made to the circuit through a commutator and brushes in the usual manner. The armature is connected to a low-resistance shunt which is in series with the load.

The **mercury type** meter is well represented by the **Sangamo meter** which is practically the same as the Sangamo direct-current watt-hour meter (Par. 195), the electromagnet being replaced by permanent magnets.

232. Maximum demand meters. Many methods of selling energy involve the maximum amount which is taken by the customer in any period of a prescribed length, that is, the maximum demand. Meters for measuring this demand variously utilize the expansion of air, the torque of a watt-hour meter, or a special recording device in connection with a standard watt-hour meter.

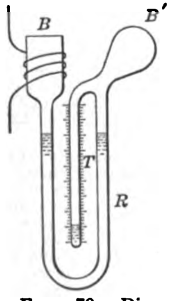

FIG. 79.—Diagram, Wright demand meter.

The **Wright demand meter** is a thermal instrument. It consists of a hermetically sealed U-shaped glass tube (Fig. 79), partly filled with a liquid. One leg *R* is connected near the top to a smaller graduated tube *T*. Around the top of the tube, *B*, is wound a resistance wire through which the current flows. The resultant heating of the air forces the liquid up the tube *R* and, if sufficient, over into the graduated tube. The air heats up gradually and the necessary **time lag** is thus obtained. According to the makers, if the overload continues 5 min., 80 per cent. of the load will be indicated; 10 min., 95 per cent.; and 30 min. 100 per cent.

233. The General Electric demand meter utilizes the principle of the induction watt-hour meter. The torque of the moving element is opposed by three long spiral springs, in series, and a powerful drag on the drag disc. This arrangement provides the necessary time lag. Two sweep-hands are provided on a dial. One is geared to the moving element, while the other is moved by the first one and left at the last position reached by it. This second pointer indicates therefore the maximum energy, until it is reset. The drag magnets and spiral springs being adjustable, the time lag can be adjusted through a considerable range. In this type of instrument, the demand is indicated at all times, as well as the maximum demand since the last setting.

234. Recording maximum-demand meters. In the **Minerallac Electric Co.'s "Printometer"** the kilowatt-hours indicated on a watt-hour meter are printed on a paper tape at intervals of any desired length. The hourly intervals are also indicated. It is separately mounted and can be electrically connected to any standard make of watt-hour meter. This device, while it indicates the time of maximum demand, is not an indicating instrument and considerable labor is involved in determining the maximum a minute, the pointer being perfectly free in the interim. The record is therefore a succession of dots. In other types of instruments, an inked thread or ribbon is interposed between the pointer and the paper chart.

238. The Westinghouse recording instruments are the principal example, in American practice, of the class where the recording mechanism is separate from the instrument proper. The moving element, by means of contacts, operates a relay which in turn operates the recording mechanism. Thus the moving element does not have to produce a large torque, while ample power can be applied to the recording mechanism, and hence friction does not affect the sensitiveness of the instrument. The direct-current instruments employ the D'Arsonval principle, using two sets of coils and magnets, astatically arranged. The alternating-current instruments use the principle of the Kelvin balance. Fig. 81 shows the scheme as employed in a voltmeter.

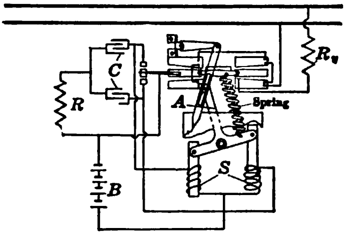

Fig. 81.—Diagram, Westinghouse graphic voltmeter.

239. The Callender recorder made by the Cambridge Scientific Instrument Co. employs the principle of a slide-wire bridge (Fig. 82) in which the resistance of one arm, *X*, varies with the current, potential or power to be measured. As soon as the bridge is unbalanced, a D'Arsonval galvanometer operates a relay, *r* or *r'*, which moves a contact, *c*, along the slide wire *s*, until balance is restored, when the relay circuit opens. This contact also carries the recording pen, which leaves an ink record on a rectilinear chart.

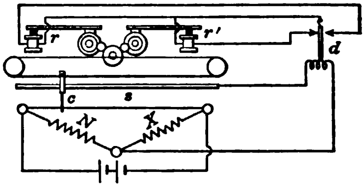

Fig. 82.—Diagram, Callender recorder.

INDUCTANCE MEASUREMENTS

240. General. The self-inductance, or coefficient of self-induction, of a circuit is the constant by which the time-rate of change of the current in the circuit must be multiplied, to give the self-induced counter e.m.f. Similarly, the **mutual inductance** between two circuits is the constant by which the time-rate of change of current in either circuit must be multiplied to give the e.m.f. thereby induced in the other circuit. Self-inductance and mutual inductance depend upon the shape and dimensions of the circuits, the number of turns and the nature of the surrounding medium.

241. Standards of inductance are usually simple coils of copper wire suitably mounted on a non-conducting, non-magnetic frame. The turns are held rigidly in place by shellac, paraffine or other insulating medium. Inductance standards are made in single units like standard resistances, or in combinations, with plug connections, like a subdivided condenser or a resistance box. In the Ayrton-Perry **variable standard** there are two concentric coils, one fixed and the other movable. When connected in series these coils form a variable inductance, the value of which at any relative position is read from a circular scale at the top. Additional range is secured by connecting sections of the two coils in series-parallel combinations by means of plugs.

242. Methods. The most commonly employed methods of measuring inductance are (a) Wheatstone-bridge methods, where the inductance is determined by comparison with a known inductance or known capacity; and (b) impedance methods where the inductance is determined by calculation from measurements made with alternating current.

where L = inductance of Z in henrys, r = ohms in parallel with C, C = capaci of condenser in micro-farads, R = total ohms of bridge arm to which condens is connected and R_2 = ohms of Z.

248. A similar method (Par. 247) is indicated in Fig. 85 in which t adjustments are independent of each other, the bridge being first balanc with a steady current and then with a transient current by adjusting r in Fig. 84. At balance,

$$L = Cr^2 10^{-6} \qquad \text{(henrys)} \qquad (2$$

where L = inductance of Z in henrys, C = capacity of the condenser in micr farads and r = ohms in parallel with C.

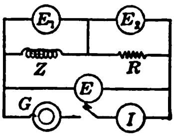

Fig. 86.—Inductance measurements—connections for three-voltmeter method.

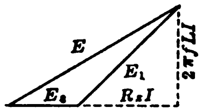

Fig. 87.—Inductance measur ments—vector diagram for thre volt-meter method.

249. Impedance methods of measuring inductance are based on t law of the impedance of a circuit carrying sine-wave alternating current an containing only inductance and resistance, that is,

$$Z = \frac{E}{I} = \sqrt{R^2 + (L2\pi f)^2} \text{ or } L = \sqrt{\frac{E^2 - I^2R^2}{(2\pi f I)^2}} \qquad \text{(henrys)} \qquad (2$$

where L = inductance in henrys, E = drop in volts, I = current in ampere R = resistance in ohms, and f = frequency in cycles per sec. Obviousl due allowance should be made for the voltmeter current where its magnitud is sufficiently important.

250. In the three-voltmeter method, the inductance to be measured i connected in series with a non-inductive resistance as shown in Fig. 8

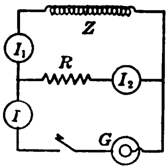

Fig. 88.—Inductance measurements—connections for three-ammeter method.

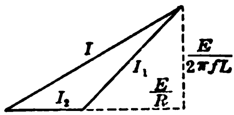

Fig. 89.—Inductance measure ments—vector diagram for three-am meter method.

The current, I, is measured, also the total volts, and the volts across th inductance Z and the resistance R. From these readings a triangle is con structed, Fig. 87. If R is known, the quantity $2\pi fLI$ can be calculated fron the triangle. If R is unknown, $2\pi fLI$ can be obtained by graphical construc tion. I and f being known, L is obtained by calculation.

251. The three-ammeter method is similar. The connections ar shown in Fig 88, and from the three currents, Fig. 89 is constructed. Th e.m.f., E, can be measured directly or, if R is known, by calculation fr the relation $E = RI_2$. Hence L can be obtained from the quantity $E/2\pi f$

252. In circuits containing iron the inductance varies with t frequency and with the current; hence alternating current of kno frequency and intensity must be used. In such cases a bridge meth with a standard inductance is convenient. A vibration galvanometer,

256. The capacity of a group of condensers in series is:

$$C = \frac{1}{\frac{1}{C^1} + \frac{1}{C^2} + \frac{1}{C^3} + \cdots \cdots \frac{1}{C^n}} \tag{32}$$

When connected **in parallel,**

$$C = C_1 + C_2 + C_3 + \ldots \ldots C_n \tag{33}$$

257. In high-grade standard condensers, the aim is to reduce the absorption, the dielectric hysteresis and the ohmic losses to a minimum. **Commercial standards** are made with tin-foil and high-grade mica, bound together under high pressure. **Primary standards,** however, are made with air as the dielectric, in which absorption and leakage are nil.

258. Methods. Electrostatic capacity measurements are made by bridge methods (Par. **259**), with a ballistic galvanometer (Par. **260**), by loss of charge (Par. **262**), and by impedance methods (Par. **263**).

259. A bridge method of measuring capacity is shown in Fig. 93. The ratio, r_1/r_2, or the standard condenser (if adjustable), is adjusted until the bridge is balanced; with an ordinary D'Arsonval galvanometer this condition is indicated when there is no "kick" as the reversing switch is changed from one position to the other. If interrupted currents or high-frequency alternating currents are used, with a telephone receiver, balance is indicated by silence in the receiver. Then $C_2 = C_1 r_1/r_2$. The resistance should be non-inductive, anti-capacity and relatively large—several hundred ohms. Obviously, maximum sensibility is obtained when C_2 and C_1 are about equal. By employing a Vreeland oscillator (Par. **246**) and an adjustable air or oil condenser, small capacities can be very accurately measured by this method.

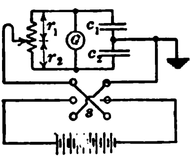

Fig. 93.—Capacity measurements, bridge method.

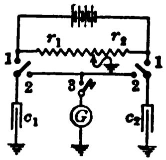

Fig. 94.—Capacity measurements, method of mixtures.

260. In the ballistic galvanometer method, the deflection is noted when the unknown capacity is discharged through it, immediately after having been charged at some known potential. A reading is then obtained with a standard condenser, the deflection being made about the same as before, by varying the capacity or the charging potential. The capacity can then be computed from the relation $d/d_1 = CE/C_1E_1$; where d, d_1, C, C_1, and E, E_1 are the respective deflections, capacities and potentials. This method is best suited to relatively large capacities, such as lead-covered, paper-insulated cables, etc.

261. The Thomson method of mixtures is shown in Fig. 94, where c_1 is a cable, transmission line or other capacity to be measured, and c_2 is a standard condenser. First the switches are closed at 1, 1, and the condensers charged to potentials corresponding to r_1 and r_2 respectively. After complete charge (a cable may require several minutes), the switches are shifted to 2, 2 and the charges equalized. If, then, the switch at 3 is closed, the deflection of the galvanometer will be proportional to the difference of the charges. This operation is repeated with various ratios r_1/r_2 until there is no deflection. Then $c_2 = c_1 r_1/r_2$.

262. In the loss of charge method, Fig. 95, the condenser to be measured is first completely charged by moving switch b to a, and then immediately discharged through a ballistic galvanometer by moving b to c. The condenser is again charged and allowed to discharge through a known high

WAVE-FORM MEASUREMENTS

267. Methods. The instantaneous variations of current and potential in a circuit are measurable by step-by-step methods (Par. **268**), and with the oscillograph, (Par. **271**.) The former is applicable only where the current and the potential are strictly periodic and recurrent, as in a normal alternating-current circuit. The oscillograph can be used under all conditions, but is especially applicable to measurements of transient phenomena (Par. **268**), such as those which occur during switching operations on direct-current and alternating-current circuits. Where the wave form is to be analyzed, the former is the more convenient and accurate.

268. A convenient "step-by-step" arrangement is shown in Fig. 98. The contact device consists of two slip-rings and a four-part commutator. One slip-ring is connected to one terminal of the source, the other to a voltmeter, and the commutator to a condenser. By means of this arrangement, the condenser after being charged is immediately discharged through the voltmeter. These impulses follow each other so rapidly that a steady deflection is obtained, and by suitable adjustment of *R* and *r* on continuous current, the voltmeter may be made direct reading. The instantaneous values at any point on the wave are obtained by shifting the brushes around the shaft. The switch is closed at 1 for voltage measurements and at 2 for current measurements.*

The General Electric **wave meter** operates on this principle. The driving motor is an eight-pole synchronous motor connected to the source being measured and there are eight segments (one per pole), instead of only one. Suitable provision is made for tracing the wave form on a photographic plate.

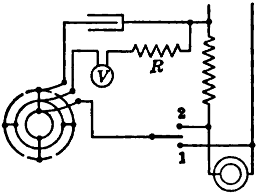

FIG. 98.—Wave-form measurements, "Step-by-step" method.

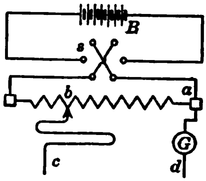

FIG. 99.—Wave-form measurements, zero method.

269. In the zero method shown in Fig. 99, the e.m.f. of a battery *B* is opposed to the potential across *c* and *d*, which are connected to the contact devices described above. The contact point, *b*, is adjusted until *G* shows no deflection; then the length *ba* is a measure of the e.m.f. *G* may be a portable galvanometer, or a telephone in conjunction with a slide wire and a contact stylus as used in the Sage ohmmeter (Par. **139**).

270. The wave form of a high-tension wave may be obtained by using the device shown in Fig. 102 and described in Par. **277**. The indication of the electrostatic voltmeter is obtained at different angular positions of the brushes on the synchronous commutator, from which the wave form may be plotted.

271. The oscillograph is a form of galvanometer in which the natural period of the moving system is so small that the deflections will always be proportional to the instantaneous value of the current flowing through the coil. The indicator is a beam of light from an arc lamp, reflected from an extremely small mirror attached to the moving system. The path of the beam is determined visually or photographically. Recurrent or periodic waves may be rendered stationary and therefore visible by suitable optical systems as indicated below. Transient phenomena must be photographed by an instantaneous process.

272. In the moving-iron type of oscillograph, first proposed by

* See also Frederick Bedell. "Condenser Current Method for the Determination of Alternating Wave Form," *Electrical World*, 1913, Vol. LXII, p. 378.

reduce iron losses, excitation currents, charging currents, etc., to a minimum. The present A. I. E. E. standard method of measuring the deviation from a sine curve is simply to measure the greatest difference between corresponding ordinates at any point along the axis of abscissæ. It has been proposed* to replace this method by another in which the increase in condenser charging-current with the given wave, over the charging current with a pure sine-wave, will be determined. This is a simple and sensitive method of determining the presence of harmonics, since the charging current of a condenser varies with the square of the frequency. The current for a given condenser on a sine-wave can be calculated from the relation $I = EC \times 2\pi f$, where I = current in amperes, E = potential in volts, C = capacity in microfarads and f = cycles per second.

277. In high-voltage testing it is particularly important that the value of the maximum instantaneous voltage be available, because the stress to which insulation is subjected depends upon this value. When the wave is distorted, the maximum value and the ratio of the maximum to mean-effective (amplitude or peak factor) have to be obtained from a plot of the wave. This may be taken with a wave meter or with an oscillograph, preferably connected to a test coil in the high-tension winding or to the secondary of a shunt-type instrument transformer connected to the high-tension circuit.

A method which can be used directly on the highest voltages† is indicated in Fig. 102, where C is a series of condensers connected across the high-tension circuit. The end condenser C_1 is grounded and connected in parallel with a commutator driven by a synchronous motor. The bars on the commutator are very narrow and are one polar space apart, so that contact is practically instantaneous. The brushes are shifted until the voltmeter indication is a maximum. The multiplying ratio is obtained from the ratio $(C + C_1)/C_1$. The instrument may be calibrated by noting the indication corresponding to the mean effective value, which is obtained with the motor stationary and the brushes resting on the bars. This indication is compared with a spark gap or other standard. The method assumes that the capacity of V is negligible in comparison with C_1. Obviously the condensers can be dispensed with by connecting directly to a test coil on the high-tension winding.

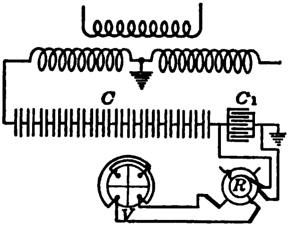

Fig. 102.—Wave meter for high voltage circuits.

FREQUENCY MEASUREMENTS

278. General. The frequency of an alternating current is $f = nr/2$, where f = frequency in cycles per second, n = number of poles, and r = revolutions per second. It may therefore be determined by measuring the speed of the generator supplying the circuit or the speed of a synchronous motor operated from the circuit.

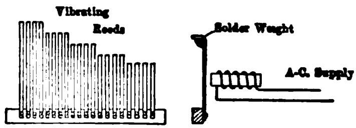

Fig. 103.—Frequency meters—Reed type.

279. Frequency meters indicate the frequency directly. In the **reed type** as made by Hartman and Braun or Siemens and Halske, there are numerous steel strips of different lengths, each rigidly fastened at one end and free to vibrate at the other. The strips are placed in the field of an electromagnet which is ener-

* Davis, C. M. "A Proposed Wave-shape Standard;" *Proc.* A. I. E. E., Feb., 1913, p. 235.

† Sharp, C. H. and Farmer, F. M. "Measurements of Maximum Values in High-voltage Testing;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1617.

which the principle of resonance (Sec. 2) in an electrical circuit is employed.* In a 60-cycle instrument, one main circuit is adjusted for resonance at about 70 cycles, another at about 58 cycles and the third circuit at about 36 cycles. The latter two are connected in parallel, and then in series with coil A; the first circuit is in series with coil A^1, both coils being in series with the field F. With the centre of a 6-in. (15 cm.) scale marked for 60 cycles, half-scale deflection is obtained for a variation of only 5 cycles either way. It is possible to adjust the instrument for a full-scale range of only 1 cycle.

SLIP MEASUREMENTS

283. General. The **slip** of a rotating alternating-current machine in per cent. is the difference between its speed and the synchronous speed, divided by the synchronous speed. It may be determined by noting the difference between the measured speed of the machine and the synchronous speed as calculated from the frequency and the number of poles. This method is obviously not accurate, because the result is a small difference between two relatively large quantities. It is therefore customary to measure the slip directly.

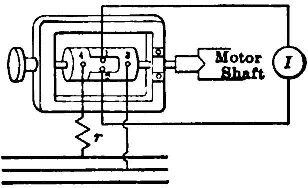

Fig. 106.—Slip measuring device.

284. Dooley's method of measuring slip. One form of device for indicating the slip of an induction motor† is shown diagrammatically in Fig. 106. A small cylinder made of conducting material, and in two parts, each insulated from the other, is mounted in a frame. Four small brushes, 1, 2, 3, and 4, bear upon the cylinder as shown. The brushes, 3, 4, are connected through a resistance, r, across one phase of the supply circuit and the brushes, 1, 2, are connected to a low-reading continuous-current ammeter, I. Each time the brushes, 1, 2, bridge the insulating strip as the cylinder rotates, the circuit is completed in alternate directions through the ammeter. The cylinder should have as many segments as the motor has poles. The ammeter will indicate a constant current at synchronous speed, and an oscillating current for any speed above or below synchronism, because the impulses of current through the brushes, 1, 2, will occur at the same point on the wave at synchronous speed, and at constantly advancing or retarding points for other speeds. Thus, the ammeter will be reversed each time the motor loses one-half of a cycle, and will reach a maximum positive value each time the motor loses one complete cycle. If the motor loses n cycles per min., then the slip in per cent. $= 100n/60f$, where $f =$ frequency of the system in cycles per sec.

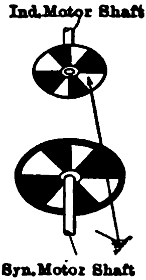

Fig. 107.—Slip measurements — Stroboscopic method.

285. Stroboscopic method. The device indicated in Fig. 107 does not require the measurement of frequency. A black disc with white sectors, equal in number to the number of poles of the induction motor, is attached with wax to the induction-motor shaft. It is observed through another disc having an equal number of sector-shaped slits and carried on the shaft of a small self-starting synchronous motor, in turn fitted with a revolution counter which can be thrown in and out of gear at will. If n is the number of passages of the sectors, then $(n/n_s)/n_r =$ slip in terms of s where $n_s =$ the number of sectors, and $n_r =$ the number of revolutions recorded by the counter during the interval of observation. For large values of slip the observations can be simplified by using only one sector ($n_s = 1$); then $n =$ the slip in revolutions.

286. A direct-reading slip-measuring device is shown in Fig. 108.

* Pratt W. H. and Price D. R. "Resonant Circuit Frequency Indicator;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1595.

† Dooley, C. R. *Elec. Club Journal*, 1904, Vol. I, p. 590.

289. The principle of the Westinghouse synchroniser is shown in Fig. 110, where a rotating field is produced by the coils, *M* and *N*, connected to the buses through the reactance *P* and the resistance *Q*, respectively. An iron vane *A*, free to rotate, is mounted in this rotating field and magnetized by the coil *C*, which in turn is connected across the incoming machine. As the vane is attracted or repelled by the rotating field from *M* and *N*, it will take up a position where this field is zero at the same instant that the field from *C* is zero. Hence the position at any instant indicates the difference in phase. When the two frequencies are different, this position is constantly changing and the pointer will rotate "fast" or "slow," coming to rest at the zero-field position when the frequencies are equal. In a larger type, the split-phase winding is placed on the movable member, similar to the arrangement shown in Fig. 111.

290. The scheme of the Weston synchroscope is shown in Fig. 112. There is no iron in

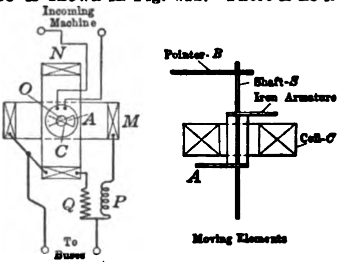

Fig. 110.—Circuits in Westinghouse synchroniser.

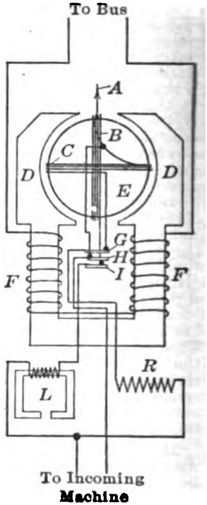

Fig. 111.—Circuits in G. E. synchroscope.

the instrument and the moving element is not allowed to rotate. The elements are practically the same as in an electrodynamometer wattmeter. The fixed coils, *F*, *F*, are connected in series with the resistance *R* and to the buses. The moving coil, *M*, is connected in series with a condenser *C* and the incoming machine. The two circuits are adjusted to exactly 90 deg.

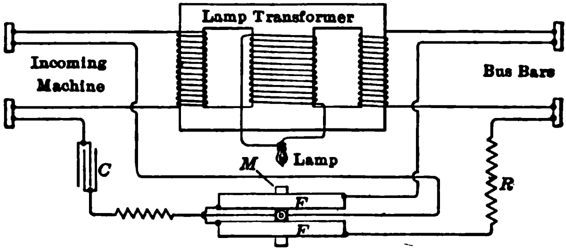

Fig. 112.—Circuits in Weston synchroscope.

difference in phase. At synchronism there is no torque and *M* is held at the zero position by the control spring. If the frequencies are the same, but there is a phase difference, a torque will be exerted and *M* will move to a position of balance at the right or left ("fast" or "slow"). If the frequencies are different, the torque will continually vary and the pointer will oscillate over the dial. A synchronizing lamp illuminates the scale simultaneously and the direction of apparent rotation indicates the faster machine.

where K = moment of inertia computed from the mass and dimensions, M = magnetic moment, and T = period of oscillation. M may be determine with a magnetometer, or by calibration in a known field (Helmholtz coil This method is only suitable for weak fields, such as the earth's field. mounted in a wooden box with a glass front, it will be protected from a currents and can be conveniently moved about when making magneti surveys.

300. Bismuth-spiral method. The resistance of bismuth wire increase when placed in a magnetic field. This property is utilized by noting th increase in resistance of a flat spiral coil of bismuth wire when placed in th field to be measured, the leading-in wires being arranged non-inductivel The device is **calibrated** with known field strengths. It is particularl suitable for exploring small air gaps such as those in motors and generators.

301. Measurement of magnetic properties. The magnetic propertie of iron and steel which are of most commercial importance are **norma induction** or **permeability, hysteresis loss** and **total losses** with alte nating magnetizing forces of commercial frequencies.

302. Normal-induction data. The various methods are distinguishe principally by the method employed to measure $\mathfrak{B}$, for in all methods $\mathfrak{H}$ i determined from the magnetizing coil. $\mathfrak{B}$ can be measured directly as in th **ballistic methods** or indirectly with **permeameters.**

303. Ballistic methods are usually employed in the more accurate meas urements. The best-known methods are the **ring method,** the **divide bar** or Hopkinson, and the **double-bar double-yoke methods.** In all o these methods the flux is measured with a ballistic galvanometer connecte to a test coil which is cut by the flux when the exciting current is reversed.

304. The ring method, devised by Rowland, is one of the earlies methods of measuring the permeability and the hysteresis of iron and steel The connections are shown diagram matically in Fig. 113, where T is th test specimen. The latter is an annula ring, either solid or built up of punch ings of sheet metal, with a diamete preferably 8 or 10 times the radia thickness. After covering with a thi layer of insulation, a test coil of ver fine double-silk-covered wire is woun on a portion of the ring. The mag netizing coil is wound over the tes coil, and distributed uniformly over th entire ring; it is usually comprised o double-cotton-covered wire, of suffi cient size to carry the maximum cur rent without raising the temperature o the iron appreciably.

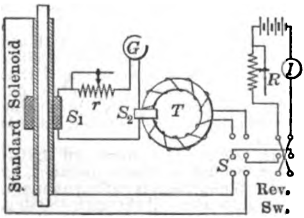

FIG. 113.—Permeability tests—ring method.

305. The divided-bar method devised by Hopkinson avoids the neces sity of winding each specimen separately, permits the use of a more con venient test piece, and avoids the errors in ring specimens.* The devic consists of a test piece, BC (Fig. 114), in the form of a bar about 15 in. (38.1 cm.) long and 0.5 in. (1.27 cm.) diameter, which is divided at A and inserted in a massive frame, F. The secondary coil, S, is so arranged that it will be thrown clear of the yoke by a spring when the part, AB, of the test bar is suddenly withdrawn. In calculating $\mathfrak{H}$, the length of the magnetic circuit is taken as that between the inside faces of the yoke, the reluctance of the yoke being considered negligible. This introduces an indeterminable

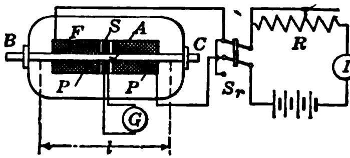

FIG. 114.—Permeability tests—divided-bar method.

* Lloyd, M. G. "Errors in Magnetic Testing with Ring Specimens;" Bureau of Standards, Bulletin, 1908, Vol. V, No. 3; p. 435.

307. Procedure in double-bar double-yoke method. The meth of procedure is as follows: After demagnetizing (Par. 321), the current N_t is adjusted to the value of $\mathcal{H}$ required. The current in all magnetizi coils is then simultaneously reversed several times to get the specimen ir cyclic condition, the current in N_a and N_j being adjusted during the proc until the flux is uniform as indicated by zero deflection when n_a and n_j a successively opposed to n_t. The galvanometer is connected to n and t deflection noted when the current in the various magnetizing coils is r versed simultaneously. Then

$$\mathcal{H} = \frac{4\pi NI}{10\,l} \qquad \text{(gilberts per cm.)} \qquad (3$$

$$\mathcal{B} = \frac{10^8 dkR}{2an} - \left(\frac{a-A}{A}\right)\mathcal{H} \qquad \text{(gausses)} \qquad (3$$

The units are the same as in Par. 305. The quantity in the parenthesis the correction factor for the space between the surface of the bar and t test coil. A = area of bar and a = area of test coil. Ordinarily this corre tion is very small because the brass tube is made very thin and the te coil is wound under the magnetizing coil.

308. Permeameters are commercial instruments for the rapid testi of iron and steel for permeability. The Thompson permeameter emplo the tractive force exerted between the pole of a magnetized bar and a pie of steel in direct contact with the pole. This force in dynes is $F = \mathcal{B}^2 a/8$ where $\mathcal{B}$ = induction in bar in lines per square centimeter and a = area bar in square centimeters. Koepsel and Picout permeameters are indu tion-type instruments.

309. S. P. Thompson's permeameter is shown schematically in Fi 117, where AB is the test specimen in the form of a rod which passes throu a hole in the top of a heavy yoke, F. The surfaces of the end of the rod ai the yoke at F are carefully machined. The force necessary to move the r is measured with a spring balance at S. The induction is

$$\mathcal{B} = 156.9\sqrt{\frac{P}{a}} + \mathcal{H} \qquad \text{(gausses)} \qquad (4$$

where $\mathcal{B}$ = induction in lines per square centimeter (gausses) P = pull in grar and a = area in square centimeters.

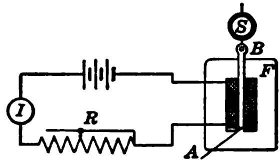

Fig. 117.—Thompson permeameter.

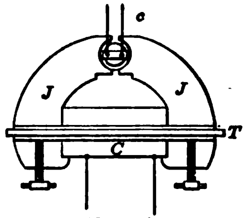

Fig. 118.—Koepsel permeamete

310. The Koepsel permeameter, as made by Siemens Halske, shown schematically in Fig. 118, where JJ is a massive yoke divided at th centre so as to admit a moving coil c to which a pointer is attached, th arrangement being similar to standard D'Arsonval-type direct-current instru ments. This pointer moves over a scale graduated directly in lines per squa centimeter. The magnetic circuit is completed through the test piece firmly clamped between the ends of the yoke in the usual manner. The valu of $\mathcal{B}$ corresponding to various magnetizing currents in C is indicated directl by the deflection with a known small current through c. Separate coils a placed on the yoke pieces, JJ, by means of which the reluctance of the variou gaps is approximately compensated. But even with these coils, there is flux leakage, so that correction or "shearing" curves have to be used. The curves, obtained by test with standardized specimens, are furnished with th instrument, as are also standardized test specimens with which the devic can be checked from time to time.

expense in preparing the sample, as well as the time spent in testing. The specimen is a bundle of strips 0.5 in. (1.27 cm.) × 10 in. (25.4 cm.), weighing 1 lb. (0.45 kg.). It is placed in a simple straight solenoid, with a sensitive wattmeter (reflecting electrodynamometer) in series with the magnetising coil. A separate winding is provided for the wattmeter potential coil, thus simplifying the correction factor for wattmeter loss. The induction is determined from the indication of a voltmeter, which is also connected to a separate winding at the centre of the specimen. The flux which it indicates is much higher than that at the ends, but experiment has shown that the ratio of the maximum to the average is 1.3 to 1. Due allowance is therefore made, when adjusting the magnetizing current to such a value that the voltmeter deflection will correspond to the required average flux-density. Measurements are made at 10 cycles, or less, in order to reduce the eddy-current loss to a point where it can be eliminated by means of empirical corrections without serious error. The precision obtained is about ±5 per cent.

317. In the Holden and the Ewing hysteresis meters, the loss is determined mechanically. In the Holden meter the test specimen, a ring of laminations about 1 cm. × 2 cm. (0.4×0.79 in.) cross-section, and 9 cm. (3.55 in.) diameter, is placed between the poles of a pair of revolving magnets. The torque exerted on the specimen is resisted by a spiral spring. The deflection of this spring which is necessary to bring the specimen back to the zero position is a measure of the loss in ergs per cycle.

The **Ewing apparatus** is operated on a similar principle, except that the specimen is rotated instead of the magnets. The specimen is a bundle of strip ⅝ in. (1.6 cm.) square and 3 in. (7.6 cm.) long.

318. Core-loss measurements. The total loss in iron or steel subjected to an alternating magnetic field is most accurately measured with a wattmeter. In making precision measurements, the Hopkinson ring-specimen can be used, but the Epstein apparatus is more convenient and has been adopted by the American Society for Testing Materials.* Fig. 120 shows the scheme diagrammatically.

The specimen is arranged in the form of a rectangle. The magnetizing winding is divided into four solenoids, each being wound on a form into which one side of the rectangular specimen is placed. The form is non-magnetic, non-conducting and has the following dimensions: inside cross-section, 4 cm. (1.57 in.) × 4 cm.; thickness of wall not over 0.3 cm. (0.12 in.); winding length, 42 cm. (16.5 in.). Each limb of the specimen consists of 2.5 kg. (5.5 lb.) of strips 3 cm. (1.18 in.) wide and 50 cm. (19.7 in.) long. Two of the bundles are made up of strips cut in the direction of rolling and two at right angles to the direction of rolling. The strips are held together with tape wound tightly around the bundle. The bundles form butt joints at the corners with tough paper 0.01 cm. (0.004 in.) thick between. They are held firmly in position by clamps placed at the corners.

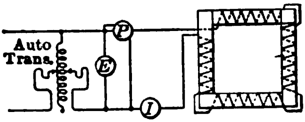

Fig. 120.—Core-loss measurements —Epstein method.

The magnetizing winding on each solenoid consists of 150 turns uniformly distributed over the 42 cm. (16.5 in.) winding-length, and has a resistance of between 0.075 and 0.125 ohm. A secondary winding is uniformly wound underneath the first; it also contains 150 turns in each solenoid, and energizes the potential circuit of the wattmeter and also the voltmeter with which the induction is measured. The resistance should not exceed 0.25 ohm per solenoid. With a sine-wave e.m.f. impressed on the magnetizing winding, the maximum induction is

$$\mathfrak{B} = \frac{E\ 4\ l D\ 10^8}{4\ f N\ n M} \quad \text{(gausses)} \qquad (41)$$

where E = volts indicated by voltmeter, l = length of specimen, D = specific gravity (7.5 for alloy or high-resistance steels and 7.7 for standard or low-

* Standard Magnetic Tests of Iron and Steel; *Trans.* A. S. T. M., 1911; Vol. XI; p. 110.

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MECHANICAL POWER MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

TORQUE MEASUREMENTS

323. Torque is best measured with dynamometers, of which there are two classes, absorption and transmission.* Absorption dynamometers absorb the total power delivered by the machine being tested, while transmission dynamometers absorb only that part represented by friction in the dynamometer itself.

324. The Prony brake is the most common type of **absorption dynamometer.** It is simply a brake applied to the surface of a pulley on the shaft of the machine being tested, together with suitable means for vary-

* Carpenter and Diedrichs. "Experimental Engineering" (Wiley Sons, 1912). J. A. Moyer. "Power Plant Testing" (McGraw-Hill Book Co. Inc., 1913).

rope. If F and L are measured in pounds and feet respectively, T will in lb. ft.

328. Dissipation of heat in friction brakes. The energy dissipated the brake appears in the form of heat. In small brakes natural cooling sufficient, but in large brakes special provisions have to be made to dissip the heat. Water-cooling is the most common method, one scheme e ploying a flanged pulley. About 100 sq. in. of rubbing surface of bra should be allowed with air cooling, or about 50 sq. in. with water cooli per horse-power.

329. For very large torques, other forms of absorption brakes a used. In the **Alden brake**, a rotating cast-iron disc rubs against tl copper discs which are held stationary. The friction is adjusted by varyi the pressure of the cooling water in the chamber surrounding the cop discs. The tendency of the copper disc member to rotate is measured w a lever as in the Prony brake.

The **Westinghouse turbine brake** employs the principle of the wa turbine and is capable of absorbing several thousand horse-power at ve high speeds.

In the **magnetic brake**, a metallic disc on the shaft of the machine bei tested is rotated between the poles of magnets mounted on a yoke which free to move. The pull due to the eddy currents induced in the discs is mea ured in the usual manner by counteracting the tendency of the yoke revolve.

330. The principal forms of transmission dynamometers are t lever, the torsion and the cradle types. An example of the **lever type**

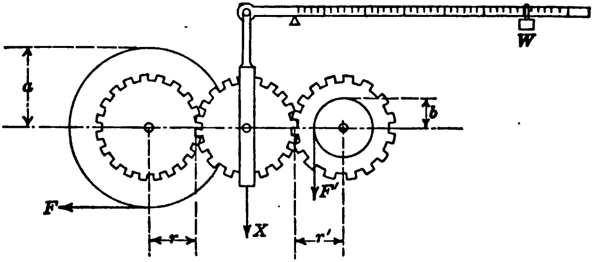


Fig. 125.—Transmission dynamometer.

shown in Fig. 125, where F is the force applied to the dynamometer, a F' is the force being delivered. When the downward force, X, is balance by the weight W, the following formula holds,

$$F = \frac{1/2(1+\mu)Xr}{a} \qquad (4$$

where μ = coefficient of friction determined experimentally.

331. In torsion dynamometers, the deflection of a shaft or spiral sprin which mechanically connects the driving and driven machines, is used measure the torque. The spring or shaft can be calibrated statically b noting the angular twist corresponding to a known weight at the end of known lever-arm perpendicular to the axis. When in use the angle can l measured by various electrical and optical methods. In one method tl angular displacement between two points on the shaft is determined by mea of two discs of insulating material, in the periphery of each of which is a very thin piece of metal. The two pieces of metal are connected electri ally through the shaft. A light, thin metal brush rests on the periphe of each disc, and the two brushes are connected together through a batte and an indicator such as a bell, or a telephone. At no load, one brush moved until the electrical circuit is completed once every revolution. T angle through which either brush has to be moved as the load is increased, i order to keep the circuit closed, is then measured.

temperature should be expressed in some one standard scale such as the thermodynamic or ideal gas scale. The hydrogen and nitrogen gas thermometers differ from this scale by various small amounts. The scale defined by the **radiation laws** is the thermodynamic scale, assuming these laws to have a sound theoretical basis. For the past 25 years it has been possible to express temperatures to 0.002 deg. cent. in the range 0 to 100 deg. cent., but outside of this interval the accuracy is far from being what is desired. Only recently for example, has the certainty of the sulfur boiling-point been closer than 0.5 deg. and of the gold melting-point 5 deg. cent. At the present time the International Bureau and the several national laboratories are interchanging communications with the object of establishing an international temperature scale.

337. Mercurial thermometers. Primary mercury thermometers are constructed of the very best thermometric glasses such as verre dur, Jena 16^{111}, Jena 59^{111}, and the scales defined by the differential expansion of these glasses and the mercury have been compared with the gas thermometer so that their corrections are fairly well established. (See Circular No. 8 of the Bureau of Standards.)

338. Laboratory and industrial mercury-in-glass thermometers (range − 35 to + 560 deg. cent.) are calibrated by direct comparison with standards. Two points which frequently occasion trouble in the use of mercury thermometers are (a) **correction for emergent stem,** (b) correction for **thermometric lag.**

339. Correction for emergent stem. In general the calibration corrections are determined for total immersion of the thermometer. When used with the stem emergent into space either hotter or colder than the temperature of the bulb, a stem correction must be applied to the observed reading of the thermometer in addition to the calibration correction. This stem-correction may amount to more than 20 deg. cent. for measurements made with a mercurial thermometer at 400 deg. cent. (750 deg. fahr.). The stem correction may be computed from the formula: Stem Correction $= K \times n(T^\circ - t^\circ)$ where K = factor for relative expansion of mercury in glass; 0.00015 to 0.00016 for centigrade thermometers, 0.000083 to 0.000089 for fahrenheit thermometers; n = number of degrees emergent from the bath; T = temperature of bath; t = mean temperature of emergent stem.

Example: Suppose that the observed temperature was 100 deg. cent. and the thermometer was immersed to the 20-deg. mark on the scale, so that 80 deg. of the mercury column projected out into the air, and the mean temperature of the emergent column was found to be 25 deg. cent.; then— stem cor. $= 0.00015 \times 80 \times (100 - 25) = 0.9$ deg. cent. As the stem was at a lower temperature than the bulb, the thermometer read too low, so that this correction must be added making the correct temp. = 100.9 deg. cent. The mean temperature of the emergent stem may be approximately measured by a small auxiliary thermometer, by a Faden thermometer, or by surrounding the stem with a water jacket and observing the temperature of this bath.

340. Correction for thermometric lag (Bur. of Standards, Reprint No. 171). When a thermometer is immersed in any medium it does not take up the temperature of the medium immediately, but approaches it asymptotically. This effect may be minimized by stirring the bath. With vigorous stirring in the case of a liquid bath, the thermometer reading should be correct to within 1 per cent. of the original difference in temperature of the thermometer and bath after 10 to 60 sec. exposure. In absolutely quiet air this degree of accuracy might require 20 min. Fanning the thermometer might reduce the time to 1 min. With caution, corrections for lag may be neglected in ordinary laboratory work.

341. High-temperature thermometers. Although mercury boils at 357 deg. cent. under atmospheric pressure, by filling the space above the mercury with CO_2 or N_2 under sufficient pressure, certain mercury-in-glass thermometers may be used at a maximum temperature of about 560 deg. cent. Glasses used are Jena 16^{111} to 450 deg. cent., Jena 59^{111} to 520 deg. cent., and special grades of combustion tubing to 560 deg. cent. Care must be exercised that the thermometer is not overheated. If the long portion of the stem is cold, the stem correction may amount to 40 deg. cent. and hence while the mercury stood at 500 deg. cent. the true temperature of the bulb would be 540 deg. cent. A few moments at that tempera-

$$E = \frac{E'(R+r+r')}{R} \tag{45}$$

where R, r, r' are the resistances of the galvanometer, thermocouple and leads respectively.

349. Cold-junction corrections. If a thermocouple is calibrated with cold junctions at 0 deg. cent. and used with cold junctions at t_0 deg. cent., one must add to the e.m.f. actually developed, the value of the e.m.f. developed when the hot junction is at t_0 deg. cent. and the cold junctions are 0 deg. cent., to obtain the correct value of the e.m.f. corresponding to temperatures shown by the calibration. If the indicator is graduated to read temperature directly, instead of e.m.f., the cold-junction correction has the form p deg. cent. = Factor $\times t_0$. For the LeChatelier couple this factor is about 0.6 in the range 300 to 700 deg. cent. and 0.5 from 700 to 1,400 deg. cent. Base-metal couples show factors varying from 0.2 to 1.2 depending upon the particular alloy used.

As an example, suppose the indicated temperature (cold junction = 40 deg. cent.; calibration temperature = 0 deg. cent.) by the LeChatelier couple is 1,000 deg. cent. Then $p = 0.5 \times 40 = 20$ deg. True temp. = 1,000 + 20 = 1,020 deg. cent.

350. Certain precautions should be taken in the use of **thermocouples.** The hot junction is usually formed by welding the dissimilar metals in an oxyhydrogen flame. Other junctions may be soldered or thoroughly secured with binding screws. The entire couple should be annealed at as high a temperature as it will safely stand in order to render it as homogeneous as possible. The couple must be protected from furnace vapors or direct contact with liquid baths, and the two leads must be insulated from each other.

351. Electrical resistance pyrometry. This method of high-temperature measurement ordinarily makes use of the variation in the electrical resistance of platinum and is capable of great sensibility. In one of its simplest forms the pyrometer consists of a coil of platinum wire wound on mica, and encased in a protecting tube of porcelain. On account of the distillation of platinum, high-resistance coils of small wire are not used much above 900 deg. cent. However, coils constructed of 0.6-mm. wire may serve satisfactorily to 1,200 deg. cent.

352. Three-lead type—Wheatstone bridge method. For the purpose of eliminating the resistance of the leads to the coil, a third wire is

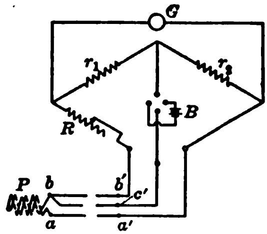


Fig. 126.—Three-lead resistance thermometer.

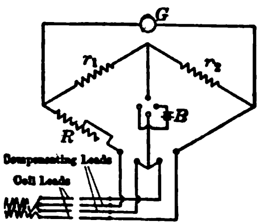


Fig. 127.—Four-lead resistance thermometer.

frequently introduced as in Fig. 126. The coil P forms one arm of a dia[l] type bridge, of which the others are r_1, r_2 and R, whence from the princip[le] of the bridge, if the galvanometer G remains undeflected,

$$P = \frac{r_2(R+bb')}{r_1} - aa' \tag{4[6]}$$

r_2 is usually made equal to r_1 and bb' is constructed as nearly as possib[le] identical with aa', so under these circumstances $P = R$ regardless of the te[m] imetry, to the determination of freezing-points, etc., and to special physical and thermochemical investigations where an accuracy of one or two parts in 10,000 may be attained (see Bur. of Standards, Reprint No. 68 and No. 124). In the technical industries this type of thermometer with one of the many forms of indicators available is highly satisfactory.

358. Radiation. The temperature of bodies may be estimated from the radiant energy which they send out in the form of visible light or of the longer infra-red rays which may be detected by their thermal effects. Since the intensity of radiation increases very rapidly with a rise in temperature, it would appear that a system of pyrometry based on the intensity of the light or total radiation from a hot body would be an ideal and simple one. However, different substances at the same temperature show vastly different intensities at a given wave length, or in other words, the **absorbing or emissive powers** may vary with the substance, with the wave length, and also with the temperature.

359. Black-body radiation. A substance which absorbs all the radiation of any wave length falling upon it is known as a **black body.** Such a body will emit the maximum intensity of radiation for any given temperature and wave length. No such material exists, but a very close approximation is obtained by heating the walls of a hollow opaque enclosure as uniformly as possible and observing the radiation coming from the inside through a very small opening in the wall.

360. Stefan-Boltzmann law. The relation between the total energy radiated by a black body and its temperature is expressed by the equation $J=\sigma(T^4-T_0^4)$, where J is the energy of all wave lengths emitted per square centimeter of surface, T and T_0 the absolute temperatures of the radiator and receiver respectively, and σ a constant of about the value 5.8×10^{-12} watts cm.$^{-2}$ deg.$^{-4}$. In general T_0^4 is negligible in comparison with T^4 so that the above relation becomes $J=\sigma T^4$. Although the total energy emitted by any substance is not that emitted by a black body at the same temperature, it may be considered as some fractional part of that from the ideal radiator, this fraction ϵ being known as the total emissivity. If S denotes the apparent absolute temperature, *i.e.*, the temperature on the black-body scale corresponding to an amount of energy equivalent to that emitted by the non-black substance at a true temperature T deg. absolute, the relation between its total emissivity ϵ and the quantities S and T is:

$$\text{Log } \epsilon = 4(\log S - \log T) \qquad (50)$$

361. Radiation pyrometry. The quantity of heat a body receives by radiation from another body depends upon certain conditions relative to each of the two bodies, namely (a) temperature, (b) area of surface, (c) distance apart, (d) emissive and absorbing powers. A pyrometer may be so constructed that conditions (b) and (c) compensate one another, at least within certain prescribed limits, so that for all technical purposes the radiation received by the instrument depends only upon the temperature of the radiating source and its emissivity. The pyrometer is calibrated by sighting upon a black body, the temperature of which may be obtained by thermocouples. Specially constructed furnaces for this purpose are available in all testing laboratories.

362. Féry mirror telescope pyrometer. (Fig. 129.) Radiation of all wave lengths is brought to a focus by means of a concave gold mirror M upon the hot junction of a minute thermocouple located at T. The cold junctions of the couple are suitably screened from the direct radiation of the hot body. The concentration of heat at the hot junction develops an e.m.f. which may be measured by a potentiometer or galvanometer. In practice the galvanometer is usually calibrated to read temperature directly. The relation between the e.m.f. and the temperature may be expressed by the equation $E=aT^b$, or in log form, $\log E = k + b \log T$, where T is the absolute tempera-

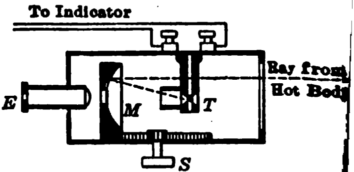


FIG. 129.—Féry radiation pyrometer.

inlet and average outlet water temperatures. For liquid fuels, a weighing device and a special burner are provided.

391. Other types of calorimeters of the **discontinuous class** differ essentially from the Berthelot only in the method of supplying the oxygen. In calorimeters of the Carpenter and the Favre and Silberman type, oxygen gas is supplied at atmospheric pressure. In instruments of the Parr class, the oxygen is supplied by chemicals with which the sample is mixed.

392. Fuel oils are, in addition to the foregoing, Par. **390**, frequently tested for **flash-point**, or temperature where the vapor given off will ignite but will not continue to burn; **fire-point**, or temperature where combustion will continue if the vapors are ignited; **viscosity; chill-point**, or congealing temperature; per cent. of asphaltum.

393. Reports of proximate analyses and heating value (in B.t.u. per pound) usually give the results calculated on at least two bases, "as received" and "**dry**." The former are of most interest to the users of the fuel, but the results must be reduced to the latter basis when comparisons are to be made.

394. Fuel or illuminating gases are analyzed for the following **components in per cent. by volume; carbon dioxide** (CO_2), **carbon monoxide** (CO), **oxygen** (O_2), **methane** (CH_4), **ethylene** (C_2H_4), **hydrogen** (H_2) and **nitrogen** (N). CO, CO_2, O_2 and C_2H_4 are usually determined by passing a known volume of the gas through a series of reagents, one at a time, each of which will absorb one, and only one, of the components. The diminution of the volume is noted after each absorption. H_2 and CH_4 are obtained by combustion in a glass tube with a known volume of air, the products of combustion being measured by absorption as in the case of the other constituents, and the original volume calculated. N is obtained by difference.

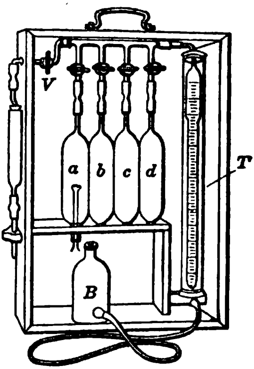


FIG. 135.—Orsat apparatus.

395. Orsat apparatus. The various forms of apparatus which employ the **absorption method** are based on the principle of the Orsat apparatus shown in Fig. 135. A given quantity of gas, usually 100 c.c., is drawn into the measuring tube, *T*, by means of the water bottle, *B*, and carefully measured. The gas is then forced into the CO_2 reagent bottle, *d*, drawn back into *T* and the decrease in volume noted. The process is repeated with each of the tubes, *c*, *b* and *a*, giving the percentages of O_2, CO, and H_2 respectively. The usual **reagents** are caustic potash solution for CO_2, ammoniacal cuprous chloride solution for CO and alkaline pyrogallic acid solution for O_2, H_2 being obtained by combustion.

396. Flue gases are analyzed for **carbon dioxide** (CO_2), **carbon monoxide** (CO), **oxygen** (O_2), **hydrogen** (H_2) and **nitrogen** (N), in the manner indicated for fuel or illuminating gas.

397. CO_2 recorders are instruments which automatically and continuously remove samples of flue gas and indicate with a pointer or record on a clock-driven chart the percentage of CO_2 in each sample. Various principles are employed, among which are the variation in the refraction index with the percentage of CO_2, the variation in density compared with air as a standard, and the variation in the position of a float with the volume remaining after the CO_2 has been removed with caustic potash, **the usual reagent.**

398. Selected list of reference literature on fuel and gas analysis.

LEWES, V. B.—"Liquid and Gaseous Fuels." D. Van Nostrand Co., New York.

GILL, A. H.—"Gas and Fuel Analysis for Engineers." John Wiley & Sons, New York.

KERSHAW, J. B. C.—"The Calorific Value of Fuels." D. Van Nostrand Co., New York.

406. The Hammond measuring-tank meter, Fig. 138, consists of two tanks, B_1 and B_2, into one of which the inflowing water is directed by the baffle G, while the other is emptying through the valve D_2. When the water level in B_1 rises high enough to lift float I_1, latch H_1 releases, the weight of water on valve D_1 throws the wrist plate over, opening D_1 and closing D_2, and changing the deflector G to fill B_2. The action is very rapid at the release period, preventing loss of water during the change period. A gage, N, is included for accurately setting the meter. This device, as with all the volumetric meters, is affected by change of temperature. For variations of approximately 50 deg. fahr. (28 deg. cent.) the error is not great, the average being 2 per cent. to 3 per cent. It is operated on gravity flow.

407. Disc meters of the general type in Fig. 139, operate by the gyration of a disc in a spherical chamber. The stem attached to the disc describes a circular path and operates the counter. These meters are used on closed lines under pressure.

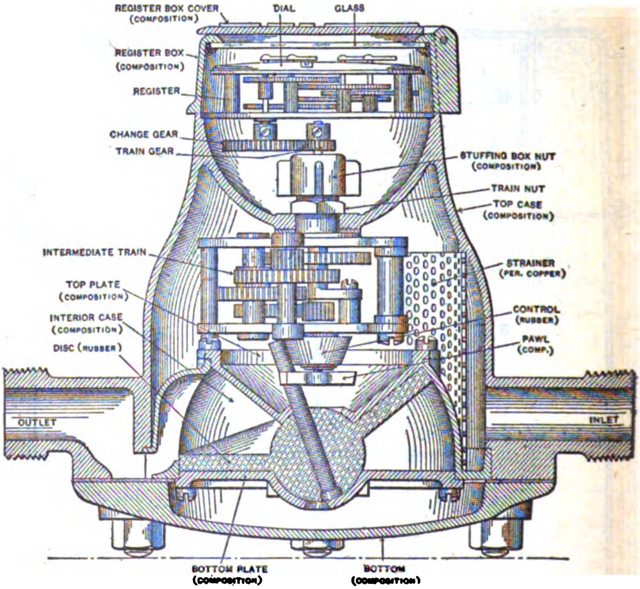


Fig. 139.—Worthington disc meter.

Disc meters vs. piston meters. Disc meters are used chiefly for small lines, up to about 3 in. diameter. Piston meters for sizes from 2 in. to 8 in. For larger flows, tank, Venturi or turbine meters are generally employed.

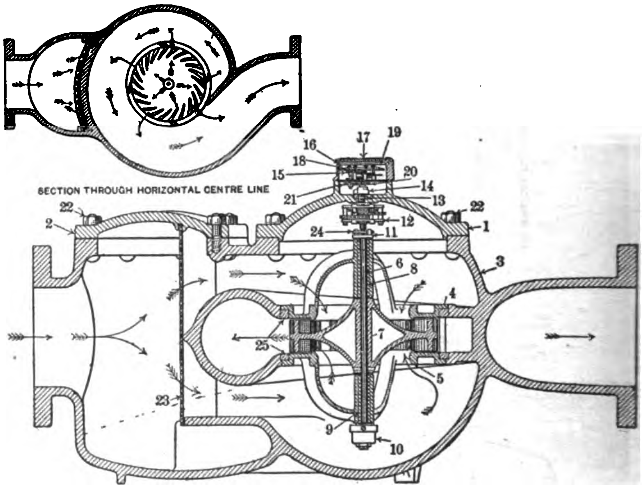
408. Piston meters of the general type shown in Fig. 140, operate like a duplex steam pump, the movement of the pistons measuring off definite volumes of water per stroke. The strokes are recorded by the counters usually in units of cubic feet. These meters are used on closed lines under pressure, and necessitate, for their operation, a pressure drop of from 2 to 6 lb. per sq. in., depending on the flow.

409. The Venturi meter is widely used, both for large and small flow, on pumping service and boiler feed. It occupies practically no space outside of the pipe line; has no moving parts in the meter proper, and operates on closed pressure lines. The accuracy is from 1.0 to 1.5 per cent. if used on reasonably steady flow. If used on rapidly fluctuating flow it becomes very inaccurate. If kept clean, the accuracy is substantially constant during the life of the meter.

A **slight** pressure drop, 0.25 to 3 lb., occurs through the meter, depending in size on the flow. For theory of the Venturi tube, see Sec. 10.

410. The Pitot meter is not satisfactory for general service, as the head differences are much less than those developed in the Venturi, consequently the registering apparatus is much more delicate and sensitive to leakage in the pressure lines leading from the main to the recording instrument. It is also very sensitive to eddies in the pipe lines in which the Pitot tube is inserted. For the theory of the Pitot tube, see Sec. 10.

411. The turbine meter, Fig. 141, is used to some extent for large-size lines and large flow. It operates like a hydraulic turbine, and as the meter



SECTION THROUGH VERTICAL CENTRE LINE

Fig. 141.—Worthington turbine meter.

opposes practically no friction or pressure loss to flow, the speed of the meter is substantially proportional to the flow. It is called a "velocity meter," but strictly speaking, this meter is volumetric; it is affected in accuracy by temperature changes. The accuracy is practically the same as the weighers and tank meters (Par. 400).

412. Weirs, usually of the V-notch type, are in considerable use, in connection with indicating and recording mechanisms for water measurement. (See Sec. 10.) In the **Lea type**, a float in a chamber above the weir, operates a grooved drum in such a fashion that the recording and integrating apparatus move over equal increments of space for equal increments of flow.

In the **Hoppes type**, a conoidal float is suspended by a coil spring, and is so shaped that the descent of the float by the weight of water forced over by the rise of the weir, is proportioned to the flow. Very good accuracy is claimed for these weir meters, from 0.5 to 1.3 per cent. over all ranges of flow. Temperature changes are approximately compensated for in both types, by the behavior of the float and the conoidal chamber respectively.

where Q = cu. ft. per sec. ($= W/\delta_1$); h = difference of pressure, upstream and throat in in. of water [$= (P_1 - P_2)(12/62.35)$].

418. The Pitot-tube formula for gas and air

$$Q = 218.44Ed^2\frac{T_s}{P_s}\sqrt{\frac{hP}{TG}} \text{(cu. ft. gas or air per hr.)} \quad (62)$$

where E = flow factor of the tube expressed as a decimal; d = internal diam. of tube (in.); T_s = absolute fahr. temperature of measurement base; P = absolute pressure of measurement base, lb. per sq. in.; G = sp. grav. of gas referred to air; if air is measured, $G = 1$; P = absolute static pressure of flowing gas in meter, lb. per sq. in.; T = absolute temperature fahr. of flowing gas; h = velocity head of flowing gas (in. of water); Q = cu. ft. of gas per hr. at T and P.

The value of E is 0.8530 for smooth tubes, 2-in. to 5-in. diameter, with the Pitot tube placed exactly in the centre of the pipe. The velocity is a maximum at the centre of a pipe, decreasing to a minimum at the pipe surface. This accounts for the fact that E is less than unity when the Pitot tube is at the centre of the pipe. The coefficient of flow for the Venturi meter approximates from 0.97 to 0.98 for properly designed meters.

419. Rotary meters of several makes are on the market; one type is shown in Fig. 142, intended for compressed-air service. Air enters the chamber at C and impels the flap pistons D and E toward the outlet side. As the pistons J, K, and L, are closed on the return side, the pressure area is greatest on the under side, causing the meter to turn.

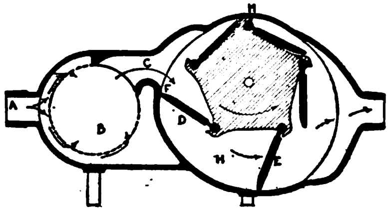


FIG. 142.—Kreutsberg air meter.

STEAM METERS

420. Steam meters. Most of the steam-flow meters such as the St. John Sargent, Hallwachs, Gehre, Eckhardt and General Electric, can be used on **compressed-air service** if desired. See Par. 419. Steam meters are divided into area meters (Par. 421 and 422) and velocity meters (Par. 423 and 424). Pressure and quality variation affect the accuracy of all area and velocity meters, so that the meters are only correct for the calibration conditions of pressure and quality, unless fitted with compensating devices.

421. "Area" steam meters. In this class are those in which a disc or cup partially closes an opening through which steam is passing. The shape of the passage or of the cup is so arranged that as it rises from zero position, the free area for passage of steam is increased. As demand for steam is increased, the increase of pressure drop past the disc or cup, causes it to move further up the passage, enlarging the area till the pressure drop is reduced and the disc again in equilibrium. The movement of the disc is communicated to an indicator and chart graduated in lb. per hr. flow. The passage is so designed that the movement of the disc or cup is directly proportional to the flow, giving an equal increment reading.

422. The Sargent meter is an example of the area type. It has a conical cup seating over a conical seat. As the stream flow is increased, the cup rises, exposing more area for flow between cup and seat. As the weight of the cup and stem is the only load, the pressure difference is constant. A pressure compensator in the form of a Bourdon tube carrying the indicating needle, is *e.g.*, the density of a sphere expressed by the relation $d = M/(\frac{1}{6}\pi D^3)$, where M is the mass obtained by means of an equal-arm balance and D the diameter measured by a micrometer caliper; or the horse-power of an engine h.p. = p.l.a.n./33,000, where p is the mean-effective pressure found by measurement, l the length of stroke, a the area of the piston found by measuring its diameter and n the number of strokes per minute found by counting them. In general these expressions take the form,

$$X = F(a, b, c \ . \ . \ . \quad A, B, C \ . \ . \ .)$$

where a b, c . . . represent measured quantities, while A, B, C . . . represent constants (like 33,000 and π in the above formulæ) and F represents that there is some functional relation between measurements, constants and the indirectly measured quantity X.

427. Every measurement has a definite precision. Thus the length of a building might be reliable to the nearest quarter inch, the current in a certain circuit to the nearest tenth of an ampere, or the time of vibration of a pendulum to the nearest hundredth of a second. To determine this reliability it is necessary to make a very careful study of all the instruments used, the care with which they are made, graduated, calibrated, adjusted for change of temperature or of position, etc., etc. It furthermore is necessary to know not only the skill of the observer, but also whether any constant errors may be due to his "personal equation." If for instance one desires to calibrate a voltmeter at 110 volts by means of a standard Weston cell, the following points must be considered: How closely must the electromotive force at standard temperature be determined? How closely must the temperature coefficient be determined? If the temperature of the cell when used is determined by means of a mercury thermometer, how closely must the thermometer be calibrated and read? How closely must the resistance of the voltmeter be known and is it necessary to take any precautions regarding its temperature; and lastly, what must be the precision of the variable resistance used for the balance? After an examination of all these probable sources of error the final question is, What is the most probable value of the combined effect of all these separate deviations or errors? (See Par. 1–6.)

428. The general problem. Given the functional relation,

$$X = F(a, b, c \ . \ . \ .) \tag{63}$$

the problem in general is as follows: First case if a, b, c . . . can be measured each with a definite degree of precision, what is the best representative value of the resultant precision in X? Second case: if it is desired to determine X to a certain definite precision, how precisely must each of the components be measured so that the combined effect of all the deviations may not produce a resultant deviation in X greater than the assigned limit?

Unless it is possible to assign some numerical estimate to the precision attained in determining any measured quantity, X, the result is of little practical value. Hours of valuable time are often wasted in determining some unimportant component of an indirect measurement with excessive precision, while at the other extreme we often find final results absolutely worthless as the result of failure to measure some important component with the necessary precision.

429. Determination of precision in final result with known precision in the measured components. Referring to Eq. 63, let δ_a, δ_b, δ_c . . . be the numerical deviations or precision measures of the direct measurements a, b, c . . . ; Δ_a, Δ_b, Δ_c be the deviations in X due to the deviations in the separate components, and Δ the combined effect of the separate effects Δ_a, Δ_b, Δ_c . . . . Then Δ/X is the fractional deviation or precision measure of X and δ_a/a, δ_b/b, δ_c/c . . . are the fractional deviations of the components a, b, c . . . and 100 times the fractional deviation is the percentage deviation. We first find the separate effect of each of these deviations δ_a, δ_b, δ_c . . . on X and then find the combined effect of these separate effects. The change in X due to a slight change in a (b, c . . . remaining constant) is found by differentiating the function with respect to a, *i.e.*,

$$\Delta_a = \frac{\partial X}{\partial a}\delta a \tag{64}$$

and a similar slight change in any component k would give

$$\Delta_k = \frac{\partial X}{\partial k}\delta k \tag{65}$$

would be very easy to reach this precision in the time measurement if a goo stop watch were used; in fact this interval could be determined to within 0. sec. and therefore the time might be treated as a constant, in which case would be two instead of three and therefore it would not be necessary t measure I and E quite so accurately as indicated above.

431. Two classes of formulæ in indirect measurements. The tw methods shown above for the direct (Par. 428) and the indirect (Par. 429 methods respectively are perfectly general; consequently by their use an problem may be solved provided all deviation or precision measures are ex pressed as actual numerical deviations and not as fractional or percentag deviations. It is found in practice that nearly all formulæ used in indirec measurements fall in one or the other of two general groups. Those of th first class include all those functions which contain sums or differences c terms, each of which may involve either measured components, or con stants, or both. The general form would be

$$X = Aa^l \pm Bb^m \pm Cc^n \pm \ . \ . \ . \qquad (68$$

where A, B, C . . . are constants and a, b, c . . . are measured quantitie entering to the l^{th}, m^{th}, and n^{th} powers respectively. Examples of formulæ o this sort are the expressions for the electromotive force of a standard Clar cell, $E = 1.4340\ [1 - 0.00078\ (t° - 15°)]$, or the resistance of a standard 10 ohm coil, $R = 10[1 + 0.00388\ (t° - 15°)]$.

Those of the second class include all those functions which involv products, quotients or powers of the measured components and constant and do not involve either trigonometric or logarithmetic functions. Th general type would be

$$X = A \cdot a^l \cdot b^m \cdot c^n \ . \ . \ . \qquad (69$$

where A, n, m, and k are constants (positive, negative, fractional or integral) An example of formulæ of this type is the expression for the modulus of elas ticity for bending, given as $E = Wl^3/4a\,bd^3$, where W is the load at th centre, l is the length between supports, a is the deflection, b the breadth an d the depth of the beam; the formula given above for density (Par. 426) is another example.

432. Percentage method of computing precision. Problems o the second class (Par. 431) may be solved much more easily by the fractiona or percentage method than by the general method, as will appear from the following. Taking the general form of the function as

$$X = A \cdot a^n \cdot b^m c^k \ . \ . \ . \qquad (70)$$

and differentiating with respect to each of the variables, and then dividing each of these results by the general formula gives,

$$\frac{\Delta a}{X} = \frac{l \cdot \delta a}{a}, \quad \frac{\Delta b}{X} = \frac{m \cdot \delta b}{b}, \quad \frac{\Delta c}{X} = \frac{n \cdot \delta c}{c}. \qquad (71)$$

This shows that a fractional deviation $\delta a/a$ in a produces a fractional deviation in X which is n times as great, or in per cent. it means that if a is unreliable by 1 per cent., X will be unreliable n times 1 per cent. and it is to be noted that the remaining factors in the formula have no effect whatever upon this relation. This enables us to state at once the separate effect of any percentage deviation of a given component and by using the relation

$$\frac{\Delta}{X} = \sqrt{\left(\frac{\Delta_a}{X}\right)^2 + \left(\frac{\Delta_b}{X}\right)^2 + \left(\frac{\Delta_c}{X}\right)^2 + \cdots} \qquad (72)$$

or its equivalent,

$$\frac{\Delta}{X} = \sqrt{\left(l\frac{\delta a}{a}\right)^2 + \left(m\frac{\delta b}{b}\right)^2 + \left(n\frac{\delta c}{c}\right)^2 + \cdots} \qquad (73)$$

we can therefore express the final resultant effect as a percentage deviation.

433. The percentage method is illustrated by the following problem. Measurements for the modulus of elasticity using the above formula are as follows. The weight is 10 kg., reliable to the nearest gram; the length is 1,000 mm., reliable to 0.5 mm.; the deflection is 6.983 mm., reliable to 0.007 mm; the breadth is 4.675 mm., reliable to 0.005 mm.; and the depth is 15.069 mm., reliable to 0.008 mm. The problem is to determine the reliability of the modulus when calculated from the formula $E = W \cdot l^3/4\ a.b.d^3$. The first step is to express all the deviations in per cent. Inspection shows that W

with change of temperature and therefore apply to the case of con-
of constant mass, usually met in engineering work. For a full
n of this subject see Dellinger, J. H. "The Temperature Coefficient
r," Bulletin of the Bureau of Standards, 1911, Vol. VII, No. 1, p.
'Copper Wire Tables," Circular No. 31, 3rd edition, 1914, Bureau of
s.

ct of chemical composition. The resistivity of most metals
nsitive to slight changes in chemical composition. Particularly is
of copper; when alloyed, for example, with 1 per cent. of another
increase in resistivity, measured in per cent., is many times 1 per
e Par. 63 and 64. Therefore it is very essential when stating a value
ity for a given substance to state also what the substance is com-
or if it be so nearly pure that there are no more than small traces of
bstances, to state its percentage of purity.

ct of mechanical treatment. When ductile metals are sub-
cold rolling, drawing, hammering, or to cold working of any kind,
me harder, stronger and slightly more dense. At the same time
vity increases, sometimes markedly, and the initial properties can
pproached again by means of the **annealing process.** While
s will sometimes restore the initial properties, at least for most
purposes, it does not always do so.

WIRE GAGES

sizes of wire have been for many years in
most entirely by gage numbers, esp
practice is accompanied by som
n common use. The most
merica, is the **American**
ommonly used gage f
in Par. 15.
no legal standard
adopted by Co
ard known a
y, France,
wire gage
his syste
The wir
Paris g
Circul
a, O

although a gage for
814). In England there is a
gage, mentioned in Par. 17.
nd other continental countries prac-
wire sizes are specified directly in milli-
the **millimeter wire gage** (see
times called the however, are based to some extent
used in France, For a history of wire
("jauge de Paris de 1857"), Bureau of Standards,
No. 31, "Copper Wire Tables,"
t. 1, 1914.
growing tendency to **abandon gage numbers** entirely and
sizes by the **diameter in mils** (thousandths of an inch). This
olds particularly in writing specifications, and has the great ad-
f being both simple and explicit. A number of the wire manufac-
o encourage this practice, and it was definitely adopted by the
tates Navy Dept. in 1911.

The mil is a term universally employed in this country in connection
re gages and is a **unit of length equal to one thousandth of an**

The circular mil is another universal used term, being a unit of
equal to the area of a circle 1 mil in diameter. Such a circle, however,
an area of 0.7854 (or $\pi/4$) sq mil. Thus a wire 10 mils in diameter has
oss-sectional area of 100 circ. mils or 78.54 sq. mils. Hence, 1 circ. mil
als 0.7854 sq. mil.

The American wire gage, also known as the **Brown & Sharpe**
was devised in 1857 by J. R. Brown. It is usually abbreviated **A.W.G.**
gage has the property, in common with a number of other gages,
its sizes represent approximately the successive steps in the process of
drawing. Also, like many other gages, its numbers are retrogressive,
er number denoting a smaller wire, corresponding to the operations of
ng. These gage numbers are not arbitrarily chosen, as in many gages,
llow the mathematical law upon which the gage is founded. The gage
bers and sizes are given in Par. 30.

0.010 || 25

The theoretically exact diameters in this gage, as given in the second column of Par. 30, contain more significant figures than there is any comme need for, and hence the large companies have standardized the sizes giv the third column, using the nearest mil for large sizes and the ne tenth of a mil for the smaller sizes. These commercial sizes were ado as standard by the United States War Dept. in 1911.

14. **The basis of the American wire gage** is a simple mathem law. The gage is formed by the specification of two diameters and th that a given number of intermediate diameters are formed by geome progression. Thus, the diameter of No. 0000 is defined as 0.4600 in. a No. 36 as 0.0050 in. There are 38 sizes between these two, hence the of any diameter to the diameter of the next greater number is given by expression

$$\sqrt[39]{\frac{0.4600}{0.0050}}=\sqrt[39]{92}=1.122\ 932\ 2$$

The square of this ratio = 1.2610. The sixth power of the ratio, i.e ratio of any diameter to the diameter of the sixth greater number = 2. The fact that this ratio is so nearly 2 is the basis of numerous useful rela or short cuts in wire computations.

15. **The steel wire gage**, also known originally as the **Washbu Moen gage** and later as the **American Steel & Wire Co.'s gage** established by Ichabod Washburn about 1830. This gage also, w

wire gage ... of its sizes rounded off to thousandths of an inch, is known a

based upon the reduct... gage. It is used exclusively for steel wire. The number

rod. Thus, a wire rod was ca... Par. 30.

gradations of size in this gage are ... wire gage, also known as **Stubs' wire gag**

This gage has been used to a considerabl... to have been established early in the eight

telegraph wires. Its numbers and sizes are ... long in use. This gage was used to

17. **The Standard wire gage**, which more pr... should not be confused with Stubs

(British) Standard wire gage, is the legal standard ... bers of the Birmingham gag

wires, adopted in 1883. It is also known as the **New** ... ctice by drawing wire from

gage, the **English legal standard gage** and the **Imp**... awing No. 1, and so on.

It was constructed by so modifying the Birmingham gage that ... will appear from its

between consecutive sizes became more regular. While this g... designating iron an

most largely used in England, there is a tendency there, as here, t... Par. 30.

numbers and specify sizes by the diameter in mils. This gage ... y should be desi

been extensively used in this country. Its numbers and sizes ar... of Great Britain

Par. 30. ... **British Sta**

18. **The Old English wire gage**, also known as the **London wi**... rial wire

differs very little from the Birmingham gage. It was formerly used ... in the diffe

extent for brass and copper wires, but is now nearly obsolete. The nu... is gage is t

and sizes are given in Par. 30. ... dro ... has

19. **The Stubs' steel wire gage** has a somewhat limited use fo... metals ... g

steel wire and drill rods. It should not be confused with the Birmingha... to have

Stubs' iron wire gage mentioned in Par. 16. The numbers and sizes ... olytes,

given in Par. 30. In addition there are twenty-six larger sizes, *Z* to *A*, ... heir res

thirty smaller sizes, No. 51 to No. 80, besides those given in Par. 30 (see ... alloys, s

catalogue of Brown & Sharpe Mfg. Co., or The L. S. Starrett Co.). ... nts, but

... case of c

20. **The Trenton Iron Co.'s gage**, of which the numbers and sizes ... as the pe

given in Par. 30, is used only to a very limited extent. It differs but slig... lard (Par

from the steel wire gage mentioned in Par. 15.

21. **The French wire gage** is an exception to the other gages giv... **stance c**

Par. 30 in the respect that its sizes are progressive, instead of retrogre... **he linear**

as the numbers advance. The sizes there given were taken from the A... **s)**

can Steel and Wire Co.'s handbook, "Electrical Wires and Cables," 19... **esistance**

d at ser

m and

change

30. Tabular comparison of wire gages

Diameters in mils

Gage No.	American Wire Gage (B. & S.) exact sizes	American Wire Gage (B. & S.) commercial sizes	Steel Wire Gage (Wash. & Moen)	Birmingham Wire Gage (Stubs')	(British) Standard Wire Gage	Old English Wire Gage (London)	Stubs' Steel Wire Gage	Trenton Iron Co. Gage	French Gage	U. S. Standard Sheet Gage	Gage No.
7–0	....	....	490.0	....	500.0	....	....	....	....	500.0	7–0
6–0	....	....	461.5	....	464.0	....	....	....	....	468.7	6–0
5–0	....	....	430.5	....	432.0	....	....	450.0	....	437.5	5–0
4–0	460.00	460.0	393.8	454.0	400.0	454.0	....	400.0	....	406.2	4–0
3–0	409.64	410.0	362.5	425.0	372.0	425.0	....	360.0	....	375.0	3–0
2–0	364.80	365.0	331.0	380.0	348.0	380.0	....	330.0	....	343.7	2–0
0	324.86	325.0	306.5	340.0	324.0	340.0	....	305.0	....	312.5	0
1	289.30	289.0	283.0	300.0	300.0	300.0	227.0	285.0	33.0	281.2	1
2	257.63	258.0	262.5	284.0	276.0	284.0	219.0	265.0	40.0	265.6	2
3	229.42	229.0	243.7	259.0	252.0	259.0	212.0	245.0	50.0	250.0	3
4	204.31	204.0	225.3	238.0	232.0	238.0	207.0	225.0	63.0	234.4	4
5	181.94	182.0	207.0	220.0	212.0	220.0	204.0	205.0	68.0	218.7	5
6	162.02	162.0	192.0	203.0	192.0	203.0	201.0	190.0	83.0	203.5	6
7	144.29	144.0	177.0	180.0	176.0	180.0	199.0	175.0	97.0	187.5	7
8	128.49	128.0	162.0	165.0	160.0	165.0	197.0	160.0	110.0	171.9	8
9	114.42	114.0	148.3	148.0	144.0	148.0	194.0	145.0	120.0	156.2	9
10	101.90	102.0	135.0	134.0	128.0	134.0	191.0	130.0	135.0	140.6	10
11	90.74	91.0	120.5	120.0	116.0	120.0	188.0	117.5	149.0	125.0	11
12	80.81	81.0	105.5	109.0	104.0	109.0	185.0	105.0	162.0	109.4	12
13	71.96	72.0	91.5	95.0	92.0	95.0	182.0	92.5	172.0	93.7	13
14	64.08	64.0	80.0	83.0	80.0	83.0	180.0	80.6	185.0	78.1	14
15	57.07	57.0	72.0	72.0	72.0	72.0	178.0	70.0	197.0	70.3	15
16	50.82	51.0	62.5	65.0	64.0	65.0	175.0	61.0	212.0	62.5	16
17	45.26	45.0	54.0	58.0	56.0	58.0	172.0	52.5	225.0	56.2	17
18	40.30	40.0	47.5	49.0	48.0	49.0	168.0	45.0	238.0	50.0	18
19	35.89	36.0	41.0	42.0	40.0	40.0	164.0	40.0	250.0	43.7	19
20	31.96	32.0	34.8	35.0	36.0	35.0	161.0	35.0	263.0	37.5	20
21	28.46	28.5	31.7	32.0	32.0	31.5	157.0	31.0	279.0	34.4	21
22	25.35	25.3	28.6	28.0	28.0	29.5	155.0	28.0	290.0	31.2	22
23	22.57	22.6	25.8	25.0	24.0	27.0	153.0	25.0	303.0	28.1	23

COPPER

31. General properties. Copper, which is by far the most important metal in the electrical industry, is a highly malleable and ductile metal, of a reddish color. The density varies slightly, depending on the physical state, an average value being 8.9. Copper melts at 1,083 deg. cent.* (1,981 deg. fahr.), and in the molten state has a sea-green color. When heated to a very high temperature it vaporizes, and burns with a characteristic green flame. Copper boils at 2,310 deg. cent. (4,190 deg. fahr.).† Molten copper readily absorbs oxygen, hydrogen, carbon monoxide and sulphur dioxide; on cooling, the occluded gases are liberated, tending to give rise to blow holes and porous castings. The presence of lead in molten copper tends to drive off both carbon dioxide and water vapor.

Copper when exposed to ordinary air becomes oxidized, turning to a black color, but the coating is protective and the oxidizing process is not progressive as with iron and steel. When exposed however to moist air containing carbon dioxide, it becomes coated with green basic carbonate. It is also affected by sulphur dioxide. It resists the action of hydrochloric, sulphuric and strong nitric acids, at ordinary temperatures, but is acted upon by dilute nitric acid.

The electrical conductivity of copper depends most critically on its degree of chemical purity (see Par. **63**) and also, in much less degree, upon the physical state, being reduced slightly (from 2 per cent. to 4 per cent.) by cold rolling and drawing. The tensile properties depend greatly upon the physical state, being much improved by cold rolling and drawing.

The alloys of copper are exceedingly numerous, both for electrical and mechanical purposes. Among the most important for electrical purposes are German or nickel silver, bronze and brass. Copper solders readily with ordinary low-temperature solders; solder alloys with copper at about 238 deg. cent. (460 deg. fahr.).

32. Commercial grades of copper. In the copper trade there are three recognised grades of copper known as **electrolytic, Lake,** and **casting.**‡ The first, electrolytic, is that refined by the electrolytic method and is highly pure (see Par. **34**). The second, Lake, is also highly pure, in its natural or mineral state, and requires simply to be melted down to bars, for convenient handling (see Par. **36**). The third kind of copper, known as casting copper, contains more impurities and consequently runs lower in conductivity. It is, as its name implies, more suitable for mechanical than electrical applications (Par. **38**).

33. Density of copper. The internationally accepted density of annealed copper,§ expressed in grams per cu. cm. at 20 deg. cent., is **8.89**; this of course is also the specific gravity at 20 deg. cent., referred to water at 4 deg. cent. The American Society for Testing Materials has accepted this value, on account of its international endorsement, but considers that a value of 8.90 is probably nearer the exact truth. A density of 8.89 at 20 deg. cent. corresponds to 8.90 at 0 deg. cent. In English units the international standard equals 0.32117 lb. per cu. in. Also see "Copper Wire Tables," circular No. 31, Bureau of Standards, Washington, D. C.; and "Smithsonian Physical Tables," Washington, D. C., 1910, 5th rev. ed., p. 85.

34. Electrolytic copper. The electrolytic refinement of copper‖ (see Sec. 19) not only produces metal of the highest purity, but it is eco-

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* "Tables Annuelles de Constantes Et Données. Numériques, de Chimie, de Physique et de Technologie;" University of Chicago Press, 1912; Vol. I (1910), p. 48.

† Fulton, C. H. "Principles of Metallurgy;" McGraw-Hill Book Co., New York, 9111; p. 74.

‡ See report of Committee B-2, on Non-ferrous Metals and Alloys; American Society for Testing Materials, 16th annual meeting, June 24–28, 1913.

§ Ratified at the meeting of the International Electrotechnical Commission held in Berlin, Sept. 1 to 6, 1913; see *Trans.* A. I. E. E., Vol. XXXII, p. 2148.

‖ Addicks, L. "Electrolytic Copper;" Journal of the Franklin Institute, Philadelphia, Pa., Dec., 1905.

40. Table of various values for resistivity, temperature coefficient, and density of annealed copper

Temperature (deg. cent.)	1 England (Eng. Stds. Com., 1904)	2 Germany, Old "Normal Kupfer," density 8.91	3 Germany, Old "Normal Kupfer," assuming density 8.89	4 Lindeck, Matthiessen value, assuming density 8.89	5 A. I. E. E. before 1907 (Matthiessen value)	6 A. I. E. E., 1907 to 1910	7 Bureau of Standards and A. I. E. E., 1911	8 "International Annealed Copper Standard"
				Restivity in Ohms (meter, gram)				
0	0.14136	0.13959	0.13927	0.14157	(**0.14172**)	(**0.14172**)	0.14106	0.14133
15	0.15043	(**0.14850**)	(**0.14816**)	(**0.14997**)	0.15014	0.15065	0.15003	0.15029
(15.6)	(**0.1508**)	...	...	...	...	...	...	...
20	0.15346	0.15147	0.15113	0.15285	0.15302	0.15363	(**0.15302**)	(**0.15328**)
25	0.15648	0.15444	0.15409	0.15576	0.15593	0.15661	0.15601	0.15626
				Temperature Coefficient				
0	(**0.00428**)	0.00425	0.00425	(*)	(*)	(**0.0042**)	** (0.00427)	** (0.00427)
15	0.00402	(**0.004**)	(**0.004**)	...	...	0.00395	** (0.00401)	** (0.00401)
20	0.00394	0.00392	0.00392	...	...	0.00387	** (**0.00394**)	** (**0.00393**)
25	0.00386	0.00384	0.00384	...	...	0.00380	** (0.00386)	** (0.00385)
				Density				
	† 8.89	8.91	(8.89)	(8.89)	8.89	8.89	†† 8.89	†† 8.89

* Matthiessen's formula: $\lambda_t = \lambda_o\,(1 - 0.0038701t + 0.000009009\,t^2)$. λ_t and λ_o = reciprocal of resistance at t deg. and 0 deg. cent. respectively.

** This temperature coefficient applies only to this particular resistivity. The temperature coefficient is considered to be proportional to conductivity. Expressed otherwise, the change of *resistivity* per deg. cent. is considered to be a constant, viz., 0.000597 ohm (meter, gram).

† At 15.6 deg. cent.

†† This is the density at 20 deg. cent. It corresponds to 8.90 at 0 deg. cent.

NOTE.—Black-faced figures refer to the particular values which were made standard.

44. Reduction of observations to standard temperature. A table of convenient corrections and factors for reducing resistivity and resistance to standard temperature, 20 deg. cent., will be found in "Copper Wire Tables," Circular No. 31, Bureau of Standards.

45. Calculation of per cent. conductivity. The per cent. conductivity of a sample of copper is calculated by dividing the resistivity of the International Annealed Copper Standard at 20 deg. cent. by the resistivity of the sample at 20 deg. cent. Either the mass resistivity or volume resistivity may be used. Inasmuch as the temperature coefficient of copper varies with the conductivity, it is to be noted that a different value will be found if the resistivity at some other temperature is used. This difference is of practical moment in some cases. In order that such differences shall not arise, it is best always to use the 20 deg. cent. value of resistivity in computing the per cent. conductivity of copper. When the resistivity of the sample is known at some other temperature, t, it is very simply reduced to 20 deg. cent. by adding the quantity $(20-t)$ multiplied by the "resistivity-temperature constant," given in Par. 46.

46. Resistivity-temperature constant. The *change of resistivity per degree* may be readily calculated, taking account of the expansion of the metal with rise of temperature. The proportional relation between temperature coefficient and conductivity may be put in the following convenient form for reducing *resistivity* from one temperature to another: *The change of resistivity of copper per degree cent. is a constant, independent of the temperature of reference and of the sample of copper. This "resistivity-temperature constant" may be taken, for general purposes, as* 0.00060 *ohm* (*meter, gram*), *or* 0.0068 *microhm-cm.* For further details, see "Copper Wire Tables," Circular No 31, Bureau of Standards, Washington, D. C.

47. Complete copper-wire tables, based on the International Annealed Copper Standard, are given in Par. 50, and represent approximately an average of the present commercial conductivity of copper. For annealed wires, the resistivity is independent of the size. These tables are reproduced directly from Circular No. 31, 3rd Edition, issued by the Bureau of Standards. The quantities were computed to five significant figures and rounded off to the fourth place, being therefore correct within 1 in the fourth significant figure. The volume resistivity at 20 deg. cent., used in calculating these tables, was 0.67879 microhm-in. and the density, 8.89 at 20 deg. cent. or 0.321,17 lb. per cu. in. The tables in Circular No. 31 contain additional columns for 0 deg., 15 deg., 25 deg. and 75 deg. cent. What the tables show is the resistance at various temperatures, of a wire which at 20 deg. cent. is 1,000 ft. long and has the specified diameter, and which varies in length and diameter at other temperatures.

48. Explanatory notes on copper wire tables.

NOTE 1.—The *fundamental resistivity* used in calculating the tables is the International Annealed Copper Standard, viz., 0.15328 ohm (meter, gram) at 20 deg. cent. The *temperature coefficient* for this particular resistivity is $\alpha_{20}=0.00393$, or $\alpha_0=0.00427$. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per deg. cent. is a constant, 0.000597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t=\frac{0.000597+0.000005}{\text{resistivity in ohms (meter, gram) at } t \text{ deg. cent.}} \qquad (4)$$

The *density* is 8.89 g. per cu. cm.

NOTE 2.—The values given in the tables are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent. higher resistivity than annealed copper.

NOTE 3.—This table is intended as an ultimate reference table, and is computed to a greater precision than is desired in practice. The practical user of a wire table is referred to the "Working Tables," Par. 51.

49. Working copper-wire tables, based on the International Annealed Copper Standard, are given in Par. 51. This table is carried only to three significant figures, and is more convenient for most practical work. The table itself is adapted from Circular No. 31, 3d edition, issued by the Bureau of Standards, and amplified by the addition of values based on the mile unit.

50. Complete wire table, standard annealed copper.—*Continued*

Gage No.	Diameter in mils at 20 deg. cent.	Pounds per ohm		Gage No.	Diameter in mils at 20 deg. cent.	Pounds per ohm	
		20 deg. cent. (=68 deg. fahr.)	50 deg. cent. (=122 deg. fahr.)			20 deg. cent. (=68 deg. fahr.)	50 deg. cent. (=122 deg. fahr.)
0000	460.0	13,070.0	11,690.0	19	35.89	0.4843	0.4332
000	409.6	8,219.0	7,352.0	20	31.96	0.3046	0.2725
00	364.8	5,169.0	4,624.0	21	28.46	0.1915	0.1713
0	324.9	3,251.0	2,908.0	22	25.35	0.1205	0.1078
1	289.3	2,044.0	1,829.0	23	22.57	0.07576	0.06777
2	257.6	1,286.0	1,150.0	24	20.10	0.04765	0.04262
3	229.4	808.6	723.3	25	17.90	0.02997	0.02680
4	204.3	508.5	454.9	26	15.94	0.01885	0.01686
5	181.9	319.8	286.1	27	14.20	0.01185	0.01060
6	162.0	201.1	179.9	28	12.64	0.007454	0.006668
7	144.3	126.5	113.2	29	11.26	0.004688	0.004193
8	128.5	79.55	71.16	30	10.03	0.002948	0.002637
9	114.4	50.03	44.75	31	8.928	0.001854	0.001659
10	101.9	31.47	28.15	32	7.950	0.001166	0.001043
11	90.74	19.79	17.70	33	7.080	0.0007333	0.0006560
12	80.81	12.45	11.13	34	6.305	0.0004612	0.0004126
13	71.96	7.827	7.001	35	5.615	0.0002901	0.0002595
14	64.08	4.922	4.403	36	5.000	0.0001824	0.0001632
15	57.07	3.096	2.769	37	4.453	0.0001147	0.0001026
16	50.82	1.947	1.742	38	3.965	0.00007215	0.00006454
17	45.26	1.224	1.095	39	3.531	0.00004538	0.00004059
18	40.30	0.7700	0.6888	40	3.145	0.00002854	0.00002553

51. Working table, standard annealed copper wire.—*Continued*

Gage No.	Diameter in mils	Cross-section		Ohms per 1,000 ft.		Ohms per mile		Pounds per 1,000 ft.	Pounds per mile
		Circular mils	Square inches	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)		
21	28.5	810.	0.000636	13.1	15.1	69.2	79.7	2.45	12.9
22	25.3	642.	0.000505	16.5	19.0	87.1	100.	1.94	10.24
23	22.6	509.	0.000400	20.8	24.0	110.	127.	1.54	8.13
24	20.1	404.	0.000317	26.2	30.2	138.	159.	1.22	6.44
25	17.9	320.	0.000252	33.0	38.1	174.	201.	0.970	5.12
26	15.9	254.	0.000200	41.6	48.0	220.	253.	0.769	4.06
27	14.2	202.	0.000158	52.5	60.6	277.	320.	0.610	3.22
28	12.6	160.	0.000126	66.2	76.4	350.	403.	0.484	2.56
29	11.3	127.	0.0000995	83.4	96.3	440.	509.	0.384	2.03
30	10.0	101.	0.0000789	105.	121.	554.	639.	0.304	1.61
31	8.9	79.7	0.0000626	133.	153.	702.	808.	0.241	1.27
32	8.0	63.2	0.0000496	167.	193.	882.	1020.	0.191	1.01
33	7.1	50.1	0.0000394	211.	243.	1110.	1280.	0.152	0.803
34	6.3	39.8	0.0000312	266.	307.	1400.	1620.	0.120	0.634
35	5.6	31.5	0.0000248	335.	387.	1770.	2040.	0.0954	0.504
36	5.0	25.0	0.0000196	423.	488.	2230.	2580.	0.0757	0.400
37	4.5	19.8	0.0000156	533.	616.	2810.	3250.	0.0600	0.317
38	4.0	15.7	0.0000123	673.	776.	3550.	4100.	0.0476	0.251
39	3.5	12.5	0.0000098	848.	979.	4480.	5170.	0.0377	0.199
40	3.1	9.9	0.0000078	1,070.	1,230.	5650.	6490.	0.0299	0.158

This table is correct to three significant figures, only.

The number of circular mils in a cable composed of N wires is

$$C.M. = Nd^2 \tag{8}$$

where d is the diameter of each wire in mils (thousandths of an inch).

The equivalent solid conductor is one having the same number of circular mils, or its diameter is

$$D' = \sqrt{Nd^2} \tag{9}$$

It is *not* equal to the normal cross-section of the cable, because in the last case the strands are cut at a slight angle (due to their pitch) and such a section is therefore larger than the true section, equal to the sum of the normal sections of all the strands, each taken normal to its own axis.

The ratio of the diameter of concentric strand to the diameter of equivalent solid conductor is given by

$$\frac{D}{D'} = \frac{2n+1}{\sqrt{N}} = \sqrt{\frac{4n^2+4n+1}{3n^2+3n+1}} \tag{10}$$

Substitution in this formula from $n=0$ to $n=8$, gives the following values of the ratio.

n	N	$\frac{D}{D'}$	n	N	$\frac{D}{D'}$	n	N	$\frac{D}{D'}$
0	1	1.000	3	37	1.151	6	127	1.154
1	7	1.134	4	61	1.152	7	169	1.154
2	19	1.147	5	91	1.153	8	217	1.154

This shows that the larger the number of strands, for a given cross-section, the larger will be the outside diameter, approaching, however, a limiting ratio of 1.154. Therefore the size and the cost of a conductor of given cross-section increase as the number of strands increases.

The individual wires of a cable can seldom be drawn to any of the standard gage numbers, because the diameter of the wire is fixed by the required size of the cable, and the number of wires composing it. Also see "Wire In Electrical Construction," John A. Roebling's Sons Co., 1906; and "Electrical Wires and Cables," Amer. Steel & Wire Co., 1910.

56. Composition of standard concentric strands*

Range of size	Number of wires: Standard concentric strands	Number of wires: Flexible concentric strands
2,000,000 to 1,600,000 cir. mils..................	127	169
1,500,000 to 1,100,000 cir. mils..................	91	127
1,000,000 to 550,000 cir. mils..................	61	91
500,000 to 250,000 cir. mils..................	37	61
No. 0000 to No. 1 A.W.G..................	19	37
No. 2 to No. 8 A.W.G..................	7	19

57. Pitch or lay of concentric strand. The axial length of one complete turn of any individual strand in a concentric-lay cable, divided by the diameter of the cable, is called the pitch or lay. The **pitch angle** of the cable is shown in Fig. 2, where ac represents the axis of the cable and l is the axial length of one complete twist; ab is the length of any individual strand, $l + \Delta l$, in one complete twist; and the angle bac, or θ, is the pitch angle. The side bc is equal to the circumference of the circle circumscribing the cable. In this case the pitch p is given by $p = l/d$. There is no fixed

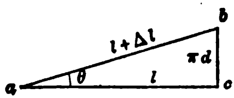

Fig. 2.—Pitch angle in concentric lay cable.

* See Circular No. 37, "Electric Wire and Cable Terminology;" Bureau of Standards; 2nd ed., Jan. 1, 1915, page 13: A. I. E. E. Standardisation Rules, 1914; also see latest edition of Standardisation Rules, Sec. 24.

50. Complete wire table, standard annealed copper.—*Continued*

Gage No.	Diameter in mils at 20 deg. cent.	Pounds per 1,000 ft.	Feet per pound	Feet per ohm* 20 deg. cent. (= 68 deg. fahr.)	Feet per ohm* 50 deg. cent. (= 122 deg. fahr.)
0000	460.0	640.5	1.561	20,400.0	18,250.0
000	409.6	507.9	1.968	16,180.0	14,470.0
00	364.8	402.8	2.482	12,830.0	11,480.0
0	324.9	319.5	3.130	10,180.0	9,103.0
1	289.3	253.3	3.947	8,070.0	7,219.0
2	257.6	200.9	4.977	6,400.0	5,725.0
3	229.4	159.3	6.276	5,075.0	4,540.0
4	204.3	126.4	7.914	4,025.0	3,600.0
5	181.9	100.2	9.980	3,192.0	2,855.0
6	162.0	79.46	12.58	2,531.0	2,264.0
7	144.3	63.02	15.87	2,007.0	1,796.0
8	128.5	49.98	20.01	1,592.0	1,424.0
9	114.4	39.63	25.23	1,262.0	1,129.0
10	101.9	31.43	31.82	1,001.0	895.6
11	90.74	24.92	40.12	794.0	710.2
12	80.81	19.77	50.59	629.6	563.2
13	71.96	15.68	63.80	499.3	446.7
14	64.08	12.43	80.44	396.0	354.2
15	57.07	9.858	101.4	314.0	280.9
16	50.82	7.818	127.9	249.0	222.8
17	45.26	6.200	161.3	197.5	176.7
18	40.30	4.917	203.4	156.6	140.1
19	35.89	3.899	256.5	124.2	111.1
20	31.96	3.092	323.4	98.50	88.11
21	28.46	2.452	407.8	78.11	69.87
22	25.35	1.945	514.2	61.95	55.41
23	22.57	1.542	648.4	49.13	43.94
24	20.10	1.223	817.7	38.96	34.85
25	17.90	0.9699	1,031.0	30.90	27.64
26	15.94	0.7692	1,300.0	24.50	21.92
27	14.20	0.6100	1,639.0	19.43	17.38
28	12.64	0.4837	2,067.0	15.41	13.78
29	11.26	0.3836	2,607.0	12.22	10.93
30	10.03	0.3042	3,287.0	9.691	8.669
31	8.928	0.2413	4,145.0	7.685	6.875
32	7.950	0.1913	5,227.0	6.095	5.452
33	7.080	0.1517	6,591.0	4.833	4.323
34	6.305	0.1203	8,310.0	3.833	3.429
35	5.615	0.09542	10,480.0	3.040	2.719
36	5.000	0.07568	13,210.0	2.411	2.156
37	4.453	0.06001	16,660.0	1.912	1.710
38	3.965	0.04759	21,010.0	1.516	1.356
39	3.531	0.03774	26,500.0	1.202	1.075
40	3.145	0.02993	33,410.0	0.9534	0.8529

* Length at 20 deg. cent. of a wire whose resistance is 1 ohm at the stated temperatures.

69. Table of breaking loads of copper wire

(Based on tensile requirements of the American Society for Testing Materials

Gage No. A.W.G.	Diam. in mils	Breaking load (lb.)		
		Annealed	Medium hard	Hard drawn
0000	460	5,980	6,980 –8,140	8,140
000	410	4,750	5,680 –6,600	6,730
00	365	3,780	4,620 –5,360	5,540
0	325	2,980	3,730 –4,310	4,520
1	289	2,370	3,020 –3,480	3,680
2	258	1,930	2,450 –2,810	3,000
3	229	1,530	1,980 –2,270	2,440
4	204	1,210	1,590 –1,820	1,970
5	182	963	1,260 –1,450	1,590
6	162	763	1,010 –1,150	1,280
7	144	607	810 – 925	1,030
8	128	481	646 – 737	828
9	114	381	515 – 587	663
10	102	314	410 – 467	528
11	91	249	328 – 373	423
12	81	198	262 – 298	337
13	72	157	209 – 237	268
14	64	124	167 – 189	214
15	57	98.6	131 – 151	170
16	51	78.2	106 – 120	135
17	45	62.0	84.8– 96.1	108
18	40	49.3	67.9– 76.8	85.8
(English gages)				
8 B.W.G.	165	792	1,050 –1,200	1,330
10 B.W.G.	134	522	698 – 797	894
12 S.W.G.	104	314	427 – 487	551
13 S.W.G.	92	256	337 – 383	435
14 S.W.G.	80	194	256 – 292	330
16 B.W.G.	65	128	171 – 195	220

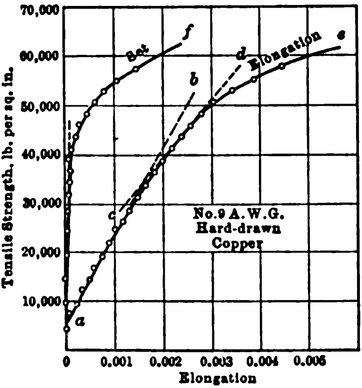

FIG. 5.—Stress-strain curves of No. 9 A.W.G. hard-drawn copper wire (Watertown Arsenal test).

70. Stress-strain dia grams. A typical stress-strai diagram of hard-drawn coppe wire is shown in Fig. 5, whic represents No. 9 A.W.G. Th curve *ae* is the actual stres strain curve; *ab* represents th portion which corresponds t true elasticity, or for whic Hooke's law holds rigorousl *cd* is the tangent to *ae* whi fixes the Johnson elastic limi and the curve *af* represen the set, or permanent elong tion due to flow of the met

* The Johnson elastic limit that point on the stress-str curve at which the natural ta gent is equal to 1.5 times t tangent of the angle of t straight or linear portion of t curve, with respect to the a of ordinates, or Y axis. S Johnson, J. B., "Materials Construction," John Wiley Sons, New York, 1912.

72. Fatigue under load. Under long-sustained loads approaching the normal tensile strength, copper has somewhat less strength than the values obtained by ordinary test. Mr. F. O. Blackwell, in the paper referred to in Par. 70, found that a 0.168-in. hard-drawn wire stressed to 54,000 lb. per sq. in., stretched continuously, and broke in 7 days, 8 hours; pieces of the same wire afterward broke at 61,000 lb. in the testing machine. He concluded that a hard-drawn wire would stand continuously a stress of about 80 per cent. of its normal tensile strength.

73. Young's modulus of elasticity for annealed and hard copper is not a very definitely known quantity and the values given for it fluctuate over a considerable range. This may be accounted for, in the case of annealed copper, by the lack of any very definite elastic limit, and the fact that the initial stress-strain diagram departs at a very early stage from Hooke's law; and as soon as a slight load has been applied the properties commence to change. The same difficulties are present, in less degree, in the case of hard-drawn copper. In all cases, the final value of the modulus, after stressing, is almost invariably greater than the initial modulus. The following values represent the extreme range, and a probable average, drawn from several authorities,* expressed in in-lb. measure.

State	Range	Probable average
Annealed wire	7×10^6 to 17×10^6	12×10^6
Annealed concentric strand	5×10^6 to 12×10^6	9×10^6
Hard-drawn wire	13×10^6 to 19×10^6	16×10^6
Hard-drawn concentric strand	10×10^6 to 14×10^6	12×10^6

74. Specific heat of copper is not independent of temperature. The following values were taken from "Tables Annuelles de Constantes et Données Numériques de Chemie, de Physique et de Technologie" (For 1910; University of Chicago Press, 1912), p. 50.

Specific heat, at −50 deg. cent. 0.0862
Specific heat, at 0 deg. cent. 0.0910
Specific heat, at +50 deg. cent. 0.0928
Specific heat, from 2.4 to 21.6 deg. cent. 0.09155
Specific heat, from 17 to 100 deg. cent. 0.0925

The Bureau of Standards gives, for the range from 15 to 50 deg. cent., the expression $0.0917+0.000048\ (t-25)$; this is in terms of water at 20 deg. cent. For values at high temperatures see Hoffman, H. O. "Metallurgy of Copper;" p. 7.

75. Thermal conductivity of copper is a function of temperature, as expressed in the formula $\lambda_t = \lambda_0 (1 + at)$. The following values of thermal conductivity, in g-cal. (cm-cube) per sec. per deg. cent. were determined by Lorenz.†

Thermal conductivity, at 0 deg. cent. 0.7189
Thermal conductivity, at 100 deg. cent. 0.7226
Temperature coefficient, from and at 0 deg. cent. 0.000051

Hoffman states the thermal conductivity as 0.72 g-cal. (cm-cube) per deg. cent.; Langmuir gives 0.84 g-cal. for commercial copper and 0.92 g-cal. for pure copper.

76. Properties of copper at very high temperatures. See a paper by Carl Hering, "The Proportioning of Electrodes for Furnaces," *Trans.* A. I. E. E., Vol. XXIX (1910), pp. 485 to 545. Also covers carbon, graphite and iron.

77. Specifications for copper wire, annealed, medium hard and hard drawn, have been adopted by the American Society For Testing Materials

* Blackwell, F. O. "Conductors for Long Spans;" *Trans.* International Elec. Congress, St. Louis, 1904; Vol. II, p. 341.
Blackwell, F. O. "Long Spans for Transmission Lines;" *Trans.* A. I. E. E., Vol. XXIII, 1904, p. 511.
"Smithsonian Physical Tables," 5th rev. ed., 1910, p. 75.
American Steel & Wire Co.; "Handbook of Electrical Wires and Cables," 1910, p. 14.

† "Smithsonian Physical Tables," 1910; p. 199.

dioxide do not affect it at ordinary temperatures; it is not attacked by sulphuretted hydrogen, or carbonic acid. It resists the action of sea water better than copper, provided there is no electrolysis, but it is a highly electropositive metal. The presence of impurities in considerable quantities lowers the resistance to corrosion in marked degree. There is also danger from electrolytic corrosion if aluminum is alloyed with an electronegative metal.

The electrical conductivity of aluminum, like that of copper, depends on its degree of chemical purity. The conductivity of hard-drawn aluminum is about 2 per cent. less than that of soft or annealed aluminum. The tensile properties, in like manner, depend greatly upon the physical state, being much improved by cold rolling and drawing.

The alloys of aluminum are very numerous. The so-called light alloys, containing but small percentages of other metals, are light, hard and strong, but do not resist corrosion from galvanic action. The heavy alloys, or aluminum-bronzes, with but 2 per cent. to 10 per cent. of aluminum, and respectively 98 per cent. to 90 per cent. of copper, have high tensile strength and strongly resist corrosion in air or sea water. A very small proportion of aluminum, about 0.01 per cent., added to iron, steel or brass in casting removes the oxide and prevents blow holes.

The tinning process, which is applied to copper wires intended to receive an insulation of rubber compound (sulphur being present), is unnecessary in the case of aluminum.

Aluminum possesses an insulating film which ordinarily has a dielectric strength of about 0.5 volt, and by electrolytic action this value can be somewhat increased.

80. Commercial grades of aluminum. The impurities most commonly found in aluminum are silicon and iron. Silicon in aluminum exists in two forms, one seemingly combined with aluminum as combined carbon exists in pig iron, and the other as an allotropic graphitoidal modification. Small quantities of copper, sodium, carbon and occluded gases are also found in aluminum. The Aluminum Company of America classifies aluminum commercially in three grades,* as follows:

Extra-pure aluminum, No. 1 grade or so-called pure aluminum, and No. 2 grade for castings, or structural shapes. The average composition is as follows:

	No. 1 (per cent.)	No. 2 (per cent.)
Aluminum	99.55	96
Silicon	0.30	2
Iron	0.15	2

Pure aluminum (No.1 grade or better) is necessary to secure high electrical conductivity, extreme malleability, ductility and maximum resistance to corrosion. For other purposes small amounts of copper, nickel, tungsten, manganese, chromium, titanium, zinc or tin may be advantageously added to aluminum to produce hardness, rigidity and strength. These metals when alloyed with aluminum do not diminish its resistance to corrosion so much as silicon or iron.

81. Typical analysis. The following analyses of aluminum are typical

	Aluminum Co. of Amer.† (per cent.)	Richards (per cent.)
Aluminum	99.57	99.25
Silicon	0.29	0.64
Iron	0.14	0.04
Copper	....	0.02
Lead	....	0.01

* "Properties of Aluminum;" Aluminum Co. of America, Pittsburgh, Pa. 1909; p. 7.

† Bureau of Standards, Circular No. 31, Third Ed., Oct. 1, 1914; p. 14.

information at the present time is largely regarded as among the secrets of the trade. The ordinary percentage of impurities in commercially pure aluminum, No. 1 grade (see Par. 80), is 0.45 per cent. In terms of the British standard for hard-drawn copper at 60 deg. fahr. (15.6 deg. cent.) Mr. Burkewood Welbourn stated* that a (volume) conductivity of 60 per cent. corresponds to 0.71 per cent. of impurities, and a conductivity of 61.7 per cent. corresponds to 0.5 per cent. of impurities.

The Aluminum Company of America states† that the electrical (volume) conductivity of pure (No. 1 grade) aluminum is about 62 per cent. in the Matthiessen standard scale. The British Aluminum Company, Ltd., gives (June, 1914) the following values of resistivity, expressed in microhm-cm.

	Annealed	Hard-drawn
Volume resistivity, microhm-cm. at 60 deg. fahr...	2.770	2.870
Volume resistivity, microhm-cm. at 32 deg. fahr...	2.610	2.70

The Bureau of Standards‡ gives the following average values of resistivity for commercial hard-drawn aluminum.

Mass resistivity, ohms (meter, gram), at 20 deg. cent.	0.0764
Mass resistivity, ohms (mile, pound), at 20 deg. cent.	436.0
Mass per cent. conductivity	200.7
Volume resistivity, microhm-cm., at 20 deg. cent.	2.828
Volume resistivity, microhm-in., at 20 deg. cent.	1.113
Volume per cent. conductivity	61.0
Density, g. per cu. cm.	2.70
Density, lb. per cu. in.	0.0975

These values given by the Bureau of Standards are the basis of the aluminum wire tables in Par. 87. Since aluminum is very rarely used as an electrical conductor in the soft state, the foregoing values given by the Bureau of Standards, for hard-drawn wire, have the most commercial significance. Annealed aluminum, however, is used abroad for the conductors of underground cables.

85. Temperature coefficient of resistance. On the authority of the British Aluminum Company, Ltd., the temperature coefficient of resistance of aluminum, for constant mass, varies from 0.0032 to 0.0040 per deg. cent. and from 0.0018 to 0.0022 per deg. fahr.

A determination made in the laboratory of the Westinghouse Electric and Manufacturing Company, under the direction of Prof. Charles F. Scott, gave as the average coefficient between 0 deg. and 50 deg. cent., the value 0.00388 per deg. cent.; in the fahrenheit scale the equivalent of this value is 0.00216 per deg. Prof Scott's determination is quoted by the Aluminum Company of America.

The Bureau of Standards gives 0.0039 per deg. cent. at 20 deg. cent. (circular No. 31, Third Edition, 1914, p. 14.)

86. Aluminum wire tables. The complete tables for aluminum wire given in Par. 87 were taken from circular No. 31, Third Edition, issued by the Bureau of Standards, and are based on a volume conductivity, in terms of the annealed copper standard, equal to 61.0 per cent.

Aluminum wire is practically never used in single strands for overhead construction, but the tables are very useful in computing the resistance of concentric strand. In commercial practice the aluminum delivered under contract varies in conductivity from 60 per cent. to 62 per cent. of the former Matthiessen standard, many contracts being placed at 61 per cent.

* Welbourn, B. "Insulated and Bare Copper and Aluminum Cables for the Transmission of Electrical Energy, with Special Reference to Mining Work;" *Trans.* (British) Institution of Mining Engineers; 1913. Gives bibliography on aluminum wire.

† "Properties of Aluminum;" Aluminum Company of America, Pittsburgh, Pa., 1909; p. 27.

‡ Circular No. 31, "Copper Wire Tables;" 1914; Third Edition, p. 14.

89. Table of bare concentric-lay cables of hard-drawn aluminum
(English Units)

Circular mils	A.W.G. No.	Ohms per 1,000 ft.		Pounds per 1,000 ft.	Concentric stranding		
		25 deg. cent. (77 deg. fahr.)	65 deg. cent. (149 deg. fahr.)		No. of wires	Diam. of wires in mils	Outside diam. in mils
1,000,000		0.0177	0.0204	938.	37	164.4	1151
900,000		0.0197	0.0227	844.	37	156.0	1092
800,000		0.0221	0.0255	750.	37	147.0	1029
700,000		0.0253	0.0291	657.	37	137.5	963
600,000		0.0295	0.0340	563.	19	177.7	890
500,000		0.0354	0.0408	469.	19	162.2	810
400,000		0.0442	0.0510	375.	19	145.1	725
300,000		0.0590	0.0680	281.	19	125.7	630
300,000		0.0590	0.0680	281.	7	207.0	621
250,000		0.0707	0.0816	235.	7	188.9	567
212,000	0000	0.0834	0.0962	199.	7	174.0	522
168,000	000	0.1053	0.1214	158.	7	154.9	465
133,000	00	0.1330	0.1533	125.	7	137.8	414
106,000	0	0.1668	0.1924	99.4	7	123.1	369
83,700	1	0.2113	0.2436	78.5	7	109.3	327
66,400	2	0.2663	0.3071	62.3	7	97.4	292
52,600	3	0.3362	0.3876	49.3	7	86.7	260
41,700	4	0.4241	0.4890	39.1	7	77.2	232
33,100	5	0.5343	0.6160	31.0	7	68.8	206
26,300	6	0.6724	0.7753	24.7	7	61.3	184

90. Reinforced (steel centre) aluminum concentric strand. A concentric strand consisting of six hard-drawn aluminum wires laid over a centre or core consisting of a galvanized steel wire has been manufactured to a very limited extent, for experimental use. The steel employed had a tensile strength of about 125,000 lb. per sq. in. On account of the different coefficients of expansion, with these metals, the distribution of stresses in a suspended cable under changing temperature conditions is quite complicated.

In another instance the core was composed of 7 strands of steel laid into a concentric cable; about this were laid 6 strands of hard-drawn aluminum. The tensile strength of the steel was about 220,000 lb. per sq. in. and the strength of the aluminum was 28,000 lb. per sq. in. This type of conductor was used in a 1,000-ft. ravine span. See *Electrical News*, Vol. XXII, p. 34; also *The Canadian Engineer*, Dec. 11, 1913, "Transmission Line Work;" by E. V. Pannell.

91. Coefficient of linear expansion. The value given by Sir Roberts-Austen for the linear coefficient of expansion is 0.0000231 per deg. cent. from 0 to 100 deg. cent.; the corresponding value per deg. fahr. is 0.0000128. The value per deg. cent. given by the British Aluminum Company is 0.0000234. The 5th revised edition (1910) of the "Smithsonian Physical Tables" (Fowle, F. E.) gives the coefficient as 0.00002313 at 40 deg. cent.; the mean value between 0 and 100 deg. cent. is 0.0000222 per deg. cent.

92. Tensile strength. The tensile strength of aluminum depends upon its state, previous working and heat treatment. The strength of aluminum is increased by cold working, as in the case of copper. The approximate range of tensile strength of aluminum in various forms is given next below, in lb. per sq. in. (Aluminum Co. of America).

indicate the number of minutes the load was held at each of several points. This specimen broke at 23,900 lb. per sq. in., with an elongation of 1.25 per cent.

95. Elongation at rupture. The total elongation at rupture, for hard-drawn wire in commercial sizes, ranges from about 2 to 4 per cent.

96. Young's modulus of elasticity in tension ranges from 8,000,000 to 12,000,000, with an average of 9,000,000 to 10,000,000. F. O. Blackwell gives the modulus for concentric cables as 7,500,000 (Trans. Int. Elec. Cong., St. Louis, 1904, Vol. II, pp. 331-347).

97. Specific heat of aluminum at 0 deg. cent. is 0.2089 and at 100 deg. cent. is 0.2226; the mean specific heat between 16 and 100 deg. cent. is 0.2122 (5th rev. ed., "Smithsonian Phys. Tables," p. 228).

98. Thermal conductivity of aluminum at 0 deg. cent. is 0.344 gram-calorie (cm-cube) per deg. cent. per sec., with a temperature coefficient of 0.00054 per deg. cent. ("Smithsonian Phys. Tables," 1910).

99. Aluminum bars are used in power-plant switchboard connections for bus bars, and for carrying very large currents in electrolytic work. Since bus bars are generally designed to have a stated carrying capacity limited by a stated temperature rise, the comparative cross-sections of aluminum and copper are not required in practice to be in inverse ratio to the respective conductivities, because of the difference in radiating surface.

COPPER-CLAD STEEL

100. Compound or bi-metallic wires composed of copper-covered iron or steel have been manufactured by a number of different methods, and were first attempted many years ago. Aluminum-covered steel has also been tried, on an experimental scale. The general object sought in the manufacture of such wires is the combination of the high conductivity of copper or aluminum with the high strength and toughness of iron or steel. The resulting conductor is obviously a compromise between copper (or aluminum) and iron, being inferior as a whole to the former and superior to the latter.

101. Union between the metals. In the early attempts to produce bi-metallic wires, the two metals were not welded, but merely in close physical contact. Consequently there was a marked tendency toward electrolysis wherever moisture and air had access to the junction between the dissimilar metals. No great success attended the use of such wires until modern processes were developed for effecting a weld or molecular union between the metals.

102. Copper-clad steel wire is manufactured by two processes, known as the **Monnot process** (Duplex Metals Co.) and the **Griffith process** (Colonial Steel Co.). The Monnot process consists briefly of dipping a mild steel billet in bath of molten copper maintained at high temperature, thus forming on the surface of the billet an iron-copper alloy; the billet is then withdrawn and placed in a mold, and a copper jacket is cast around it. The billet is then re-heated and hot-rolled to wire rods, and finally cold-drawn to wire.

The Griffith process consists briefly of coating a mild steel billet with copper by electrolytic deposition (Sec. 19), then inserting the copper-coated billet in a copper tube, closing the ends, and heating the compound billet preparatory to rolling; it is then hot-rolled to rods, and cold-drawn to wire.

103. Commercial grades of copper-clad steel wire. It has become customary commercial practice to rate copper-clad steel wire in terms of the ratio of its volume conductivity to copper. Thus one manufacturer makes three grades of wire, having respectively 30 per cent., 40 per cent. and 47 per cent. conductivity ratio to copper; another manufacturer has standardized a 30-per cent. wire. These ratios are usually average ratios, and in practice certain tolerance limits must be recognised, above and below the average; or else the rated conductivity can be specified as the absolute acceptable minimum.

105. Copper-covered steel, concentric-lay cables
(Duplex Metals Company)

Approx. diam.	Actual diam.	Diam. of each strand	Total cross-section	Weight		Approx. breaking load	Average resistance per 1,000 ft. at 75 deg. fahr.		
							30 per cent. grade	40 per cent. grade	47 per cent. grade
Inches	Inches	Inches	Circ. mils	Pounds per 1,000 ft.	Pounds per mile	Pounds	Ohms	Ohms	Ohms
Seven strand									
5/8	0.612	0.204	291,310	857	4,505	16,380	0.120	0.0901	0.0766
9/16	0.546	0.182	231,870	682	3,601	13,860	0.151	0.113	0.0963
1/2	0.486	0.162	183,710	542	2,862	11,340	0.190	0.142	0.121
7/16	0.432	0.144	145,150	430	2,270	9,140	0.241	0.181	0.154
3/8	0.384	0.128	114,690	340	1,795	7,560	0.305	0.229	0.195
5/16	0.306	0.102	72,830	215	1,135	5,040	0.481	0.360	0.306
1/4	0.243	0.081	45,930	135	713	3,220	0.762	0.571	0.486
Nineteen strand									
1	1.020	0.204	790,700	2,354	12,429	44,460	0.0443	0.0332	0.0283
7/8	0.900	0.182	629,360	1,873	9,889	37,620	0.0556	0.0417	0.0355
13/16	0.810	0.162	498,640	1,484	7,835	30,780	0.0702	0.0526	0.0447
3/4	0.720	0.144	393,990	1,172	6,188	24,800	0.0889	0.0669	0.0567
11/16	0.685	0.137	366,610	1,091	5,760	22,230	0.0983	0.0737	0.0628
5/8	0.640	0.128	311,300	926	4,889	20,520	0.112	0.0842	0.0717
9/16	0.570	0.114	246,920	735	3,880	16,680	0.141	0.106	0.0904
1/2	0.510	0.102	197,680	589	3,109	13,680	0.177	0.133	0.113
7/16	0.455	0.091	157,340	468	2,471	11,120	0.223	0.167	0.142
3/8	0.360	0.072	98,500	293	1,548	7,020	0.355	0.266	0.227
5/16	0.320	0.064	77,830	232	1,224	5,650	0.449	0.337	0.287

Electrolytic iron melted in *vacuo* 9.96
Swedish charcoal iron remelted in *vacuo* 10.30
Commercial grades:
Swedish charcoal iron cut from plate......................... 10.57
Standard transformer steel.................................. 11.09
Silicon (4 per cent.) steel.................................. 51.15

Hopkinson tested and analyzed 35 different samples of iron (Phil. Trans. p. 463, Part II, 1885) and found resistivities (microhm-cm.) ranging from 13.78 for wrought iron to 100 for cast iron.

Also see Boudouard, O. "Electric Resistivity of Special Steels," IX, 6, No. 10, Sixth Congress Int. Assoc. for Testing Materials, New York City, 1912.

116. Preece's tests on resistivity of annealed iron wire
(Munroe and Jameson)

	Composition						Ohms (mile, lb.) at 60 deg. fahr.
	Fe	C	Mn	Si	S	P	
Swedish charcoal iron.....	99.70	0.10	0.03	Trace	0.022	0.045	4502
Swedish charcoal iron.....	99.44	0.15	0.234	0.018	0.019	0.058	4820
Siemens-Martin steel.....	99.60	0.10	0.324	Trace	0.035	0.034	5308
Best puddled iron.........	99.11	0.10	0.234	0.09	0.03	0.218	5974
Bessemer steel, soft.......	98.74	0.15	0.72	0.018	0.092	0.077	6163
Bessemer steel, hard......	98.20	0.44	1.296	0.028	0.126	0.103	7468
Best cast steel...........	97.41	0.62	1.584	0.06	0.074	0.051	8033

117. Effects of different alloying elements upon the resistivity of pure iron were found by Barrett to be as follows: the values given in the table represent the increase in resistivity (microhm-cm.) resulting from the addition of 1 per cent. of different alloying elements.

Tungsten..................	2.0	Carbon...............	5.0
Cobalt....................	3.0	Manganese............	8.0
Nickel....................	3.5	Silicon................	13.0
Chromium..................	5.0	Aluminum.............	14.0

118. Temperature coefficient of resistance. The average coefficient per deg. cent., between 0 and 100 deg. cent., based on the measurements by Dewar and Fleming, is 0.00622. This value compares with 0.00635 based on recent measurements published by the Bureau of Standards (Scientific Paper No. 236). The mean value between 0 and 20 deg. cent., determined by Dewar and Fleming, is 0.00527 per deg. cent.

119. Ingot-iron, described more fully in Par. 379, has been found on test to have a volume conductivity of 16.76 per cent. and a mass conductivity of 18.96 per cent., in terms of the International annealed copper standard. See *Elec. Railway Journal*, June 6, 1914, "Pure Ingot Iron for Third Rails." Carbon steel rails containing 0.73 per cent. carbon and 0.34 per cent. manganese, have a volume conductivity equal to 13 per cent. of that of copper. (Also see Sec. 16.) Ingot iron wire weighs about 4,600 lb. per mile-ohm at 20 deg. cent. and has a tensile strength of about 52,000 lb. per sq. in.

120. Resistivity and temperature coefficient of carbon steel. Barus and Strouhal found that the temper of carbon steel affected its electrical properties as shown below.

Temper	Resistivity, microhm-cm. at 0 deg. cent.	Temperature coefficient, per deg. cent.
Soft..............................	15.9	0.00423
Light blue........................	18.4	0.00360
Blue..............................	20.5	0.00330
Yellow............................	26.3	0.00280
Light yellow......................	28.9	0.00244
Glass hard........................	45.7	0.00161

See "Smithsonian Physical Tables," 5th rev. ed., 1910, p. 263.

125. Permeability of iron wire. The permeability of iron or soft steel wire, in the ordinary commercial sizes, at frequencies of 60 cycles or less, is from 100 to 125; at 800 cycles, it is about 70. This applies to small magnetising forces, such as exist within the wire due to the current flowing through it. These values hold for the steel core of copper-clad steel.

126. Steel rails. The resistivity of common rail steel varies in considerable degree, depending upon the chemical composition. Special soft steels used for third rails have resistivities ranging from 7.9 to 9 times that of copper; track rails, from 11 to 13 times that of copper. In manganese steels the ratio sometimes exceeds 30. The effective resistance of rails conveying alternating currents will be increased somewhat on account of skin effect and eddy-currents. See "Report of the Electric Railway Test Commission," McGraw-Hill Book Co., Inc., New York, 1906. Also see Par. 119.

127. Density of pure iron is 7.86, which is fairly precise for wrought iron and steel. The National Tube Co. computes the weight of steel at 0.2833 lb. per cu. in. (489.5 lb. per cu. ft.) and iron at 2 per cent less.

128. Tensile properties of iron and steel wires. The tensile properties are dependent upon the composition of the metal from which the wire is drawn, upon the amount of working the wire has received in the process of manufacture and upon the heat treatment. For information upon the effect of the constituents of iron and steel on the tensile properties, see "Structural Materials," in another portion of this section.

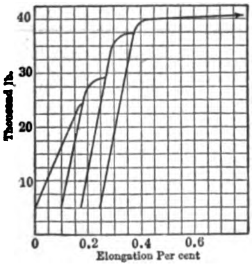

FIG. 11.—Stress-strain diagram of galvanized iron wire.

The tensile strength ranges from about 45,000 lb. per sq. in., for the purest annealed wrought iron, up to extremely high values for hard steel, in the neighborhood of 500,000 lb. per sq. in. Carbon, manganese and silicon are the chief constituents which impart strength and hardness; they also increase the electrical resistivity. Both carbon and manganese decrease the magnetic permeability.

The elastic limit and the yield point occur at about the same relative values as in structural iron and steel; in other words, the elastic ratio does not change.

Fig. 11 shows a typical stress-strain diagram; the wire was 0.164 in. in diameter and broke at 55,100 lb. per sq. in., while the elastic limit was 25,000 lb. per sq. in. and the elongation was 11 per cent. in 60 in. Time was allowed for the wire to set (see Blackwell, F. O. "Conductors for Long Spans;" Trans. Int. Elec. Cong., St. Louis, 1904, Vol. II, pp. 331–347).

Blackwell gives Young's modulus as 24×10^6 lb. per sq. in. for iron wire, 27×10^6 for steel wire, and 22×10^6 for iron and steel concentric cable.

129. Coefficient of expansion. Blackwell gives 0.0000064 per deg. fahr. for iron and steel wire.

130. Specific heat of wrought iron, from 15 to 100 deg. cent., is 0.115; hard-drawn iron, from 0 to 18 deg., 0.0986 and from 20 to 100 deg., 0.115 ("Smithsonian Phys. Tables," 1910).

131. Thermal conductivity of iron in gram-calories (cm-cube) per deg. cent. is from 0.167 to 0.207 at 0 deg. cent., with a negative temperature coefficient of 0.00023 "(Smithsonian Phys. Tables," 1910).

BRONZE

132. Bronze is an alloy of copper and tin, with the addition in some cases of zinc and other metals. There are numerous varieties of bronze, some designated by a prefix indicating the special or distinguishing constituent, and others known by trade names.

133. Phosphor bronze is an alloy of copper, tin and phosphorus, containing from 2 to 6 per cent. of tin and 0.05 to 0.13 per cent. of phosphorus. Its volume conductivity is not over 35 per cent. of that of copper. Industrial bronzes carry zinc and lead, and a larger proportion of phosphorus.

134. Silicon bronze is an alloy of copper, silicon and sodium; tin and zinc

Phono-electric wire, on account of its high tensile properties, has been used for trolley wire and for long spans in transmission lines and in telephone and telegraph lines.

The tensile strength of hard-drawn wire ranges from 68,000 to 84,000 lb. per sq. in. The total elongation at rupture is about 1 per cent. and Young's modulus is about 18,100,000. The temperature coefficient of resistance is 0.00088 per deg. fahr. and the coefficient of linear expansion is 0.0000149 per deg. fahr.

MISCELLANEOUS METALS

138. Resistivity of various metals

(Compiled from "Smithsonian Phys. Tables," 1910)

Metal	Resistivity at 0 deg. cent. (microhm-cm.)	Temp. coef. per deg. cent., at 20 deg. cent.	Density	Therm. cond. (g-cal. per cm. cube per deg. per sec.)
Antimony	35.4 to 45.8	0.00389	6.62 to 6.69	0.044
Arsenic	33.3	....	5.73	....
Bismuth	108.0	0.00354	9.70 to 9.90	0.019
Boron	8×10^{10}	....	2.5 to 2.6	....
Cadmium	6.2 to 7.0	0.00419*	8.54 to 8.67	0.22
Calcium	7.5	....	1.55	....
Cobalt	9.8	0.00325*	8.71	....
Gold	2.04 to 2.09	0.00365	19.3	0.70
Indium	8.38	....	7.12 to 7.42	....
Lead	18.4 to 19.6	0.00387	11.36	0.084
Lithium	8.8	....	0.534	....
Magnesium	4.1 to 5.0	0.00381*	1.69 to 1.75	0.37
Mercury	94.07	0.00072	13.55	0.015
Nickel	10.7 to 12.4	0.00622*	8.60 to 8.90	0.14
Palladium	10.6 to 13.6	0.00354*	11.4	0.17
Platinum	9.0 to 15.5	0.00367*	21.2 to 21.7	0.16
Potassium	25.1	....	0.86 to 0.88	....
Silver	1.5 to 1.7	0.00377	10.4 to 10.6	1.10
Thallium	17.6 to 106	0.00398	11.8 to 11.9	....
Tin	9.53 to 11.4	0.00365	7.30	0.15
Zinc	5.56 to 6.04	0.00365	7.04 to 7.19	0.26

* Average values, for range from 0 to 100 deg. cent.

139. Tungsten.* The tungsten metal of commerce, prior to the discovery of ductile tungsten, was a very hard, dark gray powder; in some cases the metal was heated with low-carbon steel in a crucible furnace, producing the alloy known as ferro-tungsten, containing 80 to 85 per cent. of tungsten. The higher-grade alloys are produced in the electric furnace. Cast tungsten is an extremely hard brittle metal, having a specific gravity of about 18.7. In 1910 a process was announced for the production of ductile tungsten, by rolling, swaging or hammering a heated body of coherent tungsten until it becomes ductile at ordinary temperatures (*Electrical World*, Jan. 10, 1914, pp. 77, 78). The melting point is 3,100 ± 60 deg. cent.

140. Ductile tungsten is a bright, tough, steel-colored metal, which can be drawn into the finest wire. The operation of wire-drawing increases the strength; Fink stated that tungsten wire of 0.0012 in. diam. had a tensile strength from 580,000 to 610,000 lb. per sq. in., and the density increased from 18.81 before drawing, to 19.30 after drawing to 0.15 in. It retains its luster almost indefinitely. Wrought tungsten has been used as a substitute for platinum contacts in electrical apparatus, for targets or anti-

* Baskerville, C. "The Chemistry of Tungsten and the Evolution of the Tungsten Lamp;" Trans. of the New York Electrical Society; New Series, No. 1; Oct. 29, 1912.

147. Table of properties of resistor wires. (See Par. 148 to 152)
(Compiled from manufacturers' data; also, Swoboda, H. O., *The Electric Journal*, May, 1913)

Material	Composition	Resistivity at 20 deg. cent.		Temp. coef. of resistance at 20 deg. cent., per deg. cent.	Thermo-electric power with copper, micro-volts at zero deg. cent.	Density	Tensile strength (lb. per sq. in.)	Coefficient of linear expansion per deg. cent.	Maximum working temp. (deg. cent.)	Approx. melting point (deg. cent.)	Manufacturer*
		Microhm-cm.	Ohms, mil-ft.								
Copper	Cu (annealed)	1.724	10.37	0.00393		8.89	34,000	0.0000166	260	1,083	
No. 312 alloy		7.47	45.0			8.9			200		1
Platinum	Pt	9.53	57.4	0.00367		21.5	50,000	0.0000090	1,500	1,754	
Iron	Fe (annealed)	9.96	59.9								
Nickel	Ni	10.67	64.3	0.004		8.9	160,000	0.0000137	540		1
No. 300 alloy		16.6	100.			8.13			400		1
Ferro-nickel	Fe-Ni	28.2	170.	0.00207		7.8	175,000		340		1
Yankee silver	(Patented)	33.0	200.	0.000155		8.6		0.0000159	480		1
German silver	Cu-Ni(18%)-Zn	33.3	200.	0.00031	20–30	8.5	150,000	0.0000173	260	1,027	1
Nickeline II		33.9	204.	0.000168		8.4					6
Tarnac	Cu-Mn-Ni	42.0	249.	0.000025							2
Manganin	Cu-Mn-Ni	41.4 to 73.8	249. to 443.	0.000011 to 0.000039	1–2				100		1
Monel metal	Cu-Ni	42.6	256.	0.00198		8.9	160,000	0.0000138	480		1
Nickeline I		43.6	262.	0.000076	8.4						6
Therlo	Cu-Mn-Al	46.7	280.	0.0000056	0.3	8.15		0.0000194	200		1
German silver	Cu-Ni(30%)-Zn	48.2	290.	0.000200		8.5				1,160	
Advance	Copper-nickel	48.8	294.	0.000018	40.0	8.9	120,000	0.0000144	480	1,260	1
Ia Ia	Copper-nickel	49.0	295.	0.000005		8.4			370	1,230	6
Raymur	Copper-nickel	49.0	295.	0.000018		8.85					4
Constantin	Copper-nickel	50.0	300.	0.000005	40.0	9.73					8
Ideal	Copper-nickel	50.0	300.	0.000018					350	1,090	2

cent. At zero deg. cent. it has a resistivity of approximately 60,000 ohm-cm. The dielectric constant ranges from 6.1 to 7.4. It has the peculiar property that its resistivity decreases upon exposure to light; the resistivity in darkness may be anywhere from 5 to 200 times the resistivity under exposure to light. See paper by W. J. Hammer, Trans. A. I. E. E., 1903, Vol. XXI, pp. 372 to 393.

RESISTOR MATERIALS

148. German silver is an alloy of copper, nickel and zinc. It is usually listed commercially in terms of its nickel content; thus 18 per cent. wire contains 18 per cent. of nickel. The properties vary considerably with the composition. Perrine gave the following composition of three grades of German silver: 57 Cu, 12.5 Ni, 30.5 Zn; 56 Cu, 20 Ni, 24 Zn; 50 Cu, 30 Ni, 20 Zn. The resistivities were respectively in the ratio 1 : 1.25 : 2.51. Eighteen per cent. alloy has about 18 times the resistivity of copper, and 30 per cent. alloy has about 28 times the resistivity of copper. See Par. **147**.

149. Copper-manganese alloy containing either nickel or aluminum is used for resistors, and has a very low temperature coefficient. The alloy composed of copper, ferro-manganese and nickel, or copper, manganese and nickel, is known as **manganin**. The composition of manganin varies somewhat, one formula being 65 Cu, 30 Fe-Mn, 5 Ni.

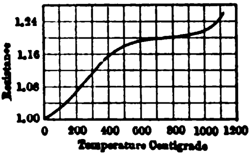

FIG. 13.—Resistance-temperature curve for nichrome.

150. Copper-nickel alloy is used extensively for resistor wires. The alloy of copper and nickel found in nature is known as Monel metal (Par. **399**). See Par. **147**.

151. Nickel-steel alloy has a very high electrical resistivity but is not as resistant to corrosion, for resistor service, as some other alloys. The nickel-chromium alloys are superior in the respect of having somewhat larger resistivity. See Par. **147**.

152. Nickel-chromium alloy is used for resistor wires where very high resistivity is desired. One alloy of this kind has a resistivity of more than 700 ohms per mil-ft. The nickel-chromium alloy known as "Nichrome" has a characteristic resistance-temperature curve of the form shown in Fig. 13.

CARBON AND GRAPHITE

153. Forms of carbon. Carbon occurs in two forms, amorphous and crystalline. The crystalline forms include **diamond** and **graphite**, the latter also being known as **plumbago**. The amorphous forms include charcoal, coke, lamp black, bone black; coal is an impure variety of amorphous carbon. The density of carbon in the diamond state is 3.47 to 3.56; graphite, 2.10 to 2.32; charcoal, 0.28 to 0.57; coke, 1.0 to 1.7; gas carbon, 1.88; lampblack, 1.7 to 1.8.

154. Resistivity. The resistivity of amorphous carbon (petroleum coke) at ordinary temperature (25 deg. cent.) may be taken as varying between 3,800 and 4,100 microhm-cm. An average value for retort carbon, such as used for electrodes in electric furnaces, at about 3,000 deg. cent., may be taken as 720 microhm-cm. Graphite at 3,000 deg. cent. has a resistivity of approximately 812 microhm-cm. Experiments by Mr. C. A. Hanson* made in the research laboratory of the General Electric Company show that the resistivity of carbon depends upon the temperature at which it is fired. As the temperature of firing increases, the resistivity decreases, approaching a constant value which is approximately the same as that of graphite. If carbon be heated above the temperature at which it was fired, its resistivity is permanently decreased, and upon cooling it will not return to its original value, but to a value corresponding to that which it would have if fired at the temperature to which it has been heated. Also see table of brush characteristics, Par. **155**, and electrode carbon, Par. **159**.

Experiments made by Morris Owen show that graphite possesses magnetic susceptibility, and under certain conditions the electrical resistivity is increased in very marked degree by magnetization.

* *Electrochem. and Met. Ind.*, Vol. VII, p. 514 (1909).

156. Resistance of arc lamp carbons. The resistance of $\frac{1}{2}$ in. × 12 in. enclosed arc carbons varies from 0.012 to 0.015 ohms per linear inch. Other sizes down to $\frac{3}{8}$ in. diameter vary according to their cross-sectional areas. The resistance of a $\frac{5}{8}$-in. diameter projector carbon varies from 0.009 to 0.011 ohms per linear inch. The $\frac{1}{2}$-in. and $\frac{9}{16}$-in. carbons vary according to their cross-sectional areas.

All high-grade forms of carbon, such as that used in the manufacture of search-light carbons and also enclosed arc carbons, may be given the value of about 0.002 ohms per cu. in. Flame-arc carbon material such as is used in the homogeneous electrodes varies from 0.004 to 0.006 ohms per cu. in. All the above values are for ordinary room temperatures.

157. Temperature coefficient of resistance. Carbon exhibits a decreasing electrical resistivity and a decreasing thermal resistivity with rising temperature. Graphite exhibits but little change in electrical resistivity, tending downward with rising temperature, but its thermal resistivity increases slightly with rising temperature. The coefficients vary over a considerable range; see Landolt and Bornstein, "Physikalish-Chemische Tabellen," 1912.

158. Resistances of carbon contacts vary with pressure, current and time. See results of investigation published by A. L. Clark in the *Physical Review*, Jan., 1913.

159. Electrode properties of carbon and graphite were given by Hering in his paper, "The Proportioning of Electrodes for Furnaces" (Trans. A. I. E. E., Vol. XXIX, 1910, pp. 485–545), from experimental determinations. The table below is abstracted from Table I in Hering's paper above mentioned; the paper itself gives elaborate details and many curves. Other papers by Hering on this general subject are noted below.*

Material	Furnace temp. (deg. cent.)	Temp. drop (deg. cent.)	Electrical resistivity, ohm (in-cube)	Thermal conductivity, †watts (in-cube)
Carbon......	20.0	0.0	0.00181	....
	360.0	260.0	166	0.95
	751.0	651.0	150	1.32
	942.0	842.0	148	1.38
Graphite.....	20.0	0.0	0.000337	....
	389.6	289.6	330	3.60
	546.1	446.1	324	3.45
	720.2	620.2	316	3.26
	913.9	813.9	323	3.10

† 1 watt = 0.2389 g-cal. per sec.; 1 g-cal. per sec. = 4.186 watts.

SKIN EFFECT

160. Skin effect is briefly defined in Sec. 2. Also see Sec. 12, Par. 41.

161. Formulas and tables for skin effect. If R' is the effective resistance of a linear cylindrical conductor to sinusoidal alternating current of given frequency and R is the true resistance with continuous current, then

$$R' = KR \qquad \text{(ohms)} \qquad (13)$$

where K is determined from the table in Par. 165, in terms of x. The value of x is given by

$$x = 2\pi a\sqrt{\frac{2f\mu}{\rho}} \qquad (14)$$

* "Laws of Electrode Losses in Electric Furnaces;" *Trans.* A. E. S., Vol. XVI, 1909.
"Empirical Laws of Furnace Electrodes;" *Trans.* A. E. S., Vol. XVII, 1910.
"The Design of Furnace Electrodes;" *Electrical World*, June 16, 1910.

10, 1914). In No. 12 B.W.G. iron wire (B. B. grade), at 800 cycles per sec., and with currents of telephonic magnitude, the increase in resistance was found by measurement to be 47 per cent. See Par. 203.

164. Effect of very high frequencies on iron has been investigated by E. F. W. Alexanderson; see "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles," *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 2433–2454. He concluded that the permeability is unaffected by the frequency. In applying Steinmetz's formula for skin effect (see "Transient Electric Phenomena and Oscillations," New York, 1909), he recommended using average constants as follows: permeability, 2,250 and conductivity, 0.9×10^5, for soft iron.

165. Table of constants for skin-effect formulas

x	*K*	*K'*	*x*	*K*	*K'*	*x*	*K*	*K'*
0.0	1.00000	1.00000	4.0	1.67787	0.68632	12.5	4.67993	0.22567
0.1	1.00000	1.00000	4.1	1.71516	0.67135	13.0	4.85631	0.21703
0.2	1.00001	1.00000	4.2	1.75233	0.65677	13.5	5.03272	0.20903
0.3	1.00004	0.99998	4.3	1.78933	0.64262	14.0	5.20915	0.20160
0.4	1.00013	0.99993	4.4	1.82614	0.62890	14.5	5.38560	0.19468
0.5	1.00032	0.99984	4.5	1.86275	0.61563	15.0	5.56208	0.18822
0.6	1.00067	0.99966	4.6	1.89914	0.60281	16.0	5.91509	0.17649
0.7	1.00124	0.99937	4.7	1.93533	0.59044	17.0	6.26817	0.16614
0.8	1.00212	0.99894	4.8	1.97131	0.57852	18.0	6.62129	0.15694
0.9	1.00340	0.99830	4.9	2.00710	0.56703	19.0	6.97446	0.14870
1.0	1.00519	0.99741	5.0	2.04272	0.55597	20.0	7.32767	0.14128
1.1	1.00758	0.99621	5.2	2.11353	0.53506	21.0	7.68091	0.13456
1.2	1.01071	0.99465	5.4	2.18389	0.51566	22.0	8.03418	0.12846
1.3	1.01470	0.99266	5.6	2.25393	0.49764	23.0	8.38748	0.12288
1.4	1.01969	0.99017	5.8	2.32380	0.48086	24.0	8.74079	0.11777
1.5	1.02582	0.98711	6.0	2.39359	0.46521	25.0	9.09412	0.11307
1.6	1.03323	0.98342	6.2	2.46338	0.45056	26.0	9.44748	0.10872
1.7	1.04205	0.97904	6.4	2.53321	0.43682	28.0	10.15422	0.10096
1.8	1.05240	0.97390	6.6	2.60313	0.42389	30.0	10.86101	0.09424
1.9	1.06440	0.96795	6.8	2.67312	0.41171	32.0	11.56785	0.08835
2.0	1.07816	0.96113	7.0	2.74319	0.40021	34.0	12.27471	0.08316
2.1	1.09375	0.95343	7.2	2.81334	0.38933	36.0	12.98160	0.07854
2.2	1.11126	0.94482	7.4	2.88355	0.37902	38.0	13.68852	0.07441
2.3	1.13069	0.93527	7.6	2.95380	0.36923	40.0	14.39545	0.07069
2.4	1.15207	0.92482	7.8	3.02411	0.35992	42.0	15.10240	0.06733
2.5	1.17538	0.91347	8.0	3.09445	0.35107	44.0	15.80936	0.06427
2.6	1.20056	0.90126	8.2	3.16480	0.34263	46.0	16.51634	0.06148
2.7	1.22753	0.88825	8.4	3.23518	0.33460	48.0	17.22333	0.05892
2.8	1.25620	0.87451	8.6	3.30557	0.32692	50.0	17.93032	0.05656
2.9	1.28644	0.86012	8.8	3.37597	0.31958	60.0	21.46541	0.04713
3.0	1.31809	0.84517	9.0	3.44638	0.31257	70.0	25.00063	0.04040
3.1	1.35102	0.82975	9.2	3.51680	0.30585	80.0	28.53593	0.03535
3.2	1.38504	0.81397	9.4	3.58723	0.29941	90.0	32.07127	0.03142
3.3	1.41999	0.79794	9.6	3.65766	0.29324	100.0	35.60666	0.02828
3.4	1.45570	0.78175	9.8	3.72812	0.28731	∞	∞	0
3.5	1.49202	0.76550	10.0	3.79857	0.28162			
3.6	1.52879	0.74929	10.5	3.97477	0.26832			
3.7	1.56587	0.73320	11.0	4.15100	0.25622			
3.8	1.60314	0.71729	11.5	4.32727	0.24516			
3.9	1.64051	0.70165	12.0	4.50358	0.23501			

gausses, after which the permeability decreases below that of soft iron, while the iron loss begins to increase rapidly. See also Ruder, W. E., "The Effect of Chemical Composition upon the Magnetic Properties of Steels;" *General Electric Review*, March, 1915, pp. 197 to 203.

174. Effect of carbon. Carbon increases the resistivity, decreases the permeability, lowers the saturation point and increases the coercive force and the retentivity. Concurrently the hysteresis loop is broadened and its area increased. These effects are greater in hardened steel than in soft or annealed material. In slowly cooled iron-carbon alloys the carbon exists as pearlite up to the eutectoid point (about 0.85 carbon); above this point the carbon exists as cementite (Fe_3C). The cementite carbon diminishes the conductivity less than does the pearlite carbon. At a quenching temperature of 850 deg. cent. the limit of dissolved carbon is about 1.4 per cent.; no excess of carbon above 1.4 is soluble at this temperature.

175. Effect of manganese. Very small proportions of manganese are not injurious in any substantial degree, but it is customary to limit the proportion of manganese as much as practicable. The true effect of small proportions of manganese is difficult to determine because of its association in most cases with carbon. See *Jour.* I. E. E., April, 1911, Vol. XLVI, No. 206, pp. 263 to 266. When the manganese content reaches 12 per cent. the steel becomes practically non-magnetic.

176. Effects of silicon and aluminum. The researches of Barrett, Brown and Hadfield (1900 and 1902) established the fact that the only magnetic alloys superior to the purest commercial iron are the alloys of iron with silicon, and with aluminum. The best silicon alloy contained 2.5 per cent. of silicon, and the best aluminum alloy contained 2.25 per cent. of aluminum.

	Maximum permeability	ℬ for maximum permeability	Hysteresis loss, ergs per cu. cm. per cycle for ℬ (max) = 9,000	Coercive force for ℬ (max) = 17.700
Swedish charcoal iron.....	2,100	4,000	2,334	1.10
2.5 per cent. silicon......	5,000	4,000	1,549	0.80
2.25 per cent. aluminum..	5,400	5,000	1,443	0.80

Guggenheim has shown (Elek. Kraft U. Bahnen, Sept. 24, 1910), for iron containing 0.2 per cent. of carbon, that silicon in quantities up to 1.8 per cent. decreases the permeability, but from 1.8 to 5 per cent. it improves the permeability and decreases the hysteresis loss; for ℬ(max) = 10,000 in sheets 0.5 mm. thick the hysteresis loss was 2,910 ergs per cu. cm. per cycle, for best silicon steel, compared with 6,000 ergs for ordinary sheet iron.

For electrical and mechanical effects of silicon and aluminum, see appropriate portions of this section.

177. Effect of nickel. The addition of nickel, up to 2 per cent., causes little change in magnetic quality (Burgess and Aston). A higher nickel content rapidly decreases the permeability. At 25 to 30 per cent. nickel the magnetic properties are greatly impaired, but improve again upon a further increase in nickel.

178. Effects of tungsten, chromium and molybdenum. These elements have the general property of increasing the magnetic hardness and particularly the coercive force, making a very desirable steel for permanent magnets. See "Magnet Steel," Par. **225** to **230**.

179. Effects of arsenic and tin. These elements are similar in their effects to silicon and aluminum, increasing the resistivity and reducing the hysteresis loss. Tin increases the permeability at higher inductions and decreases the hysteresis loss even more than silicon.

180. Sulphur, phosphorus and oxygen are in general injurious in their effects, even in small percentages.

heated for 27 days at 50 deg. cent.; 53 per cent. when heated for 25 days at 65 deg. cent.; 89 per cent. when heated for 25 days at 87 deg. cent.; 140 per cent. when heated for 25 days at 135 deg. cent. Also see Mordey, W. M., *Proc.* Roy. Soc., June, 1895; also see aging tests in "Electric Machine Design," by Parshall and Hobart; Allen, T. S., "The Comparative Aging of Electric Sheet Steels;" *Electrical World*, 1908, Vol. LII, p. 579.

187. Non-aging steel. Silicon-steel, aside from having low hysteresis and high resistivity, also possesses the valuable property of being non-aging. That is to say, its magnetic properties are not impaired by prolonged heating at moderate temperatures, but on the contrary may be slightly improved. While as much as 3 to 4 per cent. of silicon is present in silicon-steel, it is also useful, in much smaller quantities, in improving the aging qualities of low-carbon steel. Parshall and Hobart recommend ("Electric Machine Design," p. 36) the following composition for sheet steel having good aging qualities: carbon, 0.06; manganese, 0.50; silicon, 0.01; sulphur, 0.03; phosphorus, 0.08.

188. Effects of mechanical stress on magnetization. Ewing states (Chap. IX, "Magnetic Induction in Iron and Other Metals") that the presence of any moderate amount of longitudinal pull increases the susceptibility when the magnetism is weak, but reduces it when the magnetism is strong. With hardened metal the effects of stress are in general much greater than with annealed metal.

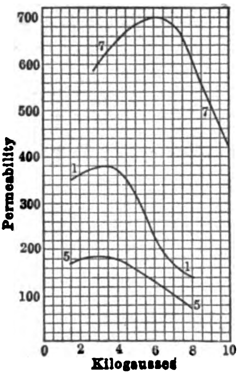

FIG. 19.—Induction-permeability curves of cast iron and malleable iron.

189. Page effect is the faint metallic sound resembling a light blow which is heard when a piece of iron is suddenly magnetised or demagnetised.

190. Cast iron is magnetically inferior to wrought iron or low steel, but is used to a limited extent on account of the facility with which it can be molded into complex forms. The permeability is decreased by the presence of carbon, the effect being in the ratio of combined to graphitic carbon. Cast iron of good magnetic quality contains from 3 to 4.5 per cent. carbon, of which from 0.2 to 0.8 per cent. is in the combined form. A normal induction curve for cast iron is given in Fig. 18. Curve 1 in Fig. 19 applies to cast iron containing 0.195 combined carbon, 3.29 graphitic carbon, 2.01 silicon, 0.320 manganese, 0.988 phosphorus and 0.08 sulphur. Curve 5 is for cast iron containing 0.72 combined carbon, 2.07 silicon, 0.38 manganese, 0.85 phosphorus and 0.035 sulphur.

Silicon and aluminum in small proportions make the casting more homogeneous and tend to reduce the combined carbon. Silicon tends also to counteract sulphur.

191. Malleable cast iron is magnetically superior to cast iron, being lower in combined carbon and improved by the heat treatment which it receives. Curve 7 in Fig. 19 is for malleable cast iron (see Parshall and Hobart, "Electric Machine Design") containing 0.83 combined carbon, 2.201 graphitic carbon, 0.93 silicon, 0.116 manganese, 0.039 phosphorus and 0.080 sulphur.

192. Wrought iron is among the best of magnetic materials from the standpoint of permeability, but has higher core losses than silicon steel. See Par. 200 comparing Swedish iron with other materials.

193. Rolled steel of the low-carbon variety is used very extensively in the form of electrical sheets and rods. A normal induction curve is shown in Fig. 18. Commercial sheets are described in Par. 217 to 224.

194. Cast steel is extensively used for those portions of magnetic circuits which carry uniform or continuous flux and need superior mechanical strength. Parshall and Hobart state ("Electric Machine Design," p. 22) that cast steel of good magnetic qualities should be limited in its composition as follows: combined carbon, 0.25; silicon, 0.20; manganese, 0.50; phosmagnetism (Hadfield, Sir R. A. and Hopkinson, B., "The Magnetic Properties of Iron and Its Alloys in Intense Fields," *Jour.* I. E. E., April, 1910, Vol. XLVI, pp. 235-306). The intensity of magnetisation is defined as the quantity J in the formula $\mathcal{B} = \mathcal{H} + 4\pi J$, or the magnetic moment per unit of volume.

Every alloy which they examined was found to have a definite saturation intensity of magnetism, which they termed the **specific magnetism.** This intensity was reached in most cases in a field of 5,000 units. The specific magnetism of commercially pure iron of density 7.80 was found to be 1,680 within 1 per cent. The presence of carbon in annealed iron-carbon steel reduces the specific magnetism by a percentage equal to six times the percentage of carbon, if other elements are present only in small proportions. No alloy was noted having a higher specific magnetism than pure iron. Quenching an iron-carbon alloy from a high temperature reduces its specific magnetism by a large but uncertain amount. The addition of silicon or aluminum to iron reduces the specific magnetism roughly in proportion to the amount added; but if carbon is present, silicon seems to neutralize it to some extent.

200. Comparisons of magnetic materials

(T. D. Yensen, Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914)

Material	Carbon content (per cent.)	Max. permeability	Flux density for max. permeability	Hysteresis loss in ergs per cu. cm. per cycle		Coercive force for $\mathcal{B}$ (max.) = 15,000	Retentivity for $\mathcal{B}$ (max.) = 15,000	Resistivity at 20 deg. cent. (microhm-cm.)
				$\mathcal{B}$ (max.) = 10,000	$\mathcal{B}$ (max.) = 15,000			
Swedish charcoal iron cut from plate.	0.163	4,870	6,600	2,490	4,530	0.95	8,000	10.57
Standard transformer steel.	......	3,850	7,000	3,320	5,910	1.33	9,900	11.09
Four per cent. silicon steel.	......	3,400	4,300	2,260	3,030	0.88	5,400	51.15
Swedish charcoal iron remelted *in vacuo.*	0.008	10,350	7,000	1,290	2,640	0.48	11,200	10.30
Electrolytic iron melted *in vacuo.*	0.0125	12,950	6,550	1,060	1,990	0.34	9,940	9.96

201. Formula for induction-permeability curve. A. S. McAllister has shown that the induction-permeability curve can be expressed with a fair degree of accuracy by an equation of the form

$$\mu = 2{,}800 - 3.2\left[\frac{(7{,}500 - \mathcal{B})^2}{10^6}\right] \qquad (17)$$

The constants in this equation hold for the ordinary grades of sheet iron, between the limits $\mathcal{B} = 0$ and $\mathcal{B} = 15{,}000$, where $\mathcal{B}$ is the maximum instantaneous value. The numerical constants take different values for cast iron, cast steel, silicon steel, etc. See McAllister, "Alternating-current Motors," New York, 1909, p. 137.

202. Permeability in weak fields. Ewing gives the permeability in very weak fields, with values of $\mathcal{H}$ less than unity, according to the following formula based on investigations by Baur.

$$\mu = 183 + 1{,}382\mathcal{H} \qquad (18)$$

This applies to soft iron. Lord Rayleigh found for harder grades of iron,

$$\mu = 81 + 64\mathcal{H} \qquad (19)$$

208. Hysteresis coefficients in Steinmetz's formula $W_h = \eta f B^{1.6}$ are given in Par. **207** (Lloyd, M. G., "Magnetic Hysteresis," Journal of the Franklin Institute, July, 1910, pp. 1–25). In this formula W_h is the loss in ergs per cu. cm. per sec., f is the frequency in cycles per sec., $\mathfrak{B}$ is the maximum induction and is here 10,000 gausses, and η is the hysteresis coefficient. The exponent of $\mathfrak{B}$, which is 1.6, departs widely from this value at very low and very high densities.

209. Total core losses for sheets are given in Fig. 29. Lloyd and Fisher give the following total core losses, in watts per lb. at 60 cycles and 10,000 gausses, for No. 29 gage (3.57 mm.): unannealed, 3.18 to 4.76; annealed, 1.25 to 2.36; silicon steel, 0.665 to 1.06. See *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 465. Also see Sec. 7, Par. **214.**

210. Effect of wave form upon hysteresis loss. Dr. M. G. Lloyd, in his paper entitled "Dependence of Magnetic Hysteresis upon Wave Form" (Bulletin of the Bureau of Standards, Vol. V, No. 3, Feb. 1909, pp. 381–411), reached the following conclusions.

"For a definite maximum value of the flux density, the hysteresis is greater with a flat wave of flux, but the effect is small, and from the industrial standpoint negligible, even with very distorted waves. If, however, the wave of flux is dimpled, the hysteresis may be much increased.

"The hysteresis determined by the ballistic method may be smaller than that which obtains with the use of alternating current, but the differences are small.

"The separation of hysteresis and eddy-current losses by means of runs at two frequencies, using the Steinmetz formula, is not accurate, but is a close approximation when the sheets are thin."

211. Effect of form-factor upon the iron loss was investigated by Dr. M. G. Lloyd (see "Effect of Wave Form upon the Iron Losses in Transformers," Bulletin of the Bureau of Standards, Vol. IV, No. 4, 1907; also Reprint No. 88), who reached the following conclusions.

"With a given effective electromotive force the iron losses in a transformer depend upon the form-factor of the e.m.f., and vary inversely with it. By proper design of the generator supplying transformers, the iron losses may be reduced to a minimum."

212. Effect of unsymmetrical periodic cycles on hysteresis loss. Mr. M. Rosenbaum in a paper entitled "Hysteresis Loss in Iron, Taken Through Unsymmetrical Cycles of Constant Amplitude," before the I. E. E. (see *Jour.* I. E. E., Mar., 1912), presented the following conclusions.

"It is seen that the hysteresis loss increases very appreciably as direct-current magnetisation is superposed on the alternating flux. This phenomenon manifests itself in practice in inductor alternators and static balancers. In some kinds of inductor alternators the flux does not reverse, but oscillates between positive maximum and positive minimum values, thus the iron loss per cu. cm. is much greater in inductor alternators than in the ordinary type for the same change of flux in the armature coil. In static balancers this effect also takes place where the direct-current magnetisation is not neutralised. It is therefore important, if high efficiency be aimed at, to neutralise the direct-current flux."

SHEET GAGES

213. Two systems of gaging sheets are in use, the U. S. Standard Gage and the Decimal Gage. These two gages are fully covered in the two succeeding paragraphs. Also see Par. **30.**

214. An act establishing a standard gage for sheet and plate iron and steel. *Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,* That for the purpose of securing uniformity, the following is established as the only standard gage for sheet and plate iron and steel in the United States of America, namely: (See Par. **215.**) And on and after July 1, 1893, the same and no other shall be used in determining duties and taxes levied by the United States of America on sheet and plate iron and steel. But this act shall not be construed to increase duties upon any articles which may be imported.

Sec. 2. That the Secretary of the Treasury is authorized and required to prepare suitable standards in accordance herewith.

Sec. 3. That in the practical use and application of the standard gage hereby established a variation of 2.5 per cent. either way may be allowed.

Approved, March 3, 1893.

215. U. S. standard sheet gage.—*Continued*

Number of gage	Approximate thickness in fractions of an inch	Approximate thickness in decimal parts of an inch	Approximate thickness in millimeters	Weight per square foot in ounces avoirdupois	Weight per square foot in pounds avoirdupois	Weight per square foot in kilograms	Weight per square meter in kilograms
19	7-160	0.043(75)	1.11(125)	28	1.75	0.79(88)	8.5(44)
20	3-80	0.0375	0.95(25)	24	1.50	0.68(04)	7.3(24)
21	11-320	0.0343(75)	0.87(3125)	22	1.37(5)	0.62(37)	6.7(13)
22	1-32	0.0312(5)	0.79(3750)	20	1.25	0.56(7)	6.1(03)
23	9-320	0.0281(25)	0.71(4375)	18	1.12(5)	0.51(03)	5.4(93)
24	1-40	0.025	0.63(5)	16	1.0	0.45(36)	4.8(82)
25	7-320	0.0218(75)	0.55(5625)	14	0.87(5)	0.396(9)	4.2(72)
26	3-160	0.0187(5)	0.47(625)	12	0.75	0.340(2)	3.66(2)
27	11-640	0.0171(875)	0.43(65625)	11	0.68(75)	0.311(9)	3.35(7)
28	1-64	0.0156(25)	0.396(875)	10	0.62(5)	0.283(5)	3.05(2)
29	9-640	0.0140(625)	0.357(1875)	9	0.56(25)	0.255(1)	2.74(6)
30	1-80	0.0125	0.317(5)	8	0.5	0.226(8)	2.44(1)
31	7-640	0.0109(375)	0.277(8125)	7	0.43(75)	0.198(4)	2.13(6)
32	13-1280	0.0101(5625)	0.257(96875)	6½	0.40(625)	0.184(3)	1.98(3)
33	3-320	0.0093(75)	0.238(125)	6	0.375	0.170(1)	1.83(1)
34	11-1280	0.0085(9375)	0.218(28125)	5½	0.343(75)	0.155(9)	1.67(8)
35	5-640	0.0078(125)	0.198(4375)	5	0.312(5)	0.141(7)	1.52(6)
36	9-1280	0.0070(3125)	0.178(59375)	4½	0.281(25)	0.127(6)	1.37(3)
37	17-2560	0.0066(40625)	0.168(671875)	4¼	0.265(625)	0.120(5)	1.29(7)
38	1-160	0.0062(5)	0.158(75)	4	0.25	0.113(4)	1.22(1)

NOTE.—Numbers within parentheses represent higher precision than the tolerance limit of plus or minus 2.5 per cent.

rotors and stators. **The Transformer grade is used very extensively in transformer cores.**

Curves of average induction, permeability and hysteresis in these three grades are given in Figs. 20 to 25.

220. Aging of sheets. The American Sheet and Tin Plate Company reports the following results of aging tests on their commercial sheets (Par. 219). Exposure to a temperature of 100 deg. cent. for 30 days resulted (on

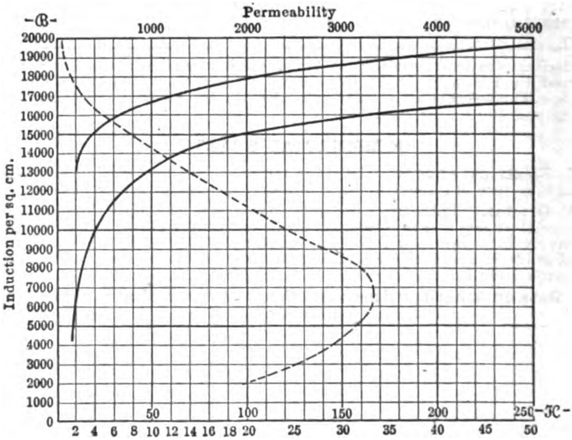

Fig. 20.—Average induction and permeability curves, "Regular Dynamo and Motor Sheets" (A. S. & T. P. Co.).

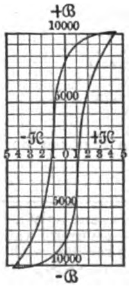

Fig. 21.—Average hysteresis loop, "Regular Dynamo and Motor Sheets" (A. S. & T. P. Co.).

the average of a number of samples of each grade) in a small increase in the iron loss (not exceeding 10 per cent.) in the Regular grade, a very slight increase in the iron loss of the Special grade, and a slight decrease in the iron loss of the Transformer grade.

221. Effect of mechanical working on sheets. The only working the material receives is punching and compression in the finished core. The

224. Curves of total core losses in electrical sheets are given in Fig. 29, taken from the article on "Transformers," by Dr. A. S. McAllister in the 3rd edition of the Standard Handbook.

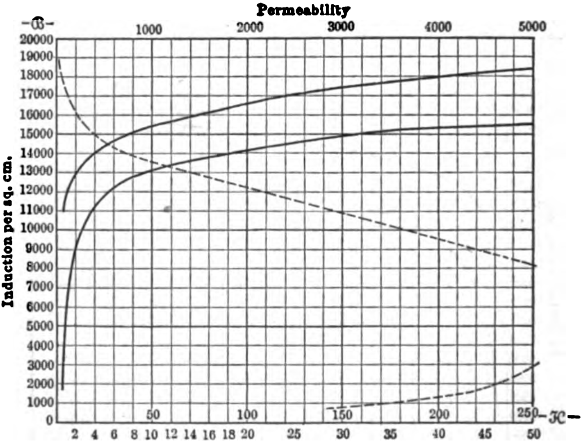

Fig. 24.—Average induction and permeability curve, "Transformer Sheets" (A. S. & T. P. Co.).

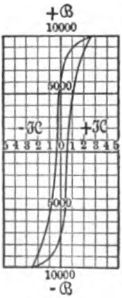

Fig. 25.—Average hysteresis loop, "Transformer Sheets" (A. S. & T. P. Co.).

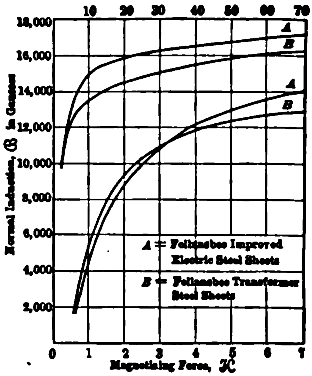

Fig. 26.—Normal induction curves of Follansbee steel sheets.

MAGNET STEEL

225. Desired characteristics in permanent magnets are maximum retentivity, coercive force, and permanence or non-aging characteristic. These characteristics are best obtained in carbon steel and certain alloy steels hereafter mentioned.

retentivity of carbon steel. The hardness tests were made with a 10-mm. Brinnell ball and a pressure of 3,000 kg. The retentivity increases with the carbon content and hardness up to a point where further increase in carbon is not accompanied by increase in hardness, then the retentivity decreases due to displacement of effective iron by the carbon. Similar experiments with various alloy steels give results shown in Par. 230.

228. Tungsten magnet steel ordinarily contains about 5 per cent. of tungsten. One satisfactory magnet steel analyzed 5.47 per cent. of tungsten, 0.57 per cent. of carbon, 0.18 per cent. of silicon, and 0.26 per cent. of manganese. Tungsten-vanadium magnet steel analyses about 7.00 per cent. of tungsten, 0.30 per cent. of vanadium, and 0.60 per cent. of carbon.

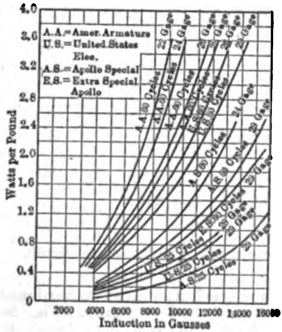

Fig. 29.—Curves of total core losses in electrical sheets.

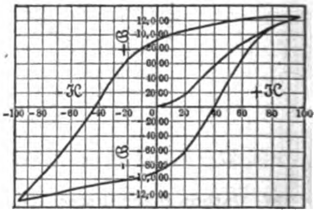

Fig. 30.—Hysteresis loop of glass-hard steel wire.

The addition of tungsten to steel increases the coercive force, and according to Hopkinson, the value of the coercive force in tungsten steel may exceed 50 (Ewing, J. A. "Magnetic Induction in Iron and Other Metals;" London, 1900; 3rd rev. ed., p. 83). Comparative tests of four tungsten steels containing respectively 3, 6, 8 and 12 per cent. of tungsten, quenched from 900 deg. cent., showed remarkably similar results and indicated that a high percentage of tungsten is unnecessary. In fact as much as 12 per cent. may produce inferior results (see Moir, M. B. *Philosophical Magazine*, Nov., 1914). Also see Sec. 5.

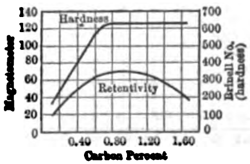

Fig. 31.—Hardness and retentivity of carbon-steel.

229. Chrome magnet steel. According to Hopkinson the addition of chrome to oil-tempered steel may increase the coercive force to as much as 40 (see *Philosophical Transactions*, 1885). Chrome-steels containing upward of 8 per cent. of chromium possess superior permanency compared with tungsten steels, but are inferior in magnetic intensity (see Moir, M. B. *Philosophical Magazine;* Nov., 1914).

Class C. This is represented by fireproof, or heat-proof materials, such as mica, so assembled that very high temperatures do not produce rapid deterioration. Such materials are used in rheostats and in the heating elements of heating appliances, etc.

The temperature limits specified by the A. I. E. E. Standardization Rules (Sec. 24, Par. 188) are as follows:

(*A*-1) Cotton, silk, paper and other fibrous materials, not so treated as to increase the temperature limit, 95 deg. cent.

(*A*-2) Same as *A*-1, but treated or impregnated, and including enameled wire, 105 deg. cent.

(*B*) Mica, asbestos or any other material capable of resisting high temperature, in which any class *A* material or binder, if used, is for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities, 125 deg. cent.

(*C*) Fireproof and refractory materials, no specified limit.

235. Physical Classification of Dielectrics

- Dielectrics
  - Solids
    - Natural: Gums and resins; Asbestos; Wood; Soapstone; Slate; Marble; Lava; Mica
    - Fabricated: Papers and sheets; Fabrics and yarns; Hard rubber; Synthetic resins; Molded compositions; Glass; Vitrified materials
  - Plastics: Caoutchouc; Gutta percha; Pitches; Asphalts; Waxes; Compounds
  - Liquids
    - Used as such: Mineral oil; Animal oil; Vegetable oil
    - Solidified on application: Varnish; Shellac; Paint; Enamel; Japan
  - Gases: Atmospheric air; Hydrogen; Nitrogen; Carbon dioxide

236. Classification of dielectrics according to type of application. Under this classification can be named: (1) Wire insulation; (2) cable insulation; (3) insulating supports, combining dielectric properties with mechanical strength; (4) coil and slot insulation for electrical apparatus and machinery; (5) insulating sheets, slabs and barriers; (6) molded insulation, shaped under the application of heat and mechanical pressure; (7) impregnating and filling compounds; (8) superficial paints and varnishes; (9) fluid insulators; (10) gaseous insulators.

237. Use of trade names in connection with insulating materials has unfortunately become very common. On account of the great number of such names no attempt has been made to state or define them all. Wherever feasible, insulating materials have been grouped and described in accordance with a rational classification, and adhering if possible to the natural or descriptive name of each thing instead of its trade name.

241. Surface insulation resistance. The surface conductivity is the reciprocal of the surface resistivity, and the **surface resistivity** is the resistance between two opposite edges of a surface film which is 1 cm. square. Since for most materials under ordinary conditions of humidity the surface resistivity is much lower than the volume resistivity, the resistance per centimeter length between two linear conductors 1 cm. apart, pressed upon the surface of a slab of the material, is approximately equal to the surface resistivity.

The relationship between surface resistivity and humidity, for a number of different materials, is given in Fig. 32. These curves are generally typical of solid dielectrics. The surface resistivity is often a million times as great at low humidity as at high humidity. Measurements made on various molded compositions at the Bureau of Standards (Scientific Paper No. 234) gave values ranging from 10^{10} to 10^{17} ohm-cm. (between opposite edges of a film 1 cm. square), at 22 deg. cent.

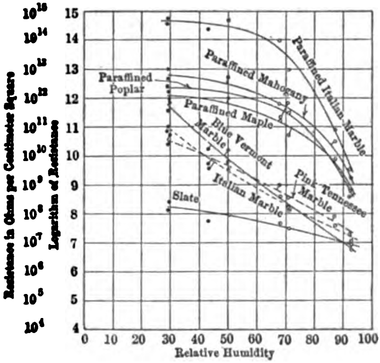

FIG. 32.

242. Dielectric constant is defined in Sec. 2. The customary medium of reference is almost universally dry air at normal temperature and pressure. For most materials the temperature coefficient is positive, but for india-rubber it appears to be negative at ordinary temperatures. The coefficient for celluloid at 15 deg. cent. is approximately 0.005 per deg. cent., whereas for mica it is about 0.0006.

243. Dielectric absorption is the term applied to the apparent soaking up of electric charge within the body of a dielectric when the electric stress is prolonged for an appreciable time. In other words, it requires appreciable time for the dielectric to become fully saturated with electric charge or displacement, when a steady stress is applied. In some materials this phenomenon is marked, while in others it is slight. Due allowance should be made for it, however, in certain classes of measurements, notably insulation resistance.

244. Dielectric strength, usually expressed in volts or kilovolts (kv.) per mil or per mm.,* is a property which it is impossible to determine with high precision, and which is affected by numerous variables such as the size and shape of the test electrodes, the time rate at which the test voltage is raised to the disruptive point, the order of frequency of the test voltage and the thickness of the test specimen. Furthermore, disruptive discharge requires not merely a sufficiently high voltage, but a certain minimum amount of energy. There is no accepted standard apparatus or method for testing dielectrics, and hence the results obtained by different investigators are comparable only as to general order of magnitude, if at all. Moreover the probable error in measurements of disruptive strength is unusually large and any one set of observations is likely of itself to be in error by as much as plus or minus 10 to 20 per cent. Consequently the values of disruptive strength stated in this section are to be considered as purely approximate and not accurately comparative.

245. The factors affecting dielectric strength may be stated as follows; internal or external heating, chemical change, absorption of moisture,

* 1 volt per mil = 39.4 volts per mm.
1 volt per mil = 0.394 kv. per cm.
1 volt per mm. = 0.0254 volt per mil.
1 kv. per cm. = 2.54 volts per mil.

before breakdown occurs is sometimes referred to as the dielectric spark lag. A good illustration of the comparative effects of slow versus fast rate of application of the disruptive voltage is given by Creighton for porcelain (see *Proc.* A. I. E. E., May, 1915, p. 818, Fig. 28). Also see Hayden and Steinmetz, "Disruptive Strength with Transient Voltages;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1125 to 1158. Fig. 33 shows typical curves (plotted from Rayner's 1912 paper, *Jour.* I. E. E.) of disruptive voltage with respect to the time required for puncture.

251. Dielectric hysteresis is a form of energy loss in dielectrics, and is independent of any loss due to pure conduction. The latter loss is expressed by gE^2, where g is the total conductance in mhos of a given body of dielectric and E is the impressed difference of potential in effective volts, the power loss given thereby being expressed in watts. The **static component** of dielectric hysteresis probably is proportional to the 1.6th power of the maximum dielectric flux density. The **viscous component** of dielectric hysteresis follows the square law. The latter component is probably the predominating one, since experimental evidence* from condenser tests with alternating currents goes to show that the angle of phase difference due to hysteresis is a constant, for any particular condenser. It follows from this that the power loss in the dielectric is proportional to the square of the flux density and the square of the frequency, which corresponds to the viscous component of hysteresis. As a rule these electrostatic hysteresis losses in a condenser are much smaller than the losses occasioned by magnetic hysteresis and are rather difficult to measure. Frequently they amount to no more than a fraction of 1 per cent. of the volt-ampere input of the condenser, at frequencies from 25 to 125 cycles. See Rayner, E. H., "High-voltage Tests and Energy Losses in Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 214, pp. 3 to 89; also see Fleming and Dyke, "On the Power-factor and Conductivity of Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 215, pp. 323 to 431.

252. Dielectric power-factor. When a dielectric is subjected to a periodic alternating e.m.f. less than the disruptive value there is a loss or expenditure of energy within the dielectric from two causes: (1) the leakage conduction current, (2) the dielectric hysteresis. Consequently, the volt-ampere input to the dielectric, instead of having a zero power-factor as in the case of the ideal dielectric of infinite resistance and zero hysteresis, has a power-factor of finite value but usually small magnitude. This total dielectric loss may, in some cases, have considerable importance. Fleming and Dyke* made tests on eleven different materials at 920, 2,760 and 4,600 cycles, and found that the power-factor was less than 1 per cent. in the case of dry Manila paper, paraffin wax, mica, ebonite, pure india-rubber, vulcanised india-rubber and sulphur; about 2 per cent. for glass and gutta percha; and 8 per cent. for dry slate.

253. Effects of temperature. If a dielectric contains moisture, the application of heat will reduce the moisture content and simultaneously increase the resistivity and the disruptive voltage. In the case of a thoroughly dry substance, however, increase of temperature has the reverse effect. Prolonged heating of a dielectric, if in excess of the safe or conservative limit of working temperature, is injurious and tends to hasten the breakdown of the material by disintegration or chemical change, and ensuing disruptive failure. Except in the case of fireproof and refractory materials, the working temperature is a most important factor in determining the life of insulation. See Par. **234** and also see the temperature limits specified in the Standardisation Rules of the A. I. E. E., Sec. 24, Par. **187** to **200**.

SOLID NATURAL MATERIALS

254. Asbestos is a mineral fibre comprised of hydrous silicate of magnesia, which melts at a temperature in the range from 1,200 to 1,300 deg. cent. It is useful as an insulating material because of its heat-resisting qualities and is fabricated into boards, paper, tape, etc., frequently in combination with a binder to make it stronger mechanically and less absorbent of moisture. It is not inherently a good insulator, and for this reason is frequently mixed with other fibres or loading material to impart greater strength, higher insulation and better finish. The commercial varieties of asbestos often

* Steinmetz, C. P. "Alternating-current Phenomena;" New York, McGraw-Hill Book Co., Inc., 1908: 4th ed., pp. 212 and 213.

switchboard panels. Its properties can be improved by treatment in molten paraffin wax or linseed oil, after all moisture has been expelled, but such treatment results in discoloration. The resistivity is on the order of 10^2 to 10^4 megohm-cm. and the disruptive voltage is in the vicinity of 50 to 100 volts per mil. See tests in Par. **269.**

264. Mica is generally recognized as the most superior insulating material known to the art, that which is imported from India being the best, the Canadian grades next and domestic varieties last. Either domestic or India mica is satisfactory for nearly all insulating purposes except for commutators, where it is too hard to wear down as fast as the copper bars. For the latter service Canadian amber mica is considered more satisfactory, being softer than the other grades. All grades of muscovite (white) mica are considered suitable for electric heating appliances. Mica sheets and washers are used in electrical apparatus and appliances in almost innumerable shapes. Cut mica in sheets becomes very expensive in the larger sizes, the largest commercial listed size being 8 in. by 10 in. On this account it is customary to build up larger sizes by connecting together thin layers of mica. Such manufactured mica plate takes a number of forms.

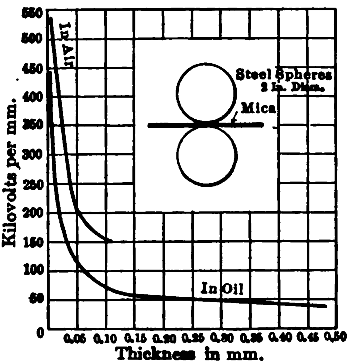

FIG. 34.—Disruptive strength of mica in air and in oil.

265. Composition and properties of mica. Mica is a refractory mineral constituted of the double silicate of alumina or magnesia, and potash or soda, combined with varying proportions of potash, soda and other impurities. Iron in excess colors it gray and black; magnesia tends to darken the color; aluminium and potassium silicates tend to make the mica transparent. Mica crystallizes in laminated form and may be split along its axis to sheets as small as 0.006 mm.

It has a high dielectric strength and is suitable to withstand high temperatures. However, in its natural state it is not flexible nor uniform, and permits large surface leakage; so that most mica is reconstructed and put on the market in the form of micanite, megomit, megotalc, etc.

The properties of mica are very fully covered in a publication by Zeitler, H. "Mica: Its History, Production and Utilization;" D. Jaroslaw, London. 1913: also in the 1912 edition of "Mica," by the Canadian Dept. of Mines. These sources were utilized in the preparation of the following table.

Origin	Resistivity in 10^{12} ohm-cm.	Dielectric constant	Disruptive strength in volts per mm.*
Madras	15 to 133	2.5 to 5.5	50,000 to 80,000
Bengal	7 to 118	2.8 to 4.7	40,000 to 120,00
Canada	0.44 to 22	2.9 to 3.0	80,000
South America	39	5.9	40,000 to 90,000

Fleming and Johnson give the dielectric strength, in sheets 2 to 3 mils thick, as about 2,000 volts per mil for amber mica and about 3,000 to 4,000 volts per mil for the white, ruby and soft green varieties; Fig. 34 shows the

* NOTE.—Test thickness, 0.3 mm.

272. Wood is used as an insulating material to a considerable extent. The varieties of wood employed are usually the hard woods, such as maple and hickory, impregnated with oil, paraffin wax, or clear air-drying varnish. The resistivity of paraffined wood, at 22 deg. cent. is of the following magnitude: mahogany, 4×10^{13} ohm-cm.; maple, 3×10^{10}; poplar, 5×10^{11}; walnut, 0.09×10^{10} to 1×10^{10} (Scientific Paper No. 234, Bur. of Standards). The dielectric constant and the disruptive voltage are both dependent upon whether the electric stress is parallel or perpendicular to the grain. Parallel to the grain the dielectric constants of red beech and oak are between 2.5 and 4.8; perpendicular to the grain, 3.6 to 7.7.

In maple boiled in transformer oil under vacuum, dried under vacuum and boiled again at atmospheric pressure, the disruptive voltage along the grain, at 1 in. of separation, was 70 kv.; at 2 in. it was 90 kv.; across the grain, at 0.5 in., it was 60 kv.; at 1 in. it was 80 kv.; dielectric constant, at 20 to 25 deg. cent., across grain, 4.1. Well-dried wood should stand 10 kv. per in. without signs of burning or heating. It is extremely important that the wood should be well dried before impregnation, because it is very difficult to remove the moisture subsequently. When wood contains moisture it is a relatively poor insulator and the water contained in the cells conducts electrolytically. Wood treated with zinc chloride to protect it against decay has comparatively low resistivity; see *Electrical World*, 1911, Vol. LVII, p. 828. For curves of disruptive strength of maple see Hendricks, A. B., "High-tension Testing of Insulating Materials;" *Trans.* A. I. E. E., 1911, Vol. XXX, pp. 167 to 213.

VITRIFIED MATERIALS

273. Glass is an insulating material in very extensive use, possessing high resistivity and dielectric strength at ordinary temperatures. The principal constituent is silica, ranging from 50 to 75 per cent. of the total contents; potash, soda, lead oxide and lime are also present, in various proportions. The resistivity at ordinary temperatures is on the order of 10^{13} to 10^{16} ohm-cm. and decreases with great rapidity as the temperature increases. Gray and Dobbie found that potash glass has higher resistivity than soda glass, and annealing increases the resistivity (*Proc.* Royal Soc., 1900, Vol. LXVII, p. 197). At very high temperatures glass becomes a fairly good conductor. Moisture readily condenses upon its surface and it has consequently a high surface leakage. It is also soluble in water to a slight degree and under weather exposure the surface tends to roughen. The dielectric constant ranges from about 5.5 to 10. The dielectric strength ordinarily ranges from 150 to 300 volts per mil, and is higher in very small thicknesses. At 920 cycles crown glass has an apparent resistivity of 17×10^{9} ohm-cm.; dielectric constant, 6.60; power-factor, 0.018. Mechanically glass is unreliable and brittle; the tensile strength is uncertain and anywhere from 1,000 to 10,000 lb. per sq. in., with somewhat higher compressive strength. Coefficient of linear expansion, 0.000008 to 0.0000095 per deg. cent. Density 2.5 to 4.5. For information on glass manufacture see Rosenhain, W., "Glass Manufacture," D. Van Nostrand Co., New York.

274. Porcelain. The three principal constituents of electrical porcelain are feldspar, clay and silica. There are three feldspars: orthoclase, or potash feldspar, which is the most important; albite or indianite, which is soda feldspar; anorthite, or lime feldspar. The two clays used are ball clay, and china clay or kaolin. A standard mixture of these constituents for testing purposes is 20 parts feldspar, 50 parts kaolin and 30 parts quartz. The function of the feldspar is to act as a flux to unite the other constituents into a vitreous mass when fired. There are two processes of manufacture, the dry process and the wet process. For details on the manufacture and properties of electrical porcelain, see an exhaustive paper by E. E. F. Creighton, "Electrical Porcelain;" *Proc.* A. I. E. E., May, 1915, pp. 753 to 841. Also see Perrine, F. A. C., "Electrical Conductors;" D. Van Nostrand Co., New York, 1903; Chap. XIII.

275. Dry-process porcelain is manufactured by molding the moist raw mixture under high mechanical pressure and then vitrifying by the usual firing process. This grade of porcelain is usually very porous and consequently has a disruptive strength on the order of atmospheric air, or less. At or near disruptive pressures, however, it heats rapidly and is not suitable for high-voltage insulation. The safe dielectric strength is on the order of 1,000 volts.

range of temperatures without injury. As a rule, it is slightly absorbent, receiving as much as 3 or 4 per cent. of water, in some cases, in 24 hr. The puncture voltage, with a 0.6-in. (1.5 cm.) wall, after 24-hr. immersion, ranges from about 16,000 to 30,000 volts. It is not affected by arcs unless in direct contact with them, and in that event will be likely to melt locally and chip or fracture in the surrounding area in consequence of unequal heating and expansion.

280. Vitreous enamel consisting of opaque white glass is extensively used for coating iron resistor grids and imbedding the resistor wires, thus forming non-inflammable and highly fireproof devices capable of withstanding unusually high operating temperatures. Enamelled iron-ware is made extensively by the process of sprinkling powdered glass upon red-hot metal, whereupon the glass fuses and forms a continuous thin coating. The formulas used for compounding the glass are quite closely guarded as manufacturing secrets. What is desired is a thin, strong elastic coating which will expand and contract with temperature changes at as nearly as possible the same rate as iron.

FIBROUS MATERIALS

281. Cellulose is the base of practically all fibrous insulating materials and is an organic compound composed of 48 per cent. carbon, 46 per cent. oxygen and 6 per cent. hydrogen. It is a carbohydrate of the formula $(C_6H_{10}O_5)_x$, similar in composition to starch. When pure it is a white amorphous mass; unsized, well-bleached linen paper is nearly pure cellulose. It has a resistivity on the order of 10^8 to 10^{10} ohm-cm. at ordinary temperatures and a dielectric constant of about 3.9 to 7.5. All untreated cellulose materials break down at about 120 deg. cent. and should not be subjected to a maximum of more than 95 deg. cent. A safe operating limit is about 80 deg. cent.

282. Untreated fibrous materials are as a whole hygroscopic and are therefore relatively inferior insulating materials. They are nevertheless employed, some of them, to a great extent, but their use is very largely confined to conditions under which moisture is restricted or expelled. Their properties are greatly improved by treatment or impregnation.

283. The impregnation of fibrous and asbestos products with varnishes, gums, bakelite, etc., produces several results: First, the treating materials fill up the pores of the basic material and eliminate moisture; second, the dielectric strength is increased even where there is no moisture to be considered; third, most treating materials assist in producing smooth surfaces; fourth, the heat-resisting quality of the basic material is often increased, and, fifth, the filling up of the pores may in certain cases reduce the tendency to shrink. Incidentally the treating materials increase the heat conductivity of the insulation, resulting in better radiation.

284. Paper is manufactured from wood pulp, rags or plant fibre. The essential processes in manufacture are (1) the reduction of the raw material to the consistency of a thin pulp, by means of operations involving the use of chemicals and steam; (2) the running of this pulp upon a continuous sieve of fine mesh, which retains the fibres that become felted together; (3) the removal, drying and finishing of the felt so formed. Finished paper retains traces of the bleaching or coloring matter employed, and in addition frequently contains a certain amount of loading matter such as china clay, calcium sulphate and other inert mineral matter. A sizing of vegetable or mineral solution is sometimes added to render the paper less porous and improve the surface.

The mechanical properties of paper are derived in large degree from the basic fibres employed in its manufacture; thus paper made from wood pulp is brittle and easily torn, whereas linen or Manila fibre produces a much tougher and stronger paper. Owing to its porosity paper is hygroscopic and normally contains from 7 to 12 per cent. of moisture. When thoroughly dry it has a very high resistivity, on the order of 10^{15} ohm-cm., but it easily absorbs water and when wet descends to the class of a poor conductor. The dielectric constant of dry paper is from 1.7 to 2.6. Dry Manila paper has a power-factor of about 0.007 at 920 cycles. The dielectric strength of various kinds of untreated paper, ranging in thickness from 1.8 to 28 mils, should average from 110 to 230 volts per mil; higher values are obtainable from extremely dry paper. The tensile strength will range from a few thousand up pressboard is about 2.9 at 20 to 25 deg. cent., measured on 0.1-in. board. The dielectric strength of treated pressboard is given in Fig. 35: curve (1) for pressboard dried and boiled in transformer oil; curve (2) for pressboard dried, boiled in linseed oil and given two coats of varnish; curve (3), dried and given two to four coats of linseed oil and gum varnish, depending on thickness. When these sheets are laid together in laminations, the puncture voltage per mil of complete thickness decreases, but in the case of very thin laminations the puncture voltage does not appear to decrease in as rapid ratio as with single thicknesses.

290. Vulcanized fibre* is a hard, dense material of which the principal ingredient is paper or cellulose made from cotton rag stock; the other ingredients are zinc chloride and coloring matter, the latter consisting of analine colors or mineral pigments. The finished material is heavily compressed into slabs, sheets, tubes, etc. The water and chemicals are not completely removed during manufacture and the product is hygroscopic and not a superior insulating material except for moderate voltages. It will absorb about 50 per cent. of its weight of water in 24 hours. The density ranges from 1.0 to 1.5 according to the grade; average 1.4. The resistivity is comparatively low for dielectrics, or on the order of 10^7 to 10^{10} ohm-cm. Certain varieties are said to have a resistivity as high as 7×10^{13} ohm-cm., probably in a very dry state. The measurements of dielectric strength by different observers are widely discrepant. Parshall and Hobart gave 10,000 volts as the dielectric strength of all thicknesses from ⅛ to 1 in. Hendricks gave about 200 volts per mil at thicknesses of 50 to 150 mils, 160 volts per mil at 0.4 in., 100 volts per mil at 0.7 in. and 90 volts per mil at 1.0 in. Others have found values ranging as high as 300 volts per mil; the results depend largely on the dryness of the material. The tensile strength ranges from 10,000 to 20,000 lb. per sq. in. and the compressive strength is from 35,000 to 60,000 lb. per sq. in. Fibre is not soluble in water or oil, but is attacked by strong acids, and swells when soaked in water; upon drying it shrinks appreciably and warps badly. Numerous grades of fibre are manufactured and known by various trade names, as horn fibre, hard fibre, indurated fibre, leatheroid, fish paper, etc. The flexible and more fibrous varieties have better insulating qualities. Impregnation improves the qualities in marked degree.

291. Treated fibre. The insulating properties of hard or vulcanized fibre are much improved by treating the pulp with bakelite. A material of this character, known as bakelite-dielecto, is manufactured by The Continental Fibre Co. and is said to have the following characteristics. It is a hard, tough material, light brown or black in color, and manufactured in sheets, tubes and certain special forms; cannot be molded, but can be machined either with or against the grain; is non-hygroscopic and impervious to hot water, oils and ordinary solvents; will withstand continuously a temperature of 150 deg. cent.; resistivity, 1.1×10^{12} ohm-cm. at ordinary temperatures, increasing with temperature up to 100 deg. cent.; dielectric strength, 700 to 1,150 volts per mil; average tensile strength, 18,000 lb. per sq. in.; compressive strength, 21,000 lb. per sq. in.

292. Impregnated fibre duct is in extensive use for both inside and outside construction. It is made in the form of a cylindrical tube by wrapping many layers of paper or pulp on a mandrel and impregnating it during the process with bitumen or a compound of liquid asphalt and coal tar. It is sometimes known as **bitumenized fibre.** Tests made on a certain grade of this material show that it absorbed from 2 to 3 per cent. of water after 96 hr. immersion; one manufacturer guarantees not more than 0.75 per cent. when the ends are sealed. The compound softens slightly at 55 deg. cent. and commences to break down at about 95 deg. cent. Manufacturer's guarantees on minimum puncture voltage, dry, through a 0.375-in. wall, range from 25 to 50 kv; after prolonged immersion the dielectric strength will usually be lowered, depending naturally upon the amount of moisture absorbed.

293. Varnished cloth is a thin white fabric of cotton or linen muslin coated with a mixture of boiled linseed oil, resin and benzine. Upon drying the oil oxidizes in contact with the air and leaves a smooth, hard surface.

* See "Manufacture of Hard Fibre," *Electrical World*, Vol. LIII, p. 1437; also see Vol. LV, p. 1342.

tables in Sec. 5). Gray gives the puncture voltage of a 7-mil thickness (composed of two layers) as about 150 volts; impregnated, about 600 volts.

300. Silk insulation for magnet wires is applied in one or two thicknesses, ranging from 1 to 2.5 mils per layer. While it is somewhat hygroscopic in the untreated condition, it has superior insulating properties compared with cotton, and is much improved by impregnation. Neither cotton nor silk are the equal of baked enamel (Par. **351**) in dielectric strength.

301. Asbestos insulation for magnet wires. Asbestos insulation can be applied to wires and small straps with the use of binding materials, but in all cases, except in that of asbestos tape which can readily be used in taping armature or field coils, the mechanical qualities are quite poor. Asbestos windings also require considerable space if used in sufficient thickness, they are not in themselves moisture-proof, they have low dielectric strength, and do not give a smooth surface.

Deltabeston magnet wire is insulated with asbestos fibre cemented to the wire with a special bond. It is claimed that the maximum continuous working temperature is 150 deg. cent.; for short periods, 260 deg. cent. The insulation thickness is about the same as double cotton and breaks down at 300 to 600 volts.

302. Tapes. Insulating tapes are chiefly of four varieties: (a) those woven from cotton or silk and untreated; (b) those woven from cotton and treated with insulating varnish, or cut from treated cloth; (c) those cut from cloth which has been loaded with rubber or adhesive compound. The lay of the threads is arranged in three different ways, straight, biased and webbed; the last one is the strongest and does not stretch readily. (d) Paper tapes, treated and untreated, are cut from finished stock. See "Specifications and Tests for Insulating Tapes," *Electrical World*, Vol. LVII, p. 488; also Vol. LVI, p. 689.

303. Untreated tapes are hygroscopic and for that reason are not entirely satisfactory unless finally impregnated or protected from moisture. Gray states that a half-lapped layer of untreated cotton tape 6 mils thick will withstand about 250 volts when dry; about 1,000 volts when impregnated. Precautions should be taken to detect the presence of bleaching and chemical matter, such as chlorine, which may attack copper. Webbing is sometimes used for mechanical protection, aside from its insulating qualities.

304. Varnish-treated tapes are cut from sheets of treated cloth, such as Empire cloth, varnished cambric and the like, and are used for taping windings which cannot readily be impregnated. They are cut straight or on the bias, the latter being sometimes preferred for taping uneven surfaces. See treated cloth, Par. **292** to **295**.

305. Rubber-treated tapes are composed of fabric loaded with plastic rubber gum or compound in a soft adhesive state. Such tapes are used extensively in making water-proof joints on underground rubber-insulated cables, or in other locations where a moisture-repellent wrapping is desired. They are frequently used in conjunction with a splicing gum of similar composition, and protected by water-proof insulating compounds and outside wrappings of adhesive tape with insulating paint over all. In the case of underground cables a lead sleeve is wiped over the whole joint, making it completely water-tight.

306. Adhesive or friction tape is composed of fabric loaded with a sticky or adhesive compound. The base of the compound in the more expensive grades is rubber gum, adulterated with fillers in various well-known ways, while the less expensive grades contain little or no rubber and its place is taken by one of the numerous bituminous compounds. This kind of tape possesses fair insulating properties and is very extensively used in low-tension work.

307. Paper tapes of both the treated and the untreated varieties have a most extensive use in the manufacture of paper-insulated cables for power and communication service. See paper, Par. **284**.

308. Asbestos tape, or a tape having a base of asbestos fibre, is superior in its heat-resisting properties to cellulose materials such as paper and cloth. Such tapes are usually known by trade names, among them being deltatape. The latter it is claimed can be raised to 260 deg. cent. before breakdown occurs; puncture voltage, about 250 volts per mil.

313. Asbestos molded with a binder, known under the trade names of gummon, hemit and tegit, is manufactured by the Hemming Mfg. Co., from whom the following data was obtained. Gummon is black and can be highly polished; tegit is dark brown and can be polished, though less highly than gummon; hemit is made in both gray and black and will also take a polish. The density varies, in the neighborhood of 2. These materials are suitable only for molding; are infusible, but will gradually carbonize at higher than working temperatures; will not resist concentrated acid; are not recommended for working pressures above 1,000 volts.

	Ohm-cm. at 22 deg. cent. (Bur. of Stds.)	Max. working temp (deg. cent.)	Dielectric strength (volts per mil)	Strength (lb. per sq. in.)		Absorption of moisture (per cent.)
				Tensile	Compressive	
Hemit.......	1×10^{10}	1,100	50	2,000	1,600	5
Gummon....	3×10^{12}	320	75	600	550	2
Tegit........	2×10^{12}	200	50	1,200	1,100	5

Also see Hemming, E. "Molded Electrical Insulation and Plastics;" Clausen and Co., New York, 1914.

314. Asbestos wood or lumber, known also by the trade names "Transite Asbestos Wood" and "Asbestos Building Lumber," consists of asbestos fibre and hydraulic cement, and is used as a substitute for wood in building construction. It is also used to some extent as a substitute for slate and marble in electrical construction. The following data (Par. **315** and **316**) was furnished by C. L. Norton; also see his paper entitled, "Some Refractory Substitutes for Wood," *Jour.* A. S. M. E., 1912; and "The Manufacture and Use of Asbestos Wood," on pp. 375 and 379 of "Technology and Industrial Efficiency," McGraw-Hill Book Co., Inc., New York, 1911.

315. Transite asbestos wood is light gray in color and is manufactured in sheets up to about 4 ft. by 8 ft. by 2 in. It has a density of about 2.0. It can be sawed and bored like wood but is harder and slower to cut. At 600 deg. cent., partial dehydration and partial loss of strength occurs, but it does not soften. At 1,100 deg. cent. the material holds shape and considerable portion of its strength, but it will not stand temperatures above 1,400 deg. cent. The temperature coefficient of expansion at ordinary temperatures is about 0.000008 per deg. cent. The thermal conductivity is 0.0005 cal. per cm-cube per sec. per deg. cent. Transverse breaking tests give a modulus of rupture of about 5,000 lb. per sq. in., and the crushing strength is from 20,000 to 25,000 lb. per sq. in. When dry, at or near 20 deg. cent., it has a resistivity of about 150,000 megohm-cm. It is dissolved slowly by acids. When used in dry or hot places it is suitable for electrical insulation and is tougher than slate or marble. Since it absorbs moisture it is not suitable for damp locations.

316. Ebony asbestos wood is asbestos bonded with magnesia, cement and saturated with an insulating compound. It is black, smooth and glossy and has a density of about 1.9. It can be worked the same as slate, but more rapidly and easily. The working temperature limit is about 200 deg. cent.; it does not soften; the melting-point is above 1,400 deg. cent. The coefficient of expansion is 0.000010 per deg. cent. The thermal conductivity is 0.00065 cal. per cm-cube per sec. per deg. cent. It has a modulus of rupture of about 5,000 lb. per sq. in. and a crushing strength of 15,000 lb. per sq. in. At 20 deg. cent. after 96 hr. immersion the resistivity is above 3×10^{6} megohm-cm. and changes 5.3 per cent. per deg. cent. The disruptive strength is greater than that of slate or marble, and it also withstands better the effects of surface arcing. It is also tougher than slate or marble.

317. Bakelite and bakelite compositions. Bakelite is a condensation product of phenol, manufactured in three grades. Bakelite "A" is the initial raw material and exists in liquid, pasty or solid condition; upon heating it is converted into "B" which is an intermediate solid product, substance which will not harden under heat; this product is heated and then combined with a hardening agent, producing a hard, infusible and practically insoluble substance which the manufacturer (Condensite Co. of America) claims is high in dielectric and mechanical strength and heat resistance. The following data on the properties of molded condensite were furnished by the manufacturer: Density, 1.25 to 2.0; not hygroscopic, unaffected by water, insoluble in the ordinary solvents and oils, attacked by strong nitric acid and caustic potash, slightly attacked by sulphuric acid. The resistivity at 22 deg cent. is about 4×10^{10} ohm-cm. (Bur. of Stds.); dielectric strength, about 300 to 400 volts per mil at a thickness of 0.15 in. and 500 to 600 volts per mil at a thickness of 0.04 in.; tensile strength, 4,300 lb. per sq. in.; compressive strength, 26,000 lb. per sq. in.; not perceptibly affected by 48 hr. of exposure to a temperature of 200 deg. cent.; maximum working temperature, 300 deg. cent. (Swoboda, *Elec. Jour.*, May, 1913). Also see *Electrical Review and West Elec.*, Vol. LX, p. 199.

320. Dielectrite is a black molded composition composed of vegetable fibre and mineral filler. It is molded and vulcanised by the application of heat. Resistivity at 22 deg. cent., 5×10^{12} ohm-cm.

321. Electrose is a dark brown or black composition of hard, tough quality which it is claimed is non-hygroscopic and not affected by water or oil. It can be molded in any form, will hold metal inserts, and can be given a smooth glossy finish. The working temperature limit is about 95 deg. cent. Resistivity at 22 deg. cent., 1×10^{14} to 200×10^{14} ohm-cm. The manufacturer (Electrose Mfg. Co.) claims a dielectric strength of at least 600 volts per mil, in a thickness of $\frac{1}{8}$ in. Electrose is used in the manufacture of many different forms of insulators and bushings and is also made in pliable insulating flooring. See *Electrical World*, Vol. LIV, p. 797 and Vol. LVI, p. 887.

322. Gohmak is a molded substitute for hard rubber made by the Vulcanized Products Co. The density ranges from 1.4 to 1.8 according to composition. The claim is made that it is non-hygroscopic and insoluble in oils and weak solutions. Resistivity, on the order of 2×10^{10} ohm-cm. at ordinary temperatures, decreasing with rising temperature. Dielectric strength, on the order of 400 volts per mil, at a thickness of 0.25 in. Tensile strength, 9,000 to 12,000 lb. per sq. in. Softens slightly at 100 deg. cent.

323. Insulate is a black molded composition composed of mineral compound and resembles hard rubber. It can be moulded in any shape and can be worked and machined. The manufacturers (General Insulate Co.) claim that it is non-hygroscopic, insoluble in all weak solutions and has a maximum working temperature of 150 deg. fahr. The resistivity of No. 2 grade at 22 deg. cent. is 8×10^{15} ohm-cm. The dielectric strength is on the order of 45 volts per mil, at a thickness of 0.4 in.

324. Molded mica is made of finely split mica scales held together by a strong insulating varnish, binder, or cement, such as shellac, the sheets or forms thus built up being subjected to heat and pressure. These compositions are more or less heat resisting, dependent upon the nature and proportions of the binder employed. They are known by a variety of trade names such as micanite, mica plate, micabond, micabeston, turbomic, formica, megomit, megotalc, etc. The less binding material they contain, the nearer they approach the properties of natural mica. Such reconstructed or molded mica is made in three commercial forms, as follows: (1) Molded plate, which becomes flexible when heated and in that condition can readily be formed into various shapes such as rings, troughs, spools, and, in thinner sheets, rolled into tubes. Upon cooling it regains its rigidity. It can be used for any purpose where very high temperatures are not encountered, except for commutator bars. (2) For insulating commutator segments. It cannot be molded and offers great resistance to heat. Canadian amber mica is preferred for this purpose. (3) Flexible sheets which may be bent to shape without application of heat, for insulating armature slots, magnet and commutator cores, etc. It is also used in conjunction with tapes for insulating wires and cables.

Rayner concluded from his tests (National Physical Laboratory) that generally speaking, thin qualities of micanite up to about 1 mm. will withstand a stress of 20,000 volts per mm. (500 volts per mil) in air for 10 min. Above this thickness, up to 2.5 mm., there is more difficulty in making material which will withstand this stress, and usually the material withstands the voltage longer under oil.

331. Reduction of crude rubber. The lumps or biscuits of crude rubber are boiled in water, ground, washed, dried, mixed with sulphur, adulterants and filler and then calendered. For details of the process see Perrine, F. A. C. "Conductors for Electrical Distribution," New York, 1903; and Esch, W. "Handbook for India-rubber Engineers," Hamburg, 1912. Owing to the high cost of pure rubber it is almost universally adulterated and many rubber products do not contain over 20 to 30 per cent. of pure gum, and sometimes much less. Among the numerous adulterants in use are rubber substitutes, ozokerite, paraffin, pitch, oil, etc., and fillers such as zinc oxide, white lead, red lead, barium sulphate, magnesium carbonate, barium carbonate, chalk, lamp-black, talc, alumin flakes, etc.

Vulcanization. When rubber and sulphur are heated to a temperature above the melting-point of the latter, 120 deg. cent., the two combine and form a new product termed vulcanized rubber, which is stronger, more elastic and less susceptible to temperature changes than pure rubber. The degree of vulcanization depends upon the proportion of sulphur, the temperature and the duration of heating.

332. Rubber substitutes in the true sense have not yet been produced on a commercial scale. There are certain so-called substitutes, produced from vegetable oils by processes of vulcanization or oxidation, which can advantageously be mixed with rubber for the production of certain articles. Rubber substitutes used not infrequently in wire insulation consist principally of oxidized oils, paraffin, resins and rubber shoddy. The latter is a compound obtained by treating old rubber with steam, sulphuric acid and chloride of zinc, thus removing most of the vegetable fibres and the sulphur, but leaving the mechanical admixtures of earth and oxides employed in the original manufacturing process. Such substitutes are usually known under trade names.

333. Electrical properties. The resistivity is on the order of 10^{14} to 10^{16} ohm-cm., varying greatly according to the composition and increasing with the content of pure rubber. The temperature coefficient is negative and unusually large, ranging from 2 to 4 per cent. per deg. cent. Del Mar states that at any given temperature the rate of change of resistance per deg. of temperature change is approximately proportional to the resistance at that temperature, values of the factor ranging from 0.02 to 0.03 for 30 per cent. Para compound. Values of k in the formula $R = k \log_{10}(D/d)$ for insulation resistance of cylindrical wires in megohm-miles, are variable between wide limits, ranging from about 1,000 to 20,000; d is the diameter of the wire and D is the outer diameter of the insulation, in the same units. The value of k is very much higher with alternating currents.

The dielectric constant of pure vulcanized rubber is from 2 to 3; rubber compounds, 3 to 4. Jona gives values as high as 6 for certain compounds containing relatively large percentages of Para.

The dielectric strength of high-grade rubber compound ranges from 300 to 500 volts per mil; it decreases quite appreciably for long periods of electrification. Lufkin states (*Electrical World*, 1913, Vol. LXI, p. 1310) that for each rubber compound there is a critical temperature at which the puncture voltage is a maximum. This ranged between 40 deg. and 80 deg. cent. for five different grades, in a certain series of tests. One particular grade, or high quality, gave a maximum at 70 deg. cent., being 30 per cent. above the value at 20 deg. The range was carried to 100 deg. cent. at the upper limit, and 0 deg. at the lower.

Fleming and Dyke measured the power-factor of rubber at 920 cycles and found values of 0.005 for pure India-rubber and 0.002 for vulcanized India-rubber. For further data on electrical properties, consult the following:

Jona, E. "Insulating Materials in High-tension Cables;" *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, pp. 550 to 571.

Fisher, H. W. "Rubber-covered Wires;" *Trans.* A. I. E. E., 1907, Vol. XXVI, pp. 997 to 1025.

Osborne, H. S. "Potential Stresses in Dielectrics;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1553 to 1581.

Hering, C. "Thickness of Electric and Thermal Insulation," *Electrical World*, 1911, Vol. LVIII, pp. 1303 to 1305.

Lendi, J. H. "The Thickness of Insulation on Wires and Cables," *Electrical World*, 1912, Vol. LIX, pp. 590 to 592.

percha and Balata," Cologne, 1903; Seeligmann, Torrilhon and Falcounet, "India-rubber and Gutta Percha," 1910; Del Mar, W. A., "Electric Power Conductors," 2d edition, New York, 1914; Kempe, H. R., "A Handbook of Electrical Testing," 7th edition, London, 1908.

341. Hard rubber or ebonite is a rubber compound containing a large percentage of sulphur and highly vulcanized. It is a hard dense material possessing many desirable properties as an insulator at temperatures not greatly exceeding normal. The resistivity is on the order of 10^{15} to 10^{18} ohm-cm. at ordinary temperatures; the surface resistivity is impaired by exposure to sunlight (See Scientific Paper No. 234, Bureau of Standards.) The dielectric constant is from 1.9 to 3.5. In small thicknesses, of 20 mils, the dielectric strength ranges from 1,700 to 3,750 volts per mil, tested between 2-in. spheres; 1,000 to 2,000 volts per mil, tested between flat electrodes. At 920 cycles it has an effective resistivity of about 1.5×10^{11} ohm-cm.; dielectric constant, 3.17; power-factor 0.005 (Fleming and Dyke). Mechanically it is brittle, but can be worked, machined and polished; tensile strength, about 1,100 lb. per sq. in. and compressive strength about double; density, 1.2 to 1.25. It is attacked by oils and ozone, but is non-hygroscopic. See Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials," *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131; also Paterson, Rayner and Kinnes, "Notes on the Testing of Ebonite for Electrical Purposes," *Jour.* I. E. E., 1913, Part 217, Vol. L.

342. Kerite is a vulcanized compound of oxidized linseed oil and rubber combined with various vegetable oils, invented by A. G. Day. According to Perrine* it has a specific insulation resistance somewhat less than pure rubber, but is said to be mechanically more durable than any insulation manufactured from pure rubber. It is employed in the insulation of wires and cables as a substitute for the usual rubber compound. The value of the constant k in the formula $R = k \log_{10} (D/d)$ is given by the Kerite Ins. Wire and Cable Co. as 4,000 at 60 deg. fahr.; R is the insulation resistance of the wire in megohm-miles, d is the diameter of the conductor and D is the outside diameter of the insulation.

343. Sulphur has a resistivity of 10^{17} ohm-cm. at 22 deg. cent.; dielectric constant, 2.2 to 3.9; power-factor at 920 cycles, 0.0003.

344. Vulcanite. See hard rubber, Par. **341**.

VARNISHES AND COMPOUNDS

345. Solidifying materials, such as varnishes, which are applied as liquids and emerge as solids, are of interest chiefly in their final state. They are divisible broadly into two classes: (1) those employed to impregnate or treat basic materials, such as the fibres and the pulps; (2) those employed as filling compounds, to permeate or seal extensive voids which otherwise would offer lodgment for moisture and deleterious foreign matter. The properties of the former class are obviously of importance, principally, in association with the treated or impregnated base; while materials of the latter class constitute a species to themselves.

346. Insulating varnishes are divisible, according to their applications, into four groups:† (A) For impregnating windings; (B) for treating papers and fabrics; (C) for cementing purposes; (D) finishing varnishes. They are also divisible, according to their properties, into (a) oxidizing and (b) non-oxidizing, and again into (1) air-drying and (2) baking. Oxidizing varnishes of class A are frequently composed of linseed oil with a resinous base of copal or other fossil gum, and when thoroughly oxidized are almost impervious to oil and moisture. The drying action in linseed-oil varnishes takes place first by the evaporation of the volatile solvent and then by the oxidation of the oil and the gum; the latter action is hastened by the addition of mineral drier, the quantity of which depends upon whether air-drying or baking varnish is desired. In another form of oxidizing varnish the gum base is replaced by asphaltum, but this is said to lower the dielectric strength and the resistance to attack by oil. Non-oxidizing varnishes of class A contain a

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* Perrine, F. A. C. "Conductors for Electrical Distribution," New York D. Van Nostrand Co., 1903, p. 106.

† See Fleming and Johnson. "Insulation and Design of Electrical Windings;" Longmans, Green and Co., London, 1913; pp. 63 to 76.

per mil, an average value being 500 to 600 volts per mil, or about four times the value for silk. The electrical resistivity at ordinary temperatures is very high, on the order of 10^{14} ohm-cm. Baked enamel should stand a temperature of 100 deg. cent. continuously without injury, but breaks down electrically at about 300 deg. cent. It is a fairly good thermal conductor and much superior to cotton and silk. An enameled wire should withstand bending around a mandrel four times its own diameter without injury. Turpentine, shellac, alcohol, vegetable or animal oils, and coal-tar solvents will attack it, but it is not injured by clean mineral oil and is moisture-proof. It should be carefully handled to avoid injuring the coating.

352. Linseed oil is a vegetable material derived from flaxseed, having a density of 0.932 to 0.936 at 15 deg. cent. It has excellent insulating properties and is extensively used in paints and varnishes. For specifications and general properties see "Year Book," A. S. T. M.; and Technologic Paper No. 9, Bureau of Standards, 1912. Boiled linseed oil has the property of oxidising under ordinary exposure to air and the process will continue until it becomes viscous or even hard; the action can be hastened by drying agents and the application of heat.

353. Ozokerite (ozocerite) is a wax-like mineral, colorless or white when pure and consisting of a mixture of hydrocarbons. It is used in making ceresin, candles, etc. Crude ozokerite has a resistivity on the order of 4.5×10^{16} ohm-cm. Liquid ozokerite has a dielectric constant of about 2.1. **Ceresin** is a yellow or white wax made by bleaching and purifying ozokerite and is employed as a constituent of insulating compounds; its density is 0.75; resistivity, over 5×10^{18} ohm-cm. at 22 deg. cent.

354. Paraffin is a colorless or white waxy substance, consisting of a complex mixture of hydrocarbons, obtained by the distillation of wood, coal or oil. Chemically it is inert, being unaffected by most strong reagents. According to composition, it melts at from 45 to 80 deg. cent. and has a density of 0.87 to 0.94; resistivity, 10^{15} to 10^{19} ohm-cm.; dielectric constant, 1.9 to 2.3; dielectric strength, about 300 volts per mil; power-factor at 920 cycles, 0.0003.

355. Resin is defined as any of various solid or semi-solid organic substances, chiefly of vegetable origin, usually yellowish to brown in color, transparent or translucent, and soluble in ether, alcohol, etc., but not in water. They soften and melt on heating. Chemically they differ widely, but all are rich in carbon and hydrogen and contain also some oxygen. Among the commercial resins are amber, copal, dammar, guaiacum, lac, mastic, rosin and sandarac. Lac is the raw material used in making **shellac**, which has a resistivity on the order of 10^{15} to 10^{16} ohm-cm. and a dielectric constant of about 2.7 to 3.8.

356. Wax is defined as any of a class of natural substances composed of carbon, hydrogen and oxygen and consisting chiefly of esters other than those of glycerin or of free fatty acids. In this class are included beeswax, spermaceti, Chinese wax, carnauba wax, etc. Beeswax is a dull yellow solid, of density 0.96 to 0.97 at 15 deg. cent. and melting at 62 to 64 deg. cent.; resistivity, 10^{14} to 10^{17} ohm-cm.; dielectric strength, about 250 volts per mil.

357. Weatherproof compounds for saturating the cotton braids on weatherproof wire usually contain an asphaltum base, with an admixture of wax so that the surface of the braid may be given a dull polish.

INSULATING OILS

358. Oil is employed as an insulating medium in many ways. It is employed by itself to insulate transformers and switches by immersion; it is used for saturating fibrous and other materials, as in cable work; drying oils (linseed) are used for coating papers and cloths in sheet insulation; various kinds of oil are employed in mixing insulating paints and varnishes. Oils of practically every variety are possessed of very high resistivity and dielectric strength. Chemically oil is composed of hydrocarbons having the general formulas C_nH_{2n+2} and C_nH_{2n}. The desired characteristics of an insulating oil are high resistivity and dielectric strength, low viscosity, high flash point, chemical neutrality toward metals and insulating materials, freedom from moisture, sediment and impurities, and chemical stability under local high temperatures.

362. Dielectric constants of various kinds of oils are given in the accompanying table. The values probably change very appreciably with the temperature.

Arachid	3.17	Petroleum	2.02 to 2.19
Castor	4.6 to 4.8	Rape seed	2.2 to 3.0
Colza	3.07 to 3.14	Sesame	3.17
Lemon	2.25	Sperm	3.02 to 3.09
Neatsfoot	3.07	Turpentine	2.15 to 2.28
Olive	3.08 to 3.16	Vaseline	2.17

363. Effects of moisture and dust on insulating properties of oil. The presence of moisture in transformer oil has a very serious effect on the dielectric strength, as shown by Fig. 36. In order to obtain a dielectric strength of 40,000 volts (0.2-in. gap between 0.5-in. discs), the water present as distributed moisture in the oil must not exceed 0.001 per cent. Fine dust is also very injurious to the dielectric strength. For these reasons, various manufacturers have developed oil dryers and purifiers, which operate on the principle of a filter press.

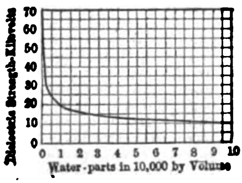

Fig. 36.—Effect of water on dielectric strength of oil.

364. Formation of deposits in oil-cooled transformers. The foregoing subject formed the title of a paper by Dr. A. C. Michie before the I. E. E. in April, 1913. The author stated that all oils oxidise in time, but the formation of deposits can be prevented or minimised by avoiding the following conditions: (1) Overheating; (2) undue access of air to the oil; (3) conditions likely to give rise to the formation of ozone; (4) contact of the oil with clean surfaces of copper, lead and iron.

365. U. S. Government specification for transformer oil calls for a pure mineral oil obtained by the fractional distillation of petroleum, unmixed with any other substance. It shall be prepared and refined especially for the purpose; shall be free from moisture, acid and alkali, and shall contain a minimum of sulphur compounds. The flash-point determined in a closed cup shall be not less than 170 deg. cent.; on cold test it shall not begin to solidify and no wax shall form in the oil above 0 deg. cent. It shall stand a breakdown test of 30,000 volts between spheres of 0.5 cm. radius, 0.40 cm. apart. See Circular No. 22, Bureau of Standards, 1911.

GASES

366. The insulating properties of gases depend upon, and vary with, the pressure and the temperature, and are affected also by the humidity. The only gaseous dielectric in extensive use is atmospheric air, whose properties have been the subject of extended research.

367. Air. The dielectric properties of air, and particularly its disruptive strength, have been the subject of more investigation than any other dielectric in use. Extended investigations and researches have been made by Ryan, Mershon, Fisher, Peek, Whitehead, Faccioli, Harding, Bennett, Fortescue and Farnsworth, whose results have been published during the past 10 years in the *Trans.* A. I. E. E., and by Russell (see *Jour.* I. E. E.).

Air in the free state has electrical conductivity. The results obtained (see Whitehead, *Proc.* A. I. E. E., May, 1915, p. 846) indicate that in the open the current passing between two parallel plates 10 cm. apart and each 100 cm. square, assuming perfect insulation, would be of the order of magnitude 3×10^{-18} amp. This is the maximum current which may be obtained and does not increase with increase of voltage; it diminishes greatly if the air is confined in a closed vessel. The conductivity may be greatly increased by exposing the air to Röntgen rays, ultra-violet light, etc., but the magnitude of current still remains very small.

The dielectric constant of air is usually taken as unity, and air is almost universally the medium of reference in all measurements of this constant.

THERMAL CONDUCTIVITIES.—*Continued*

Material	Watt-cm. per deg. cent.	Material	Watt-cm per deg. cent.
Slate	0.020	Woolen (pure) wadding, slightly packed	0.00036
Water, 25 deg. cent.	0.0057	Woolen (pure) wadding, tightly packed	0.00023
Woolen (pure) wadding, loose	0.00049		

1 watt = 0.2389 g-cal. per sec. 1 g-cal. = 4.186 watt-sec.
1 watt = 0.0009468 B.t.u. per sec. 1 B.t.u. = 251.8 g-cal.
1 g-cal. = 0.003971 B.t.u. 1 B.t.u. = 1,054 watt-sec.

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Trans. A. I. E. E., *Jour*. I. E. E., *Jour. Franklin Inst.*, *Electric Journal* *General Electric Review* and *Science Abstracts* (*B*).

STRUCTURAL MATERIALS

CAST IRON

371. Cast iron derives its characteristic qualities from the impuritie present. These impurities are the same as those in steel, except for graphite which is one form of carbon. The carbon is always present in two forms (1) combined carbon, in the form of cementite; (2) uncombined carbon, o graphite. The total carbon seldom exceeds. 4.5 per cent. or falls below 3.2 per cent. The larger the proportion of carbon in the combined state, th harder and more brittle will be the metal. Cast iron is not ductile, in eithe hot or cold state.

Silicon is a desirable impurity, because it tends to precipitate carbo in the graphitic form; about 3 per cent. of silicon gives the best results. Sul phur has the opposite effect of silicon, and is undesirable. Managnese in creases the total carbon and also the proportion of combined carbon, bu tends to neutralize the similar effect of sulphur. Phosphorus, if present i sufficient proportions to be chemically active, tends to hold the carbon i combined form, and also tends to weaken the metal.

372. White cast iron. If slowly cooled, white cast iron will contai combined carbon in the form of cementite, which imparts the qualities o hardness and brittleneess to the metal. Where the carbon is from 3 to 4 per cent., cementite will form from 45 to 50 per cent. of the material. Unles the cooling is slow some of the carbon will be in the austenitic form. Whit cast iron has few uses, except as a hard coating or skin for gray iron casting.

0.67 watt-cm. per deg. cent., for pure iron. Coefficient of linear expansion, 0.0000114 per deg. cent., between −18 and 100 deg. cent.

381. Electrolytic iron melted in vacuo, forged into half-inch rods and annealed at 900 deg. cent., has the following average tensile properties.

	Tensile strength (lb. per sq. in.)	Yield point (lb. per sq. in.)	Elongation (per cent.)	Reduction of area (per cent.)
As forged	54,800	48,400	33.3	83.0
Annealed at 900 deg. cent. and cooled in 12 hr.	38,100	18,000	51.8	87.4

The average carbon content of this iron was 0.0125 per cent. See Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914.

382. Tensile properties of wrought iron. The following properties were taken from Campbell's "Manufacture and Properties of Iron and Steel," 4th edition, p. 91. Also see Holley, "The Strength of Wrought Iron as Affected by its Composition and its Reduction in Rolling," *Trans.* A. I. M. E., Vol. VI, p. 101.

	Minimum	Maximum
Carbon, per cent	0.015	0.512
Phosphorus, per cent	0.065	0.317
Silicon, per cent	0.028	0.321
Manganese, per cent	trace	0.097
Slag, per cent	0.192	2.262
Ultimate strength, lb. per sq. in	47,478	69,779
Elongation in 8 in., per cent	6.5	32.7
Reduction of area, per cent	7.7	59.8

The general influence of reduction in rolling is to increase the tensile strength and the elastic limit, and diminish the elongation and the reduction of area.

STEEL

383. Carbon steel. Increasing the carbon content of steel increases its strength, hardness, brittleness, and susceptibility to cracking under sudden cooling or heating; it also diminishes the elongation and reduction of area at fracture. In acid steel, according to Campbell, each 0.01 per cent. of carbon increases the strength by 1,000 lb. per sq. in., when the carbon is determined by combustion; or 1,140 lb. per sq. in. when the carbon is determined by color. In basic steel each 0.01 per cent. of carbon increases the strength by 770 lb. per sq. in., when the carbon is determined by combustion, or 820 lb. when determined by color.

Phosphorus increases the tensile strength 1,000 lb. per sq. in. for each 0.01 per cent., but tends to make the metal "cold short" or brittle. **Sulphur** does not alter the tensile strength appreciably, but tends to make the metal "hot short." **Manganese** increases the tensile strength from 80 to 400 lb. per sq. in. for each 0.01 per cent., depending upon the carbon present, and whether the steel is acid or basic; it also increases the ductility when hot. **Silicon** in small quantities has little effect. **Copper** has also little effect on the cold properties as far as known. **Nickel** gives a metal with a high elastic limit and great toughness under shock. **Aluminum** in small quantities is added to molten steel to absorb oxygen and improve the fluidity; when present in the finished metal it increases the strength and impairs the ductility.

The thermal conductivity of steel containing 1 per cent. of carbon, at 18 deg. cent., is 0.45 watt-cm. per deg. cent. The coefficient of linear expansion ranges between 0.0000104 and 0.0000132 per deg. cent.

is practically zero. **Platinite** (42 per cent. Ni) has the same coefficient of expansion as glass. See Colby, A. L. "Nickel Steel," *Proc.* A. S. T. M., Vol. III, 1903.

391. Silicon steel.* The addition of silicon to steel appears to increase the strength about 80 lb. per sq. in. for every 0.01 per cent., up to a content of 4 per cent.; beyond this point it severely impairs the ductility. A steel containing 3.40 silicon, 0.21 carbon and 0.29 manganese had a tensile strength of 106,000 lb. per sq. in.; elastic ratio, 0.74; elongation, 11 per cent.; reduction of area, 14 per cent.; annealed strength, 87,000 lb. per sq. in. Silicon is used in electrical sheets, because it substantially increases the electrical resistivity and thus reduces the core loss; such sheets are much harder than ordinary dynamo sheets of soft steel; see "Magnetic Materials" in this section. The thermal conductivity of 4 per cent. silicon-steel, between 20 and 250 deg. cent., is 0.32 watt-cm. per deg. cent.

392. Tungsten steel is characterized by great hardness and toughness and its remarkable tempering properties. The tungsten content ranges from 0.5 per cent. in ordinary bar steel to 2 to 5 per cent. in finishing and intermediate steels, 4.5 to 12 per cent. in self-hardening or air-hardening steels, and 14 to 26 per cent. in high-speed steels. See Baskerville, C. "The Chemistry of Tungsten, Etc.," *Trans.* N. Y. Elec. Soc., Oct. 29, 1912; also see "Magnet Steel," Sec. 4.

393. Vanadium steel. The use of vanadium as an alloy with steel produces more remarkable results than any other element except carbon. Oil-tempered vanadium steel containing 0.25 to 0.30 carbon, 0.50 manganese, 1.0 chromium and 0.17 vanadium has been found to have a tensile strength as high as 233,000 lb. per sq. in., elastic ratio 96 per cent., elongation 11 per cent., and contraction of area 39 per cent. The vanadium content is usually less than 0.3 per cent.; its effect in general is to improve the tensile properties, hardness and toughness.

394. Protective coatings for iron and steel consist of the following: (a) pigments of various kinds; (b) galvanizing or zinc coating, applied by hot-dipping, electroplating or dry-heating with zinc dust; (c) coating with aluminum alloy, by dry-heating with the powdered alloy; (d) tinning, by hot-dipping and rolling; (e) terne coating, of lead-tin alloy, applied in the same manner as tinning; (f) nickel-plating, applied electrolytically; (g) coating of black oxide of iron, produced by application of oil to the metal when black hot; (h) enamel coating of glass. For out-door exposures, methods (a) and (b) are the ones chiefly used, but neither is free from faults or objections. For particulars see Wood, M. P. "Rustless Coatings; Corrosion and Electrolysis of Iron and Steel," New York, 1905; "Report of the Committee on Preservative Coatings for Structural Materials," 1903 to 1913, A. S. T. M., Phila., Pa.; Bulletins No. 30, 35 and 239, U. S. Dept. of Agriculture, Wash., D. C. Stoughton, B. "The Metallurgy of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1911. Cushman and Gardner. "Corrosion and Preservation of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1910.

STEEL WIRE AND CABLE

395. Table of steel wire

(Roebling)

Number, Roebling gage	Diameter in inches	Area in square inches	Breaking load at rate of 100,000 lb. per sq. in.	Weight in pounds	
				Per 1,000 ft.	Per mile
000000	0.460	0.1662	16,620	558.4	2,948
00000	0.430	0.1452	14,520	487.9	2,576
0000	0.393	0.1213	12,130	407.6	2,152
000	0.362	0.1029	10,290	345.8	1,826
00	0.331	0.08605	8,605	289.1	1,527
0	0.307	0.07402	7,402	248.7	1,313

* Hadfield, R. A. *Jour.* Iron and Steel Inst., 1889; *Jour.* Inst. of Elec. Eng. 1902; Royal Dublin Society, 1900 and 1904; *Trans.* Faraday Society, 1914.

398. Tensile tests of steel spring wire, of best quality tempered music-wire, from about 0.04 to 0.05 in. in diameter, gave from 342,000 to 388,000 lb. per sq. in.; elongation between 1 and 2 per cent.; contraction of area, 38 to 46 per cent. (Report of Tests of Metals, 1904; Watertown Arsenal).

NON-FERROUS METALS AND ALLOYS

399. Properties of miscellaneous non-ferrous metals and alloys

(Compiled from various authorities)

Metal	Density	Strength (1,000 lb. per sq. in.)		Young's modulus (10^6 lb. per sq. in.)	Coefficient of expansion per deg. cent. $\times 10^{-6}$	Thermal conductivity (g-cal. per cm-cube per deg. cent. per sec.)
		Tension	Compression			
Aluminum, cast	2.56	12–15	12	9–11		
Aluminum, rolled	2.68	24–40		11	23.1	0.34
Aluminum, wire	2.70	20–40		9–12	23.1	0.34
Aluminum, alloys	2.7–3.1	15–45	16–100			
Aluminum, bronze	7.7–8.3	60–90	120			
Brass, cast	8.5	18–24	30	9	17–22	0.23
Brass, wire	8.46	40–150		14		0.31
Bronze, bearing	8.5–8.9	25–50	80		17–22	
Bronze, gun metal		25–55		10–12		
Bronze, manganese	8.4	75–90	125–150	15		
Bronze, phosphorus		35–50		14	17	
Bronze, phosphorus, hard-drawn.		110–140			17	
Bronze, silicon		55–75				
Bronze, silicon, hard-drawn.		95–115				
Bronze, Tobin	8.40	60–100	180	4.5		
Copper, cast	8.5–8.9	22–25	40–60	10–12		
Copper, rolled	8.9	29–35			16.7	0.84
Copper, wire	8.89	35–70		12–16	16.7	0.84
Delta metal, cast		45				
Delta metal, rolled		70–85		13		
Delta metal, wire		100				
Duralumin	2.8	87				
Gold	19.3	20–30		8	14.4	0.70
Gun metal		22–27		10–11		
Lead	11.3	1.6–3.0			28.	0.084
Magnesium	1.74	30			26.	0.37
Monel metal	8.87	70–110		22–23	13.8	
Nickel	8.6–8.9	40–85		24–27	12.6	0.14
Palladium	11.4	39			11.	0.17
Platinum	21.4	30–50			8.8	0.17
Silver	10.5	40–45			19.	1.10
Tin	7.30	3.5–5		4	21.	0.15
Zinc, cast	6.87	6–13	18	11–13	26.	
Zinc, rolled	7.19	22–28		11–13	26.	0.27

Brick piers laid up in 1 part Portland cement, and 3 of sand, have from 20 to 40 per cent. of the crushing strength of the brick. Also see "Report of Tests of Metals," Gov. Printing Office, Washington, D. C., 1909.

407. Fire-brick when tested on end, at atmospheric temperature, should exhibit a crushing strength of more than 1,000 lb. per sq. in. More important is the ability to withstand a compression load of 50 lb. per sq. in. at 1,350 deg. cent. without failure; if the specimen shows marked deformation or contracts more than 1 in. in the standard length of 9 in., failure is considered to have taken place. Fire-brick should have average melting points as follows, in deg. cent.: fire clay, 1,650; bauxite, 1,695; silica, 1,700; chromite, 2,050; magnesia, 2,165.

408. Clay tile. The strength of drain tile is covered by standard specifications of the A. S. T. M. (see "Year Book"). Also see Bulletins No. 31 and No. 36, Iowa Eng. Exp. Sta., Ames, Ia.

409. Crushing strength of stone. (Smithsonian Phys. Tables, 1910; based on data furnished by U. S. Geol. Survey.)

Material	Size	Lb. per sq. in.
Marble	4-in. cubes	7,600 to 20,700
Brownstone	....	7,300 to 23,600
Sandstone	4-in. cubes	2,400 to 29,300
Granite	4-in. cubes	9,700 to 34,000
Limestone	4-in. cubes	6,000 to 25,000

TIMBER

410. Wood consists of a skeleton of cellulose permeated by a mixture of other organic substances collectively known as lignum, and particles of mineral matter (or ashes). Wood dried at 300 deg. fahr. is comprised of more than 99 per cent. organic matter, and less than 1 per cent. inorganic or non-combustible matter. In 100 lb. of wood dried at 300 deg. fahr. will be found about 49 lb. of carbon, 6 lb. of hydrogen and 44 lb. of oxygen; the composition is fairly uniform for the different species.

411. Spring wood and summer wood in coniferous trees are distinguished by the different colors in each ring. The inner light-colored portion of a ring is termed the spring wood, and the outer dark-colored portion is the summer wood. In oak and other broad-leaved woods, however, the darker portions are the spring wood and the lighter parts are summer wood.

412. Annual or yearly concentric rings which appear at the cross-section of a log are so many thin layers of wood, forming a consecutive series of enveloping cones, each ring or cone representing one year's growth. As a rule the rings are widest near the pith or centre of the tree.

413. Sapwood and heartwood. A zone of wood next to the bark, 1 in. to 3 in. or more wide, of light color and containing 30 to 50 or more annual rings, is the sapwood; the darker central portion is the heartwood. Only the outer portions of the sapwood assist in the growing processes and ultimately the sapwood changes to heartwood. The cells of the latter are lifeless and serve merely a structural function. The proportion of sapwood in coniferous trees constitutes 40 per cent. or more of the bulk, and a much larger proportion in young trees.

414. Moisture in wood. Water occurs in wood in three forms: (1) It forms the greater part (over 90 per cent.) of the protoplasmic contents of the living cells; (2) it saturates the walls of all cells; (3) it wholly or partly fills the cavities of the lifeless cells. In drying green wood in a kiln, from 40 to 65 per cent. of the weight of the sapwood and 16 to 40 per cent. of the weight of the heartwood are lost as excluded moisture. The weight is obviously dependent in large degree on the extent of seasoning or drying.

415. Shrinkage takes place as green wood is dried, but does not commence until the fibre saturation point is reached; then it commences to shrink both laterally and longitudinally, but the latter in most species is negligible. The shrinkage of transverse area in drying from green to oven-dry condition (3.5 per cent. of moisture) varies with different species from as much as 20 per cent. with hickory to as low as 7 per cent. with red cedar. The radial

Working unit stresses for structural timber (Par. 420)
(Unit stresses in pounds per square inch)

Kind of timber	Bending			Shearing				Compression					
	Extreme fiber stress		Modulus of elasticity	Parallel to the grain		Longitudinal shear in beams		Perpendicular to the grain		Parallel to the grain		Working stresses for columns	
	Average ultimate	Working stress	Average	Average ultimate	Working stress	Average ultimate	Working stress	Elastic limit	Working stress	Average ultimate	Working stress	Length under 15×d	Length over 15×d
Douglas Fir	6100	1200	1510000	690	170	270	110	630	310	3600	1200	900	1200 (1—$L/60D$)
Long-leaf Pine	6500	1300	1610000	720	180	300	120	520	260	3800	1300	975	1300 (1—$L/60D$)
Short-leaf Pine	5600	1100	1480000	710	170	330	130	340	170	3400	1100	825	1100 (1—$L/60D$)
White Pine	4400	900	1130000	400	100	180	70	290	150	3000	1000	750	1000 (1—$L/60D$)
Spruce	4800	1000	1310000	600	150	170	70	370	180	3200	1100	825	1100 (1—$L/60D$)
Norway Pine	4200	800	1190000	590*	130	250	100	.....	150	2600*	800	600	800 (1—$L/60D$)
Tamarack	4600	900	1220000	670	170	260	100	.....	220	3200*	1000	750	1000 (1—$L/60D$)
Western Hemlock	5800	1100	1480000	630	160	270*	100	440	220	3500	1200	900	1200 (1—$L/60D$)
Redwood	5000	900	800000	300	80	.....	.....	400	150	3300	900	675	900 (1—$L/60D$)
Bald Cypress	4800	900	1150000	500	120	.....	.....	340	170	3900	1100	825	1100 (1—$L/60D$)
Red Cedar	4200	800	800000	....	.....	.....	.....	470	230	2800	900	675	900 (1—$L/60D$)
White Oak	5700	1100	1150000	840	210	270	110	920	450	3500	1300	975	1300 (1—$L/60D$)

Unit stresses are for green timber and are to be used without increasing the live load stresses for impact. Value noted* are for partially air-dry timber. In the formulas given for columns, L = length of column, in inches, and D = least side or diameter, in inches.

finally the preservative is introduced under pressure. This method secures the maximum penetration and absorption.

The open-tank treatment, hot process at atmospheric pressure, is used extensively for treating the butts of poles. The penetration in open-grained porous wood is from 0.75 to 1.00 in., and in dense wood from 0.25 to 0.50 in. The brush treatment secures a penetration ranging from 0.06 to 0.25 in., or from two to three annual rings. The absorption in all cases is increased by seasoning. Also see Bulletin No. 78, U. S. Forest Service, 1909.

427. Strength of treated timber. Talbot concluded from his tests of timber (Bulletin No. 41, Eng. Exp. Sta., Univ. of Ill., 1909; also see Forest Service Circular No. 39) that creosoting, under ordinary practice, decreases the strength and the stiffness.

ROPE AND BELTING

428. Manila rope. The weight of Manila rope, based on the tests of the C. W. Hunt Co., is expressed by the formula

$$\text{Wt. per ft.} = 0.34d^2 \quad \text{(lb.)} \qquad (22)$$

where d is the diameter in inches. The tensile strength is given by the formula

$$T = 7{,}160d^2 \quad \text{(lb.)} \qquad (23)$$

where T is the total strength of the rope and d is the diameter in inches. Kirsch concluded from his tests that a rope having a diameter of 1 in. would have an average breaking strength as follows: Italian hemp, 9,910 lb.; Hungarian hemp, 9,293 lb.; Manila rope, 7,100 lb.

The Plymouth Cordage Co. gives the following rules for Manila rope: the weight per ft. is equal to the square of the diameter in inches, multiplied by 0.34; the breaking strength is equal to the square of the diameter, multiplied by 7,500; the maximum permissible tension (rope drives) is equal to the square of the diameter, multiplied by 200.

The C. W. Hunt Co. gives factors of safety, for computing the allowable working loads, approximately as follows: tackle, 7; hoisting, 18; transmission, 35. The efficiency of knots in rope ranges from 50 to 90 per cent.

For further data on tests of rope, see "Tests of Metals," reporting Watertown Arsenal tests, Gov. Printing Office, Wash., D. C.

429. Danger of metal filaments or strands in rope. Metal filaments are sometimes introduced in ropes to give added strength; when such ropes are used by linemen they become exceedingly dangerous, owing to the probability of communicating electrical shock. Similar danger exists from tape lines made of a fabric base and containing metal threads.

430. Leather belting weighs about 60 lb. per cu. ft. and has a tensile strength of from 2,000 to 5,000 lb. per sq. in., or an average of about 650 lb. per in. of width of single belt. See tests of leather belting in Watertown Arsenal Reports ("Tests of Metals") for 1893, Gov. Printing Office, Wash., D. C.

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Table 432.—*Continued*

Element	Symbol	Atomic weight	Density	Specific heat	Melting point (deg. cent.)
Lanthanum	La	139.0	6.15	0.045	810
Lead	Pb	207.10	11.37	0.030	327.4
Lithium	Li	6.94	0.534	0.85	186
Lutecium	Lu	174.0	....	....	....
Magnesium	Mg	24.32	1.72	0.249	651
Manganese	Mn	54.93	7.4	0.111	1260
Mercury	Hg	200.6	13.55	0.033	−38.7
Molybdenum	Mo	96.0	8.5	0.064	2500
Neodymium	Nd	144.3	....	....	840
Neon	Ne	20.2	....	....	−253
Nickel	Ni	58.68	8.80	0.109	1452
Niton	Nt	222.4	....	....	....
Nitrogen	N	14.01	0.83	....	−210
Osmium	Os	190.9	22.5	0.031	2700
Oxygen	O	16.00	1.14	....	−218
Palladium	Pd	106.7	11.4	0.059	1549
Phosphorus	P	31.04	2.34	0.19	44
Platinum	Pt	195.2	21.45	0.032	1755
Potassium	K	39.10	0.87	0.170	62.3
Praseodymium	Pr	140.6	6.475	....	940
Radium	Ra	226.4	....	....	....
Rhodium	Rh	102.9	12.4	0.058	1940
Rubidium	Rb	85.45	1.532	....	38
Ruthenium	Ru	101.7	12.3	0.061	>1950
Samarium	Sa	150.4	7.75	....	1350
Scandium	Sc	44.1	....	....	....
Selenium	Se	79.2	4.55	0.068	218.5
Silicon	Si	28.3	2.1	0.175	1420
Silver	Ag	107.88	10.6	0.055	960.5
Sodium	Na	23.0	0.971	0.253	97.5
Strontium	Sr	87.63	2.54	....	....
Sulphur (S_I)	S	32.07	2.05	0.173	112.8
Tantalum	Ta	181.5	16.6	0.033	2850
Tellurium	Te	127.5	6.25	0.048	452
Terbium	Tb	159.2	....	....	....
Thallium	Tl	204.0	11.85	0.033	302
Thorium	Th	232.4	11.0	0.027	>1700
Thulium	Tm	168.5	....	....	....
Tin	Sn	119.0	7.30	0.054	231.9
Titanium	Ti	48.1	8.5	0.110	1795
Tungsten	W	184.0	18.85	0.034	3000
Uranium	U	238.5	18.7	0.028	....
Vanadium	V	51.0	5.5	0.115	1720
Xenon	Xe	130.2	3.52	....	−140
Ytterbium	Yb	172.0	....	....	....
Yttrium	Y	89.0	3.8	....	....
Zinc	Zn	65.37	7.19	0.093	419.4
Zirconium	Zr	90.6	4.14	0.066	1700

433. Density of water, from 0 to 100 deg. cent. (Circular No. 19, Bureau of Standards).

Temp.	Density	Temp.	Density	Temp.	Density	Temp.	Density
0	0.99987	25	0.99707	50	0.98807	75	0.97489
4	1.00000	30	0.99567	55	0.98573	80	0.97183
10	0.99973	35	0.99406	60	0.98324	85	0.96865
15	0.99913	40	0.99224	65	0.98059	90	0.96534
20	0.99823	45	0.99024	70	0.97781	100	0.95838

SECTION 5

MAGNETS

BY CHARLES R. UNDERHILL

GENERAL

1. A magnet is a body which possesses the property of attracting magnetic substances. All magnets may be divided into two classes, *i.e.*, permanent magnets and electromagnets.

2. A permanent magnet is one which retains a nearly constant value of m.m.f. for an indefinite period. The permanent magnets used in practice are made of hardened steel and are magnetized by placing them in a strong magnetic field.

3. An electromagnet or temporary magnet is one in which the magnetic field is produced by an electric current. In its simplest form, it consists of a helix of conducting material which, when energized by an electric current, possesses many of the magnetic-field characteristics of a permanent magnet. Since soft iron is capable of being magnetized to a high degree and retains very little permanent magnetism, with the result that the magnetic field may be varied in great degree by regulating the strength of the current, electromagnets are usually provided with soft-iron cores.

PERMANENT MAGNETS

4. Permanent magnets are used where a constant field is desired, as in electrical instruments, magneto-generators, etc. In order to retain its strength, a permanent magnet should have as short an air-gap as possible and the ratio of its length to its cross-sectional area should be great. Unless proper precautions are taken, the steel is likely to crack and warp in hardening.

5. Permanent magnets lose a portion of their original magnetism when used for a long time, so that they become what is termed aged. Those used in instruments, magnetos, etc., are **artificially aged** in the process of manufacture. This is accomplished in various ways. One method of aging magnets for watt-hour meters is to pass them several times through a bath of boiling water or oil and then to demagnetize them to about 7 per cent. of the original value by rotating a copper disc between the poles. Another method is to place a large number of magnets parallel to each other, with a copper strip between the poles, and then to demagnetize them by passing a strong current through the strip. (Also see Par. 10.)

6. Permanent magnets are made from the best grade of crucible tungsten steel which contains about 5 per cent. of tungsten, a small percentage each of chromium and manganese, and from 0.63 to 0.66 per cent. carbon. Domestic steel of this variety is found to be equal to or better than any imported magnet steel.

7. Details of manufacture. The practice of the Sangamo Electric Co. is as follows: After preliminary tests, the steel bars are sheared cold and then heated in a special fuel-oil furnace so arranged that the products of combustion do not come directly in contact with the steel. The pieces are forged at a bright red heat, in a large press, using but one heat if possible. A vertical type press is preferred to the "bull-doser" type. The pieces are then allowed to cool in the air, if no drilling is required; or, if drilling is necessary, they are packed in mica dust to prevent air-hardening, which takes place to a certain extent even with steel containing no more than

19. An iron-clad solenoid is a solenoid-and-plunger provided with an iron or steel frame or jacket. The effect is to confine the magnetic field within the limits of the frame. When provided with a stop, as in Fig. 1, this type is commonly known as a **plunger electromagnet.**

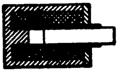


FIG. 1.—Plunger electromagnet.

20. A bar electromagnet is a solenoid-and-plunger with the plunger inserted in the solenoid and rigidly fixed in position.

21. A horseshoe electromagnet is a bar electromagnet bent into U form in order to bring the pole ends near together. The practical type consists of two bar electromagnets magnetically joined together at one end by means of a **yoke or backiron.** Both coils are usually wound in the same direction and their inside wires connected together. The **armature** consists of a piece of soft iron or steel of sufficient length to bridge the gap from pole to pole, and of cross-section great enough to conduct the flux economically.

22. An iron-clad electromagnet is a bar electromagnet inserted in a soft-iron or steel cup, so that the rim of the cup and the core of the electromagnet form the attracting surfaces (or poles) for the armature, which usually consists of a disc of soft iron or steel.

23. Modified types. There are many modifications of the above fundamental types. For instance, plunger electromagnets are sometimes made in the horseshoe form, and a modification of the horseshoe electromagnet will be recognized in the iron-clad electromagnet. In some telephone relays, an angle-iron is employed instead of the shell or cup.

GENERAL THEORY OF ELECTROMAGNETS

24. Maxwell's fundamental equation for the pull applies strictly to a portative electromagnet consisting of a bar electromagnet separated at its middle and having a hypothetically zero air-gap, so that no flux can leak back from the abutting ends of the half-cores to their opposite ends. The equation for the pull in dynes per sq. cm. is $P = \mathfrak{B}^2/8\pi$. But $\mathfrak{B} = 4\pi\mathfrak{J} + \mathfrak{H}$, wherein $\mathfrak{J}$ is the intensity of magnetization in the iron only. It is convenient to reduce $4\pi\mathfrak{J}$ to ϕ_i/s, and $\mathfrak{H}$ to ϕ_a/s, wherein ϕ_i is the iron flux, equivalent to the flux in a permanent magnet; ϕ_a is the flux in the air-core only, and s is the cross-sectional area of the core in square centimeters. Then

$$\mathfrak{B} = \frac{\phi_i + \phi_a}{s} \qquad \text{(gausses)} \qquad (1)$$

$$\text{whence } P = \frac{\phi_i^2 + 2\phi_i\phi_a + \phi_a^2}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (2)$$

25. Theoretical components of pull. Conventionally stated, $\phi_i^2/8\pi s^2$ is the purely magnetic pull between the two half-cores; $2\phi_i\phi_a/8\pi S^2$ is the pull due to the "solenoid effect" between the half-coils and the half-cores; and $\phi_a^2/8\pi s^2$ is the pull between the half-coils, which cannot be utilized in practical electromagnets with solidly wound coils. The actual pull, in dynes per square centimeter, for such a portative electromagnet, *i.e.*, when there is no appreciable air-gap between the attracting surfaces of the half-cores, and the coil is solidly wound, is

$$P = \frac{\phi_i^2 + 2\phi_i\phi_a}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (3)$$

26. Total pull between two polar surfaces. An electromagnet can do work only when there is an air-gap. The longitudinal contraction of the flux in the air-gap of a tractive electromagnet causes the pull. The pull in dynes per square centimeter between the polar surfaces of the cores of a horseshoe electromagnet and its armature, or for any other type of electromagnet with the coils and cores rigidly fixed, relatively, is $P = \phi_g^2/8\pi s^2$, wherein ϕ_g is the total average flux producing the pull. This equation expresses the pull in an air-gap, or the pull between two magnetic masses in contact, and holds for permanent magnets.

27. The pull due to an iron-clad solenoid or a plunger electromagnet consists of two components, since there are two magnetic circuits in shunt ductance (Par. 31) in henrys, and t the elapsed time in seconds from the moment the circuit was closed. Solving the above equation for t,

$$t = -\frac{L}{R} \log_e\left(1 - \frac{R_i}{E}\right) \qquad \text{(sec.)} \qquad (7)$$

wherein L/R is called the time-constant. From this it is seen that for a given ratio of instantaneous current to the Ohm's law or steady current the time-constant is the only factor which determines the time required to establish it. The time-constant is fixed by the magnetic circuit and by the ampere-turns (when iron is present), and is independent of the number of turns, since both the resistance and the inductance vary as the square of the number of turns, for a given winding volume.

31. The approximate inductance of a magnet, in which the air-gap is not very long, can be found by assuming the magnet to be connected to a source of alternating e.m.f., of known frequency and having a sine-wave form. Let l_i be the length in cm. of the iron circuit; l_a the length in centimeters of the air-gap; N the number of turns; s the cross-sectional area in square centimeters of the magnetic circuit, and ϕ the maximum value of the total flux. Then the alternating e.m.f. which must be impressed upon the winding to produce a maximum flux ϕ, is

$$E = 4.44 f N \phi 10^{-8} \qquad \text{(volts, effective)} \qquad (8)$$

where f is the frequency in cycles per second. The approximate reluctance is,

$$\mathcal{R} = \frac{1}{s}\left(\frac{l_i}{\mu} + l_a\right) \qquad \text{(oersteds)} \qquad (9)$$

μ can be taken from curves in Sec. 4. The m.m.f. is $\mathcal{F} = 1.257NI$ wherein I is the effective (root mean square) current in amperes. It follows from $\mathcal{F} = \phi\mathcal{R}$ that

$$I = \frac{\phi\mathcal{R}}{1.257N} \qquad \text{(amp.)} \qquad (10)$$

and then

$$L = \frac{E}{2\pi f I} \qquad \text{(henrys)} \qquad (11)$$

32. Effect of movable plunger. Magnets with movable plungers which are designed for quick and powerful action require careful study of the initial conditions. At the first instant, the value of the current increases at such a rate that the flux interlinked with the winding will generate a counter-e.m.f. equal to the impressed e.m.f. The pull produced by the flux due to this current will start the plunger, and the sudden decrease in reluctance due to the closing of the air-gap will produce a corresponding increase in flux and thus decrease the rate of change of the current, that is, the current will be retarded in reaching its final and permanent value. Because of this phenomenon it is usual to design such magnets (for instance, those used on automatic starters) for a much lower impressed e.m.f. than is actually used at the start; in order then to protect the winding, a higher resistance is automatically inserted in series with it at the moment the plunger arrives at the end of its stroke. This resistance limits the current to that value necessary to maintain the required final pull on the plunger.

33. The action of the plunger in reducing the reluctance of the magnetic circuit may be approached from the energy standpoint; thus, the total energy which is supplied to the magnetic field up to any instant is

$$W = E\int_0^t i\,dt = \frac{i^2L}{2} + 0.113Fl \qquad \text{(watt-seconds)} \qquad (12)$$

wherein i is the instantaneous value of the current in amperes, L the instantaneous value of the inductance in henrys, F the average pull on the plunger in pounds, and l the distance traveled in inches.

curves represent the energy transferred to the magnetic field, in each case. With the moving plunger, the total energy input to the magnetic field is the area *cdihf*, while that left as stored energy at the end of the stroke and which must be dissipated when the circuit is broken is the area *cghf*. The difference between these two, *cdihg* (cross-hatched) represents the energy transformed into mechanical work and dissipated by friction and impact of the plunger during its travel, iron losses being neglected.

36. Impressed e.m.f. The final permanent value of impressed e.m.f. in continuous-current magnets is determined by the resistance.

37. The speed of the magnet action also depends upon the secondary losses (eddy currents, Sec. 2). These losses tend to reduce the flux in the core and thus retard the attainment of the maximum pull. This effect can be reduced by **laminating** the core and frame and by avoiding the use of a metallic bobbin. It can also be reduced by using fewer turns and larger current.

38. Slow-speed magnet action is obtained by increasing the time-constant and the secondary losses. The secondary losses can be greatly increased by dividing the winding into sections and short-circuiting more or less of the sections. Fig. 5 shows the effect of short-circuiting a portion of the winding.* The total number of turns was 8,400; in curve (1), only 2,165 turns were energized, while in curve (2), 2,165 turns were energized and 6,235 turns short-circuited. In the first case it required about 2.5 seconds to reach the maximum current, while in the second case, 4 seconds were required.

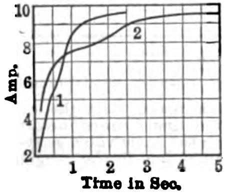


Fig. 5.—Showing the effect on the current-time curve of short-circuiting a portion of the winding.

39. Inertia of moving system. When the speed of action is an important factor, the inertia of the load to be moved must be considered. For the same pull and range, a quicker action will be obtained in overcoming the tension of a spring than in moving a mass whose weight is equivalent to the tension of the spring. The total mass to be moved is the sum of that of the plunger and the external load.

40. The selection of the type of electromagnet for specific work depends upon the nature of the e.m.f. (whether continuous or alternating) the range or distance of travel, and the rate of travel or the quickness of action. In general, the iron-clad solenoid type is mechanically the better protected and is the best adapted for a long range and a strong pull, but it is slow in action. The horseshoe type has the quicker action, but is only adapted for short ranges. The plunger-electromagnet type has an action intermediate between the above-mentioned types and may approximate one or the other according to the range and the dimensions of the plunger. The bar type possesses the quickest action of all, but its pull is comparatively feeble. The general rule is that what is lost in time is gained in pull and *vice versa*.

41. The required dimensions of an electromagnet are proportional to the load, the range, the duration of excitation and the interval between excitations. The cross-sections of the plungers, cores and frames will depend upon the flux required to produce the desired pull. In long-range electromagnets of the solenoid type, wherein the pull is proportional to the product of the magnetizing force times the flux in the plunger, the plunger may be of small cross-section, if the duration of excitation is to be brief, since the magnetizing force of a comparatively small coil may be made great for a short period without danger of injury from overheating. This does not hold for a horseshoe type, since the main pull is dependent upon the flux which the cores are able to conduct, and is only slightly affected by an increase in the magnetizing force after the cores approach saturation.

42. Electromagnets designed for continuous service must have windings of such volume and radiating surface, and wires of such cross-sections,

* Lindquist, D. L. "Alternating-current Magnets;" *Electrical World*, 1906, Vol. XLVII, p. 1295.

ing force has a high value as compared with the cross-sectional area of the plunger, the maximum pull may occur for a considerable distance on each side of the middle of the solenoid. On the other hand, with very short solenoids, the maximum pull may occur at or near the end of the solenoid opposite to that at which the plunger enters.

48. Characteristic pull with solenoid and plunger. Fig. 8 shows the approximate pull diagram for different positions of the plunger. The expression for the maximum uniform pull is

$$F = Cs\frac{NI}{l} \quad \text{(lb.)} \qquad (15)$$

where I is the current in amp., N the number of turns, s the cross-sectional area of the core or plunger in square inches, l the length of the solenoid in inches and C the pull in pound per square inch per ampere-turn per inch. C depends upon the proportions of the coil, the degree of saturation, and the length, physical character and chemical purity of the plunger. Par. 50 gives values for C for various solenoids tested by the author.

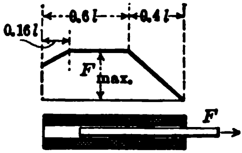


Fig. 8.—Diagram of plunger pull for simple solenoid and plunger.

49. In magnets with long air-gaps, the path through the iron can be considered as having no reluctance. Therefore the **saturation characteristic** can be assumed to be a straight line, and the ampere-turns for the air-gap directly proportional to the flux density.

50. Maximum Pull per Square Inch of Core for Solenoids with Open Magnetic Circuit*

Length of coil (in.)	Length of plunger (in.)	Area of core (sq. in.)	Total amp-turns	Amp-turns per in.	Max. pull, lb. per sq. in	Lb. per sq. in. per 1,000 amp-turn per in.
6	Long	1	15,000	2,500	22.4	9.0
9	Long	1	11,330	1,260	11.5	9.1
9	Long	1	14,200	1,580	14.6	9.2
10	10	2.76	40,000	4,000	40.2	10.0
10	10	2.76	60,000	6,000	61.6	10.3
10	10	2.76	80,000	8,000	80.8	10.1
12	Long	1	11,200	930	8.75	9.4
12	Long	1	20,500	1,710	16.75	9.8
18	36	1	18,200	1,010	9.8	9.7
18	36	1	41,000	2,280	22.5	9.8
18	18	1	18,200	1,010	9.8	9.7
18	18	1	41,000	2,280	22.5	9.8

Note.—These tests indicate that nothing is gained in maximum pull by making the plunger considerably longer than the coil.

51. The diameter of the coil should be about three times that of the plunger, and the **length of the coil** should be at least two or three times its outside diameter whenever possible.

52. The range is directly proportional to the length of the coil, **regardless** of the ampere-turns.

53. The pull in an iron-clad solenoid, with or without a stop, is composed of two components; one is the pull between the end of the stop or frame and the plunger, and the other is that between the winding and the plunger. The latter is all important at the beginning of the stroke, but near the end the stop-pull becomes predominant. The expression for the pull is

$$F = s\left(\frac{NI}{l_aC}\right)^2 + \frac{sCNI}{l} = sNI\left[\frac{NI}{l_a^2C^2} + \frac{C}{l}\right] \quad \text{(lb.)} \qquad (16)$$

* Underhill, C. R. "The Practical Design of the Solenoid;" *Electrical World and Engineer*, 1905, Vol. XLV, p. 796.

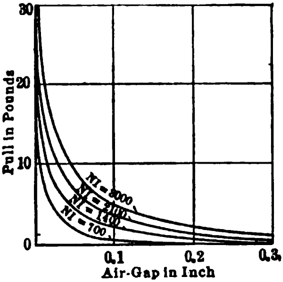


FIG. 10.—Test curves on pull of horseshoe electromagnet.

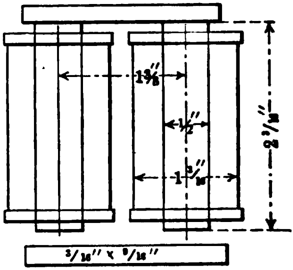


FIG. 11.—Horseshoe type of electromagnet.

magnetic material located in the armature directly under the centre of the magnet cores. The total amp-turns, with 0.075 amp., are 127.5; the cores are ⅝ in. in diameter, and each spool is 4 in. long by 2 in. in diameter. In general, signal relays are required to release their armatures when the energising current is reduced one-half.

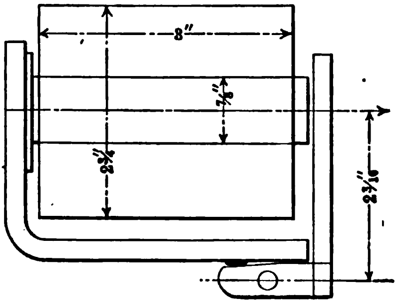


FIG. 12.—Clapper type of horseshoe electromagnet.

60. Electromagnets for telegraph and telephone service, like those for signal apparatus, are designed to perform the sole function of closing or opening one or more local contacts which control other circuits and apparatus. The armatures of these magnets customarily work through very limited ranges, not exceeding as a rule a very small fraction of an inch; the opposing force is sometimes gravity, sometimes a light spring. Such relays are also wound differentially for certain kinds of work, and sometimes are polarized (having a permanently magnetized steel core) in order to respond only to currents flowing in a given predetermined direction around the windings (see Sec. 21).

61. The equation for the pull due to electromagnets of the horseshoe type is given by

$$F = s\left(\frac{NI}{l_a c}\right)^2 \quad \text{(lb.)} \qquad (18)$$

where the constants are the same as those given in Par. 58. The total length of all the air-gaps is to be taken for l_a. The equation is only approximately correct, in this case, owing to leakage. It is better to increase the

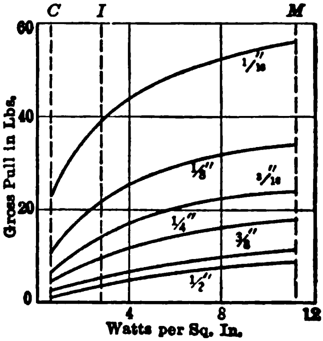
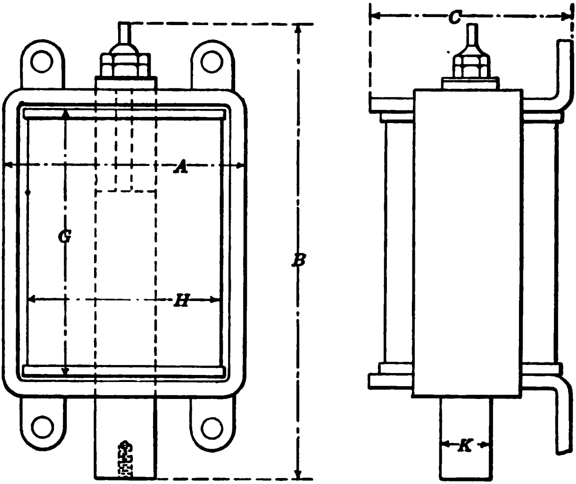


FIG. 13.—Test curves on pull of clapper type of electromagnet.



No.	Curve	*A*	*B*	*C*	*G*	*H*	*K*
3	Fig.18	3¼"	6¼"	3"	3"	2¾"	¾"
5	Fig.19	4⅛"	8¾"	3¾"	4¾"	3⅜"	1"

Fig. 17.—Standard type of plunger electromagnet with flat-end plunger.

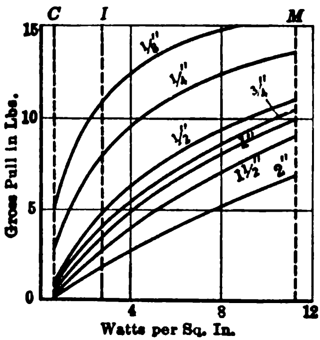


Fig. 18.—Test curves on pull of standard type of plunger electromagnet No. 3 in Fig. 17.

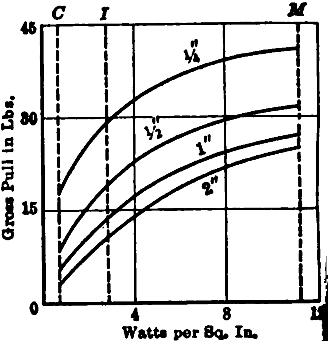


Fig. 19.—Test curves on pull of standard type of plunger electromagnet No. 5 in Fig. 17.

64. Continuous-duty electromagnets may be excited at full voltage continuously without dangerous heating of the coils, but the pull becomes somewhat reduced when the windings reach full temperature, due to the increased resistance in the coil.

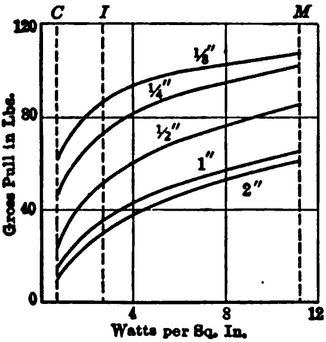


FIG. 23.—Test curves on pull of standard type of plunger electromagnet No. 6 in Fig. 20.

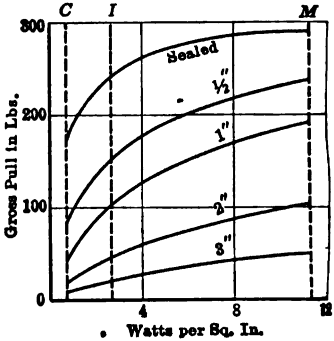


FIG. 24.—Test curves on pull of standard type of plunger electromagnet No. 22 in Fig. 20.

65. Intermittent duty is an arbitrary rating and, in general, these magnets may be excited at full voltage for not over 7 min. during any half-hour, without dangerous heating.

66. Momentary duty is also an arbitrary rating which represents the

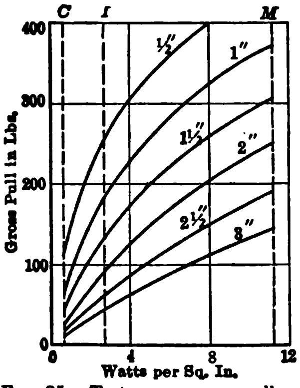


FIG. 25.—Test curves on pull of standard type of plunger electromagnet No. 23 in Fig. 20.

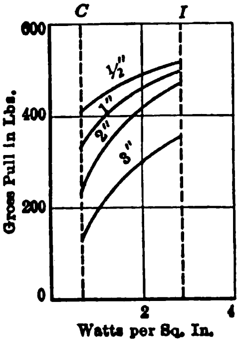


FIG. 26.—Test curves on pull of standard type of plunger electromagnet No. 26 in Fig. 20.

highest practicable rating of these magnets, and full voltage should not be maintained on them for more than 2 min. during any half-hour.

67. Protected coils have a resistance which is cut into circuit by the action of the plunger at the completion of the stroke, for the purpose of reducing the voltage at the coil terminals to a continuous-duty value.

69. Two forms of plungers are shown; one is conical, and the other square at the ends. The curves show the former to be preferable on most of the long-stroke types, as the tendency is to increase the starting pull and reduce the final pull. For short strokes, the square-end type is preferable.

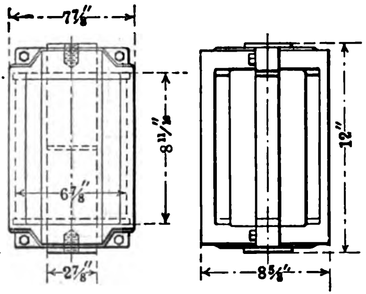


Fig. 30.—Standard type of plunger electromagnet with flat-end plungers. (See Fig. 31.)

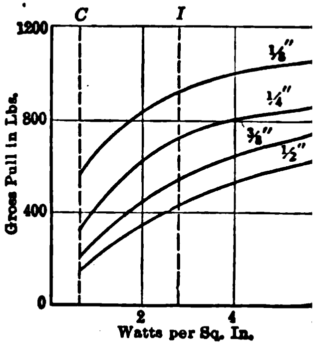


Fig. 31.—Test curves on pull standard type plunger electromagn in Fig. 30.

PORTATIVE ELECTROMAGNETS

70. Lifting magnets. Large iron-clad magnets called lifting magnets are now extensively used for the handling of materials in all branches of the iron and steel industry. They are used for handling pig iron, scrap, castings, billets, tubes, rails, plates and crop ends; for loading and unloading cars and ore vessels, and for handling skull-cracker balls and miscellaneous material.

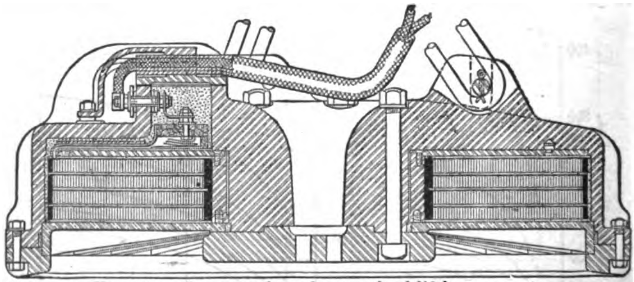


Fig. 32.—Cross-section of a standard lifting magnet.

71. Operation. All lifting magnets, of whatever make, are suitable for use on continuous-current circuits only. It is not customary to operate the magnets on very high voltages, owing to the difficulty of securing insulating material that will withstand the high inductive reaction that occurs when the circuit of a magnet is suddenly opened. Standard magnets are designed for operation on 220-volt continuous-current circuits.

72. Lifting load. It is quite impossible to calculate the load which may be lifted, owing to the varying contact of the load, but Par. 73, giving a table published by one of the leading manufacturers, shows the approximate lifts for various magnets and materials.

74. General construction. These magnets are very rugged in construction, as they are subject to exceedingly rough usage. The frame or body of the magnet is made, in one instance, of a special grade of dynamo steel which combines great strength and ductility with excellent magnetic qualities. They are designed to withstand heat without injury and are waterproof. Fig. 32 shows the construction of a lifting magnet made by the Cutler-Hammer Clutch Co.

75. Operating cost. The Cambria Steel Co. state that their costs for unloading material from broad-gage cars into open-hearth charging boxes are as follows: Handling light scrap, 3.15 cents per ton; handling heavy scrap, 2.28 cents per ton; handling pig iron, 3.06 cents per ton. These costs include: electric energy, repairs, interest and depreciation for crane and magnet, and all labor. About 50 per cent. of the foregoing cost is for labor in trimming the charging boxes.

The Inland Steel Co. reports that about 4,000,000 lb. of machine cast pig iron were unloaded in 10.5 hr. by two 62-in. magnets. The average lift per magnet was 3,427 lb.

76. Holding magnets. Portative magnets are extensively used for holding tools and materials in grinding and other machines. The no-load release magnet belongs to this class.

ALTERNATING-CURRENT TRACTIVE ELECTROMAGNETS

77. The design of an alternating-current magnet involves calculations which are essentially the same as those for an ordinary transformer. The total flux is determined by the number of turns, the supply voltage and the frequency; thus

$$E = \frac{2\pi f N \phi_{max}}{\sqrt{2}\, 10^8} = 4.44 N \phi_{max}\, 10^{-8} \text{ (volts, effective)} \quad (19)$$

and

$$\phi_{max} = \frac{E\, 10^8}{4.44 f N} \qquad \text{(maxwells)} \quad (20)$$

where f is the frequency in cycles per second, N the number of turns, and E the impressed e.m.f. in volts.

Taking f and N as constant,

$$\phi_{max} = s\mathcal{B}_{max} = KE \qquad \text{(maxwells)} \quad (21)$$

and

$$\mathcal{B}_{max} = K\frac{E}{s} \qquad \text{(gausses)} \quad (22)$$

That is, for a given impressed e.m.f. the flux density will vary inversely as the area of the core.

78. Flux density. Since the air-gap pull varies approximately as the square of the flux density, it would appear that the flux density should be as great as possible. However, the iron losses also increase with the flux density, so that the maximum possible flux density is not the most efficient.

79. Iron losses. The major portion of the total loss takes place in the iron rather than in the copper. The **hysteresis loss** (Sec. 2) is calculated in the same way as that of a transformer, and denoted by P_h. The **eddy-current loss** (Sec. 2) is denoted by P_e. Then the total core loss is

$$P_c = P_h + P_e \qquad \text{(watts)} \quad (23)$$

80. The quadrature exciting watts are expressed thus:

$$P_x = 2.5 f \frac{\phi^2_{max}}{s}\left(l_a + \frac{l_i}{\mu}\right)10^{-8} \qquad \text{(watts)} \quad (24)$$

wherein l_a is the length of the air-gap in centimeters, l_i the mean length in centimeters of the magnetic circuit in the iron, and s is the cross-sectional area of the core in square centimeters. Expressing this in terms of the volume of the air-gap and of the iron, which quantities must be known in determining the core losses,

$$P_x = 2.5 f \mathcal{B}^2_{max}\left(V_a + \frac{V_i}{\mu}\right)10^{-8} \qquad \text{(watts)} \quad (25)$$

POLYPHASE ELECTROMAGNETS

87. Test data on two-phase electromagnet. Fig. 33 shows the relation between volt-amperes and pounds pull for a two-phase magnet designed and tested by D. L. Lindquist.* The magnet contained four coils, each wound with 220 turns of No. 14 A.W.G. copper wire, the cross-sectional area of the core being 1.94 sq. in. The test was made with the magnet-winding connected to a two-phase 60-cycle system. The method of connecting the coils is shown in Fig. 34.

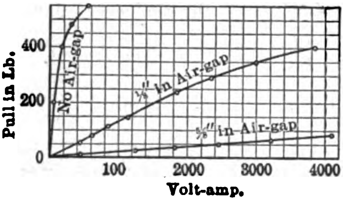


FIG. 33.—Relation between volt-amp. and pull for a two-phase electromagnet.

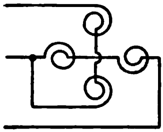


FIG. 34.—Connections of two-phase electromagnet.

88. Pulsation of pull. Theoretically, the pull in magnets equipped with polyphase windings should be constant and equal to the maximum pull due to the maximum flux produced in one phase. This, however, is only true when the e.m.f. wave is a pure sine-function. Distortion of the e.m.f. wave will alter the mean effective pull. In any case, if the load exceeds the minimum instantaneous pull, there will be chattering exactly similar to that in a single-phase magnet.

89. Polyphase magnets used in signal relays are, in effect, induction motors so designed that the rotor can revolve through a sufficient angle to operate the contacts. This gives a constant drag on the rotor due to the rotary magnetic field and avoids chattering.

HEATING OF ELECTROMAGNETS

90. Capacity limited by heating. The capacity of a given electromagnet is limited by the amount of heat which it can dissipate per unit time without exceeding a given or safe temperature rise.

91. The temperature rise can be measured by placing a thermometer against the outside surface or by measuring the change in resistance (Sec. 3). The general formula given below supposes the mean temperature rise to be measured by the thermometer method. The resistance method gives results which are from 1.5 to 2 times greater than those obtained with a thermometer, depending upon the depth of the winding, circulation of the air, etc.

92. Formula for temperature rise. The general equation for the final temperature rise in a given coil is

$$t_e = k\frac{P}{A} \quad \text{(deg. cent.)} \qquad (33)$$

where P is the power, in watts, dissipated in the coil; A the outside cylindrical surface of the coil (the ends are counted only in short coils, and the inside surface is not counted), and k is the temperature rise in centigrade degrees per watt per square inch of outside cylindrical surface. Values for the constant, k, in the above formula differ widely according to the proportions of the coil, the depth of the winding, etc. The following values represent average practice. For open electromagnets, $k = 130$; for iron-clad electromagnets, $k = 95$.

93. Safe temperature limits. The final temperature rise varies between 50 deg. cent. and 75 deg. cent. according to the specifications, the climate, the depth of winding, etc. The internal temperature rise is limited to that which

* Lindquist, D. L. "Polyphase Magnets;" *Electrical World*, 1906, Vol. XLVIII, p. 128. "Characteristic Performance of Polyphase Magnets," *Electrical World*, 1906, Vol. XLVIII, p. 564.

99. Space factor. The most efficient winding is that which contains the maximum amount of conducting material; hence a thin insulation of high dielectric strength is desirable. The space factor or **activity coefficient** is the ratio of the space occupied by the insulated conductor to that occupied by the bare conductor. This is conveniently expressed in terms of turns per square inch. The Tables (Par. **98, 102, 104, 106**) show the relative values for the various wires. Enamel and silk, and enamel and cotton, are designed to replace double-silk- and double-cotton-covered wires, respectively; the former two have higher activity coefficients and greater dielectric strengths than the latter two.

WINDING CALCULATIONS

100. Winding formulas. In what follows let

d = diameter of bare copper wire in inch,
R_l = ohms per linear inch,
d_l = diameter of insulated wire in inch,
t'' = turns per linear inch,
n'' = layers per inch,
N_s = turns per square inch,
R_v = ohms per cubic inch.

Then the number of **ohms per linear inch** is

$$R_l = 8{,}628 d^{-2} 10^{-10} \quad (35)$$

and

$$t'' = d_l^{-1} \text{ (or is found by actual count)} \quad (36)$$

For layer windings with no paper between layers,

$$n'' = t'' \text{ (approx.)} \quad (37)$$

When paper is used,

$$n'' = (d_l + t_p)^{-1} \quad (38)$$

wherein t_p is the thickness of the paper layer.

The **turns per square inch** and the **ohms per cubic inch** are given by

$$N_s = t''n'' \quad (39)$$

$$R_v = N_s R_l \quad (40)$$

The properties and dimensions of bare copper wires will be found in Sec. 4. Furthermore let

T = thickness of wall of winding in inches,
L = actual length of winding in inches,
p_a = average perimeter or mean length of turn in inches,
S = longitudinal cross-sectional area of winding in square inches,
V = volume of winding in cubic inches.

The **winding cross-section** and the **winding volume** are

$$S = TL \quad (41)$$

$$V = Sp_a \quad (42)$$

In all usual shapes of coils, the **thickness of coil-wall** is $T = n/n''$, where n is the number of layers. For coils wound on cores or forms of the shapes in Fig. 35, the equation

$$p_a = 2(a + b + 1.571T - 0.859r) \quad (43)$$

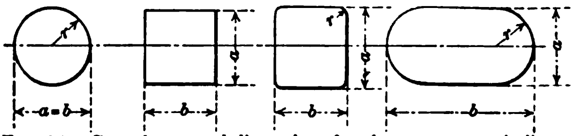


FIG. 35.—Core shapes and dimensions for electromagnet windings.

is general and gives the **mean length of turn** for coils with cores of any of these shapes. In the case of the perfectly square or rectangular core, the radius, r, is zero; whereas, in the case of the round core, it is, of course, equal to one-half of the diameter.

For a round core only,

$$p_a = \pi(D_l + T) \quad (44)$$

where D_l is the inside diameter of the coil. In all cases, the dimensions of then to make the final calculations after the turns per layer and number of layers have been determined from the preliminary data.

For a round winding, with given core, length, size of wire and resistance, the **outside diameter** will be

$$D = \left[\frac{4}{\pi L}\left(\frac{R}{R_v}\right) + D_i^2\right]^{\frac{1}{2}} \tag{48}$$

The approximate **thickness of wall** of winding will be

$$T = \frac{D - D_i}{2} \tag{49}$$

The **number of layers** will be $n = Tn''$, and a new value for T will be found for an exact number of layers, by $T = n/n''$. The **mean length of turn** will be $p_a = \pi(D_i + T)$ and the **outside diameter** will now be $D = D_i + 2T$. The **number of turns** will be $N = nt''L$, and the **resistance**, $R = Np_aR_l$. For round windings, the **radiating surface is** $A = \pi DL$, where A is the cylindrical surface.

104. Ohms per Cubic Inch; Solid Layer Winding

(The Acme Wire Co.)

Size A.W.G.	Single-cotton covered	Enamel and cotton	Single-silk covered	Enamel and silk	Enamel
10	.00727	.00702	....	....	.00768
11	.0114	.0110	....	....	.0123
12	.0180	.0172	....	....	.0194
13	.0282	.0268	....	....	.0307
14	.0442	.0418	....	....	.0485
15	.0690	.0658	....	....	.0774
16	.1072	.1017	....	....	.1225
17	.167	.158	....	....	.193
18	.260	.243	....	....	.305
19	.401	.373	....	....	.479
20	.652	.610	.731	.682	.767
21	1.01	.948	1.145	1.075	1.225
22	1.55	1.45	1.788	1.652	1.915
23	2.39	2.21	2.79	2.56	3.01
24	3.67	3.36	4.37	3.97	4.74
25	5.60	5.14	6.79	6.17	7.54
26	8.50	7.85	10.5	9.62	12.03
27	12.93	11.85	16.3	14.8	19.0
28	19.6	17.8	25.3	22.8	30.1
29	29.1	26.6	38.5	34.8	47.3
30	43.8	39.7	59.6	53.2	74.8
31	64.1	57.7	91.1	79.1	115.3
32	94.9	86.0	136.5	121.5	184.2
33	140	125.8	208	183.5	291
34	205	183	315	274	456
35	297	263	473	408	711
36	426	375	705	597	1100
37	....	....	1032	888	1742
38	....	....	1525	1300	2710

CONSTRUCTION OF COILS

105. Methods of winding. There are two standard methods of winding coils. The original method is to prepare the bobbin for the wire and then to wind the coil by rotating the bobbin in a small special lathe and guiding the wire by hand. The second method involves the use of patented automatic machinery.

at the ends so that the fringes will overlap one another when bent at right angles to the tube. The coil is then mounted on the muslin-covered tube and several oiled muslin washers are placed on each end. A slotted fiber washer is mounted at the end with the inside lead, and the lead is brought out through the slot after being wound once around the tube; the inside diameter of this washer should be sufficient to slip over the turn of the lead. More oiled-muslin washers are then put on, and the fringes are fanned out at both ends of the coil, after which heavy fibre end washers are put on and the ends of the brass tube spun over. This makes a very solidly constructed and well-insulated coil. In alternating-current coils, the brass tube must be slotted lengthwise. When flat ribbon leads are used, it is not necessary to use a slotted washer.

All splices should be soldered and thoroughly protected with oiled muslin. The leads should be tied in position with stout twine.

111. Covering. Mounted coils are covered with cord, pressboard, oiled muslin, etc., and are often dipped in black air-drying varnish to give them a protecting finish.

TESTING OF MAGNETS

112. Measurement of pull. The attracting effort of a small portative magnet or a small tractive magnet, with the armature or plunger in contact with the pole faces or stop, may be measured with a spring balance. Large magnets may be tested by direct loading or by loading through a system of levers. The **pullout point** is not preceded by any warning and, in order to obtain accurate load readings, the load must be applied at a uniform rate and under perfect control.

A simple method is to hang a bucket below the weights and to pour water or shot into it until an amount equal to a weight unit is exceeded, when the bucket may be removed and the equivalent weight placed in position; then the empty bucket is again hung in place and filled, this cycle of operations being continued until the pullout point is reached, when the total weight is determined.

113. The pull tests, for various lengths of air-gaps, may be made by the use of brass discs or rings of thicknesses arranged in decades. Thus the first group may be 1 in., 2 in., 3 in., and 4 in. respectively, with which any combination in thickness from 1 in. to 10 in. may be obtained. This idea may be carried out as far as desired. Twelve spacers will give 1,000 combinations. The measurement of the pull should be made as outlined in Par. 112.

114. The heating test requires an ammeter, a thermometer (or voltmeter), a watch and a rheostat. Fig. 36 shows the connections for a test where the temperature rise is determined by the change in resistance (Sec. 3). Instruments and general measurements are treated in Sec. 3. The temperature rise can be measured either by the resistance method or with a thermometer placed against the outside of the winding. In making the test the current should be kept at a constant value I by means of the rheostat, and the thermometer (or, in Fig. 36, the voltmeter) read at regular time intervals. While making the test, either the temperature or the e.m.f. drop should be plotted with time; this will give the heating curve and show when the final temperature has been reached.

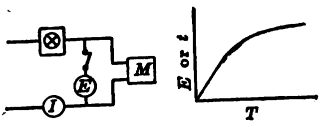


FIG. 36.—Connections for heat run, determining temperature rise by resistance method.

115. The resistance test is usually made with a Wheatstone bridge or a modification* of the same designed to test the coils very rapidly.

116. Test for short-circuited turns. Coils designed for use on alternating-current circuits are tested for short-circuited turns by placing them on the core of a special transformer, whereby a high e.m.f. is induced in them.

117. The breakdown test for direct-current coils is accomplished by placing them on a laminated core before mounting; then heavily overloading

* Underhill, C. R. "The Design of a Quick-acting Wheatstone Bridge," *Electrical World*, 1910, Vol. LVI, p. 29.

ings. The former are used almost exclusively in connection with the ignition of internal-combustion motors. The function of both types is to respond to very sudden fluctuations of the e.m.f. in the primary circuit. For this reason, they have open magnetic circuits, which partly accounts for their generally low efficiency.

In telephony, the function of the induction coil is to accurately transform the complex waves of e.m.f. and current corresponding to the sound waves produced by articulate speech. It is, therefore, in this particular case, simply a transformer with an open magnetic circuit. Induction coils of the secondary type are also used in radiography, wireless telegraphy, internal-combustion motor ignition, etc.; they operate on the principle of the gradual or progressive storage of energy, which is then suddenly discharged, and the cycle repeated.

The performance of the primary type of induction coil has an important bearing on the behavior of secondary-type coils of the jump-spark type and, for this reason, the primary-type coil is treated first and separately.

PRIMARY-TYPE INDUCTION COILS

120. Definition. A primary-type coil is a reactor (Sec. 6) designed to receive electrical energy, then convert it into magnetic energy, storing as much of the latter as feasible, and finally to reconvert it suddenly into electrical energy. The ultimate object is to utilise the heat of the resulting spark, when the circuit is suddenly broken. The rupture of the circuit usually takes place in the cylinder of an internal-combustion engine or motor.

121. Theory. As commonly made, the primary-type induction coil consists of relatively few layers of coarse magnet wire wound over a core consisting of a bundle of soft-iron wires. When the circuit is closed through a battery, current flows through the coil and magnetizes the core; the counter-e.m.f. generated by the lines of flux cutting the turns of wire in the coil opposes the e.m.f. of the battery, so that a definite time interval is required to fully charge the iron core with magnetism.

The break is designed to have a snap-action which causes the circuit to be opened very rapidly, as soon as the flux in the core attains its most efficient value; thereupon the current and the flux decrease at a very rapid rate, and at the same rate, to zero. This sudden rate of change in the flux induces a high e.m.f. in the coil, proportional to $\partial\phi/\partial t$, in the same direction as the battery e.m.f., tending to retard the decrease of the current, and thus prevent the sudden collapse of the magnetic field. Hence, at the point of rupture, or break, there results a bright spark or arc, usually varying from $\frac{1}{16}$ in. to $\frac{1}{16}$ in. in length, the energy of which is the equivalent (barring losses) of the magnetic energy previously stored in the core. The value of the current at the instant that the metallic circuit is broken is given in Par. 30, Eq. 6, under "Magnets."

122. Stored magnetic energy. The magnetic energy, in joules, stored in time t is

$$W = \frac{L}{2}I^2 \qquad \text{(joules)} \qquad (50)$$

where L is the inductance in henrys and I is the value of the current in amperes at the end of time t in seconds. This is the **energy of the spark** (less losses).

123. The inductance of the coil is expressed by

$$L = 80N^2d10^{-9} \qquad \text{(henrys)} \qquad (51)$$

approximately, for cores having ratios of length to diameter between 10 and 15, where N is the number of turns in the coil, and d is the diameter of the core in centimeters.* The time, t, required for the current to attain 63 per cent. of its final value is the **time constant** (Sec. 2) of the circuit; it is numerically equal to L/R. By assuming that the rate of current increase is nearly uniform between 0 and L/R seconds, which is approximately correct, the value of the current strength may be estimated for any corresponding time after closing the circuit.

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* Armagnat, H. "Induction Coils" (Translated from the French by O. A. Kenyon); New York, McGraw-Hill Book Co., Inc., 1908.

SECONDARY-TYPE INDUCTION COILS

128. Theory. Fig. 39 shows the circuit diagram of a typical secondary-type induction coil. The circuit is closed at *S* and current established in

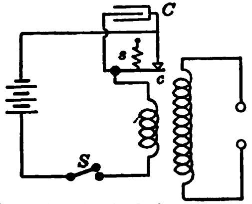

Fig. 39.—Typical circuit diagram for secondary-type induction coil.

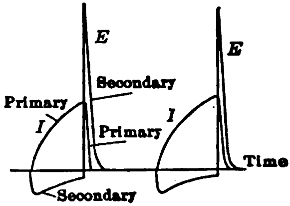

Fig. 40.—Current and e.m.f. curves of a secondary-type induction coil without condenser.

the primary circuit; this current produces a flux in the core and when the flux reaches a certain value the pull exerted on the interrupter contact arm

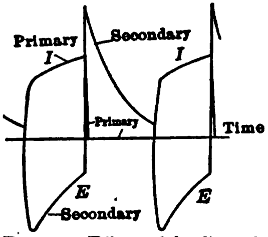

Fig. 41.—Effect of loading the secondary. (No condenser.)

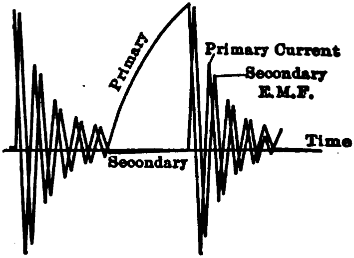

Fig. 42.—Curves of current and e.m.f. in an unloaded secondary-type coil with condenser.

is sufficient to overcome the pull of the spring, *s*, and opens the circuit at *C*. The circuit being open, the flux quickly decreases to zero and thus generates a high value of e.m.f. in the secondary winding, which consists of many turns.

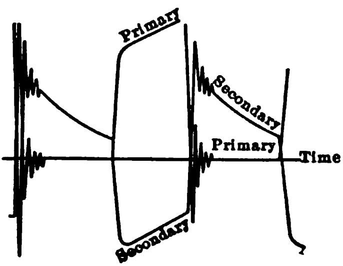

Fig. 43.—Current curves of a loaded secondary-type coil with condenser.

When no condenser (Par. 169) is used and the secondary circuit is open, no current flows through the secondary and, consequently, the effect of the secondary upon the primary is nil, excepting for the negligible charging current in large coils. All actions in the primary take place exactly as though the secondary were not present. Fig. 40* is the same as Fig. 38 with the secondary e.m.f. curves added. The effect of **loading the secondary** (without condenser) is shown in Fig. 41.

129. Effect of condenser. Fig. 42 shows the effect of the condenser

* Bailey, B. F. "The Induction Coil;" *Electrical World*, 1910, Vol. LV, p. 943.

134. The space factor of the core is that per cent. of the total area which is occupied by iron. In the cores tested by Mr. Springer, the space factor varied from 0.675 to 0.70 and averaged 0.687.

135. Table of Core Dimensions from Practice

(Ehnert) *

Spark length (cm.)	Core length (cm.)	Core-wire diameter (mm.)	Space-factor
8	15–20	0.8	0.84
10	20–25	1.0	0.82
15	25–35	1.2	0.80
20	30–42	1.4	0.78
25	35–50	1.5	0.77
30	48–60	1.6	0.76
35	52–58	1.7	0.75
40	62–70	1.8	0.74
50	80–90	1.9	0.73
60	100–120	2.2	0.715
70	120–140	2.5	0.70

136. The size of the primary wire should be so chosen as to produce heat at a very low rate, since there is almost no ventilation of the primary coil. The **current density** in the primary coil can vary between 600 and 1,200 amp. per square inch. It must be remembered also that in coils with large cores the **hysteresis** loss is important. See Par. 79.

137. Table of Sizes of Primary Wire from Practice

(Ehnert) *

Spark length, cm............	8	10	15	25	35	50
Wire diameter, mm.........	1	1.2	1.5	2.0	2.5	3
Nearest size A. W. G........	18	17	15	12	10	9

SECONDARY WINDINGS

138. The necessary number of secondary turns to give a certain secondary e.m.f. depends upon the value of the flux in the core, the type of interrupter, the constants of the circuit, etc. As yet there is no law of general application which will permit the accurate or even approximate determination of the number of secondary turns. When the magnetic circuit and the primary winding are finished, an experiment can be made which will determine the approximate number of secondary turns. Using an interrupter that will give a definite and invariable duration of contact, find the value of e.m.f. generated per turn, in a coil of only a few turns, and then divide the total desired e.m.f. by this value to obtain the required number of secondary turns.

139. Table of Dimensions of Secondary Winding from Practice

(Ehnert) *

Spark length, cm..........	5 to 10	12	15	25	35	50
t, cm. (Fig. 46).............	0.4	0.5	0.6	0.7	0.8	0.9
h, cm. (Fig. 46)............	1.5	2.0	2.5	3 to 3.5	4.5	6 to 7

* Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Electrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.

coil; in the second, the difference in potential between two adjacent coils is zero at the points where they are connected (alternately inside and outside), and increases from that point to a maximum value equal to twice the e.m.f. generated in one coil.

At first sight it appears that the first system would require only half the insulation between sections or "pies" that the second would, but in practice the connecting wire, which must run through the insulation between the coils, is run straight out through the middle and requires sufficient insulation on each side to resist the coil e.m.f.; thus it will be seen that both systems require the same insulation.

145. Details of winding process. The pies are wound in thicknesses varying from 0.0625 in. to 0.25 in. As a rule, silk-covered wire is used (Par. **96, 102, 104, 106**). The core of the winding form is given a bevel, in order to tell the polarity of the coil at a glance, provided, of course, that all coils are wound in the same direction. When cotton-covered or silk-covered wire is used, it is passed through a bath of melted paraffin wax or compound while winding; the amount of wax retained by the wire is controlled by passing the wire from the bath through several paper slits, varied to suit the requirements; in this manner the wax is scraped off the wire to any desired extent. Care should be taken to have the temperature of the wax sufficiently high to prevent cooling before it is in place, since the wax serves to hold the wires together. Before winding, the wire should be thoroughly dried out in an oven.

146. Table of Dimensions of Induction Coils

Authority	Eddy*	Eddy*	*Elec. World*†
Spark, inches	12	6	1.5
Core:			
size wire A.W.G.	22	22	
diameter, inches	2.125	1(?)	1
length, inches	24	12.5	8
Primary:			
size wire A.W.G.	12	12	14
layers	2.5	2	
turns per layer	230	115(?)	
length coil, inches	22	11(?)	6
Ebonite tube:			
length, inches	26	14.5	
dia. outside, inches	3.5	2.75	1.69
dia. inside, inches	2.75	2.25	1.38
Secondary:			
size wire A.W.G.	34	34	‡
No. of pies	64	34	4
total turns	75.256	38,000	
Total length, inches	8	4.25	
dia. outside, inches	6	4.87	3.5

147. Insulation. The properties of insulators and other materials are given in Sec. 4 (see index). The **major insulation** between the primary and the secondary generally consists of a tube of such material as ebonite, hard rubber or micanite; or, in small coils, paraffined paper. The new material "Micarta" may also be used. The **minor insulation** is generally obtained by impregnating the coils with paraffin wax or some compound. Over each layer of the primary winding is wound a thickness of paraffi

* Eddy, W. O. "The Design of a 12-in. Induction Coil;" *Electrical World*, 1907, Vol. XLIX, p. 40.

† "Questions and Answers;" *Electrical World*, 1906, Vol. XLVIII, p. 1064.

‡ The size or number of turns of secondary wire is not given. It is stated that 2 lb. of wire are required.

to such an extent that the circuit becomes practically interrupted. As soon as the current density falls the resistance decreases and the current again rises to its original value. Experiments show that electrolytic interrupters will operate in synchronism when connected in series or in parallel.

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CONDENSERS

BY CHARLES R. UNDERHILL

TYPES

155. Types and properties of condensers. There are three principal types of condensers. The most familiar one is the ordinary **plate condenser** used with induction coils, telephone and telegraph apparatus, where a very large capacity is not required. The plate type is also used for laboratory standards (Sec. 3) in measurements of various kinds. Where a very large capacity is required, the **synchronous condenser** (synchronous motor or synchronous converter with overexcited fields) is employed; such apparatus is outside the scope of this Section and will be found under Sec. 9. The third type is the **electrolytic condenser** which is treated later under its own head (Par. 173).

The properties of a condenser are covered fully in Sec. 2, but in brief, the chief function of a condenser is to store electrical energy for subsequent usage. Such storage of energy may take place in a variety of ways, according to circumstances: thus it may be constant, if the condenser is connected to a source of continuous e.m.f., or it may be intermittent, as in the case of a condenser in a telegraph circuit (Sec. 21); or it may be transient; or, in the case of alternating-current circuits, it may be periodic. In consequence of this property of storing electrical energy, condensers can be used in numerous ways to alter or modify the characteristics of circuits in some desired manner, such as to change the relative phase of e.m.f. and current in an alternating-current circuit, improve the power-factor, or to prevent the flow of continuous current simultaneously in the same circuit with an alternating current.

PLATE CONDENSERS

156. Types and limits of size. Plate condensers are made commercially in a number of types, usually designated by the kind of dielectric employed. The earliest type, still used in laboratory and class-room work, is the **Leyden jar**, which is merely a two-plate condenser with a glass dielectric, constructed in the form of a wide-mouthed bottle or jar with tin-foil coatings inside and out. Other types of simple plate condensers are made where L_t is the dielectric thickness in inches, after impregnation, between each pair of metal strips; N is the number of such dielectric strips in the condenser; C is the desired capacity in microfarads; k is the specific inductive capacity of the paper after impregnation, and l is the short dimension of the foil (Fig. 51). This construction insures the lowest possible internal ohmic resistance and also permits the use of extremely thin metal foil.

161. Internal losses and leakage. A condenser may have internal losses of two kinds. The first is due to the **resistance of the plates** themselves, and this is most prominent in rolled condensers of very thin tin-foil, inasmuch as each plate is one long continuous strip and the resistance of the whole strip from outer terminal to inner end may be appreciable. The second kind is the loss in the dielectric itself, due to **dielectric hysteresis**, so-called (Sec. 4); this loss can be expressed as an equivalent series resistance, which should be added to the resistance of the plates. Both forms of resistance absorb energy and reduce the normal angle of lead of current with respect to terminal e.m.f. from 90 deg. to some lesser angle; this is equivalent to saying that the power-factor is increased from a value which is theoretically (or in the ideal case) zero to some definite value, although not usually large.

Besides these two forms of loss, there also may be a pure conduction current flowing through a condenser, in phase with the terminal e.m.f., which results from the lack of perfect insulation, or the presence of leakage. The resistance of the condenser to a continuous e.m.f., after the steady state has been reached, is termed the **insulation resistance.** The value of insulation resistance, of course, should be as high as possible.

162. The power-factor of a condenser determines to what extent it will be heated when used in alternating-current circuits. The power-factor is the cosine of the angle by which the current leads the impressed voltage, with simple sine-wave forms. It varies with the frequency and impressed voltage, with the temperature of operation, and with the dielectric used. The power-factor of a condenser may be determined by measuring the energy loss or by measuring the variation from 90 deg. phase angle directly.* The specific inductive capacities, power-factors, and breakdown strengths of some materials suitable for condenser dielectrics are given in Par. 169. The constants of kerosene oil are included for comparison. The values given hold only for 60-cycle circuits, at about 20 deg. cent. The breakdown sine-wave strengths are in effective (root-mean-square) volts per mil thickness of dielectric. In connecting condensers in series for use on high-voltage circuits (static voltmeters and the like), it is important to know the several power-factors, as the distribution of voltage is affected thereby. The voltage distribution among the several condensers will be proportional to the product of capacity by power-factor, for small power-factors.

163. Absorption of charge. Many dielectrics do not become fully charged instantaneously, nor do they, when fully charged, give up their complete charges instantaneously. The time lag in receiving full or complete charge is usually referred to as absorption. It is noticeable in testing such dielectrics as glass, rubber, gutta-percha, etc. The effect of absorption on the phase of the current is equivalent to resistance in series with capacity.

164. Glass condensers are made both in the form of Leyden jars, and in flat plates. Glass-plate condensers are commonly made of the best plate-glass with sheets of tin-foil shellaced to each side of the plate. The edges of the surface of the plate, not covered with the tin-foil, are varnished to prevent leakage. The finished plates are mounted in a rack and connected together by flat springs which touch the foil of adjacent plates. Condensers of this class are employed on the transmitting side of wireless telegraph apparatus.

L. W. Austin† summarizes the results of his tests as follows: The losses in the **compressed air condenser** used, at a pressure of 15 atmospheres, amount to an equivalent resistance of between 0.1 and 0.2 ohms. Condensers in which "brushing" (brush discharge) is prevented by the nature of their construction show no change in resistance between the limits of observation,

* Grover, F. W. "Simultaneous Measurement of the Capacity and Power Factor of Condensers;" Bulletin of the Bureau of Standards, 1907, Vol. III, p. 371.

† Austin, L. W. "Energy Losses in some Condensers used in High-frequency Circuits;" Bulletin of the Bureau of Standards, 1912, Vol. IX, p. 73.

and melted into one solid bar. The whole is then vacuum dried and impregnated with paraffin, beeswax or the like, and cooled under a pressure not exceeding 10 lb. per sq. in. Fig. 51 shows the method of placing the sheets of foil and paper. The paper sheets are best made in square form, each edge being slightly wider than the narrow dimension of the metal foil. Diagram (1) in Fig. 51 shows four fibre or wooden upright pegs forming a jig, used in building such condensers, with a strip of metal foil laid one way between the pegs; (2) shows a square piece of dielectric (paper) laid over the strip of foil (the pegs are recessed to fit); (3) shows a second piece of foil laid between the pegs, at right angles to the first. This constitutes one element of the condenser. This process is repeated until as many sheets of dielectric as desired have been used, after which the projecting sheets of foil are rolled up and melted into a solid bar, as in (4). The condenser is then ready for impregnation.

167. Effect of Temperature on Paraffin-paper and Mica Condensers
(Abst. from Proc. I. E. E., 1896, Vol. XXV, p. 723)

Temp. deg. cent....		0.4	12.5	20.1	26.9	32	37.8	43.3
Paraffin paper.	*R*	17,740	7,216	3,622	1,947	1,231	792	551
	C	0.98	0.98	0.98	0.98	0.97	0.96	0.95
Mica..........	*R*	31,427	28,427	22,000	16,272	17,010	15,270	10,521
	C	0.5	0.5	0.5	0.5	0.5	0.5	0.5

R = effective series resistance, in ohms. *C* = capacity in microfarads.

168. Table of Commercial Ratings and Sizes of Telephone Condensers
(Paraffin paper, rolled type, commercial telephone condensers)

Capacity (mf.)	Dimensions			Safe maximum effective voltage	
	Length (in.)	Breadth (in.)	Thickness (in.)	Continuous (volts)	Alternating (volts)
0.05	4.44	1.75	0.94	....	1,200
0.10	4.44	1.75	0.94	....	1,000
0.10	4.44	1.75	0.41	500	....
0.25	4.44	1.75	1.63	....	1,000
0.30	4.44	1.75	1.06	750	....
0.50	4.44	1.75	0.53	....	....
0.50	2.38	1.25	0.75	....	....
1.00	4.44	1.75	0.94	500	....
1.00	3.00	2.38	1.00	....	....
1.00	8.72	6.25	1.48	....	1,000
1.50	4.44	1.75	1.63	500	....
2.00	4.44	1.75	1.63	500	....
2.00	4.38	2.06	1.13	....	....

It should be kept in mind in considering the above dimensions that the capacity varies directly as the area of the plates and inversely as the distance between them (thickness of dielectric or insulation). Hence the volume per unit of capacity increases rapidly as the safe maximum working voltage increases. Condensers of the rolled paper type are not as a rule tested at less than 500 volts, continuous e.m.f. The insulation resistance should be so high that the leakage is entirely negligible in comparison with the charging current. The cost of such condensers ranges from about 35 cents for the 0.05-mf., condenser, to about 85 cents for the 2-mf. condenser. Also see Par. 171.

169. Condensers for use with induction coils and, in general, condensers shunted across gaps to minimize sparking, are usually of the plate type, since it is difficult and expensive to construct rolled condensers having sufficiently low ohmic resistance in their conducting plates. The

These curves show that the changes of capacity and phase difference with changes of temperature and frequency are much larger than the corresponding changes with mica condensers. In general, these effects of temperature and frequency are larger as the absolute value of the phase difference becomes larger. The phase differences observed lie between 6 min. and the enormous value of 22 deg. A phase difference of several degrees is not uncommon in commercial telephone condensers. It is shown that the internal resistance of the plates and leads of a paper condenser are often large, especially in the case of telephone condensers made by rolling together sheets of tin-foil and paper. In one example the energy loss in the condenser, external to the dielectric, at 1,000 cycles, was three times as great as the energy loss in the dielectric.

171. Ratings of commercial paper condensers. A 2-mf. condenser made by one American manufacturer, using paraffin paper, is 4.5 in. long, 2 in. wide and 1 in. thick, and the price is about 55 cents. The volume per microfarad is 4.5 in. The rated voltage limit is 400 volts, alternating; one of these condensers failed on test at 650 volts, alternating. The energy loss was from 1 per cent. to 2 per cent. Another condenser of the paper type,* built to stand 10,000 volts (alternating), occupied 2 cu. ft. per microfarad. Generally speaking, the ordinary paper condensers of the rolled type used in telephony and telegraphy are built to stand about 500 volts, alternating, and range in size from a few hundredths of a microfarad up to 4 mf. to 6 mf.; some of these condensers are built to stand 1,000 volts, alternating. The higher the voltage limit, the more bulky and expensive the condensers become. The table (Par. 168) gives the sizes, dimensions, voltage limits, and approximate costs of rolled paper condensers used in telephone practice.

172. Table of Dimensions of Condensers Used with Induction Coils (Ehnert)†

Spark-length, cm	5	10	15	20	25	30	35	50
No. of layers	60	65	70	75	80	90	100	150
Dimensions of tin-foil sheets, cm.	15 by 10	17 by 10	22 by 10	22 by 11	25 by 13	25 by 17	27 by 20	32 by 23

ELECTROLYTIC CONDENSERS

173. Elements of electrolytic condenser. Certain metals such as aluminum, magnesium, and tantulum, when immersed in an electrolyte, possess the property of allowing electricity to flow in one direction and not in the other, providing a certain critical value of e.m.f. is not exceeded. Two electrodes of this kind practically prevent all flow of electricity and constitute a condenser which is known as an electrolytic condenser. Such condensers are usually constructed with aluminum electrodes and can be made in large units at a cost well within commercial economic limits. The greatest disadvantage of the aluminum electrolytic condenser, as compared with dry condensers, is that it has an appreciable energy loss. Electrolytic condensers used as lightning arresters are usually connected in series with a spark gap so as to avoid the energy loss which would exist were the line voltage continually impressed across its terminals.

174. The critical voltage of an electrolytic condenser is the maximum value of impressed e.m.f. which it will stand without permitting an appreciable leakage current. The table in Par. 175 gives the critical voltages for aluminum electrodes with different electrolytes.

* Mordey, W. M. "Some Tests and Uses of Condensers;" *Journal of Proceedings* of the Institution of Electrical Engineers, 1909, Vol. XLIII, p. 618.
† Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Elektrotechnik und Maschinenbau,* 1907, Vol. XXV, pp. 337, 361 and 377.

of time, but as the voltage is increased the losses increase with time at an increasing rate. In cases where condensers are to be used continuously, it is advisable to connect several low-voltage condensers in series. Dr. Gunther Schulze* carried out an extensive investigation of electrolytic condensers in the Reichsanstalt which was described and discussed in an article: "Aluminum Electrolytic Condensers of High Capacity," published in *Electrochemical and Metallurgical Industry*, Vol. VII, p. 216 (1909).

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RESISTORS AND RHEOSTATS

BY LEONARD KEBLER

TYPES OF RHEOSTATS

183. Plate-type rheostats have a resistance in the form of a reflexed metal wire or ribbon attached to a plate of porcelain-covered cast iron, or to a plate of insulating material such as soapstone, by means of a coating of fused enamel or by cement. They are used almost universally for small field rheostats, theatre dimmers, small motor-speed controllers, battery charging rheostats, etc.

184. Box-type rheostats have a resistance in the form of wire-wound, enamel-covered porcelain tubes; cast-iron grids; coils of bare wire; metallic ribbon; carbon discs, or a conducting liquid. They are used for large field rheostats, motor starters, large motor-speed controllers, battery-charging rheostats of the larger sizes, etc. (Also see Par. **197**.)

FIELD RHEOSTATS

185. Field rheostats are used in series with the fields of dynamos for regulating the field strength and in turn the voltage of the dynamo, or in the fields of motors for varying the field strength and in turn the speed.

186. Generator field rheostats for direct-current machines usually are provided with such a value of total resistance that it is about equal to that

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* Schulze, G., "Kondensatoren Grober Kapazität;" *Elektrotechnik und Maschinenbau*, 1909, Vol. XXVII, p. 247.

195. Temperature rise of plate-type rheostats. For each wa dissipated per sq. in. of free radiating surface, the rheostat plate will ri about 100 deg. fahr., and usually but one side of a plate-type rheostat c radiate freely. Therefore where A is the area of one side of the rheost (sq. in.), I the current flowing (amp.) and R the resistance of the rheost (ohms) in circuit, the temperature rise will be 100 (I^2R/A) in deg. fal (approx.).

196. A reasonable temperature rise for box-type rheostats is reach when there is 1 cu. in. of contents for each watt to be dissipated continuou and 1 sq. in. of external surface for each 2 watts to be dissipated continuous

197. Calculations of resistance, current-carrying capacity, et for box-type rheostats, regardless of the use to be made of them, m be carried out in the same manner as for plate-type rheostats.

198. Automatic features on armature speed controllers consist no-voltage release, overload release and overload circuit-breaker. **No vo tage release** and **overload release** are used with contact arms which a held in the operating position against the action of a spring. On no-volta or overload the spring is magnetically released and moves the arm to the ope circuit position.

An **overload circuit-breaker** on armature speed controllers consists a separate switch arm held closed by a latch. On overload this latch tripped by a magnet, the switch is opened by a spring and breaks the mai line circuit irrespective of the movement of the resistance controlling arm.

199. Speed regulators for series-wound motors. For series moto the calculation of the exact resistance for a definite speed variation requir a curve of the motor characteristics. Lacking this it will be found that controller designed as above for a shunt machine (Par. 193) will gi approximately the same regulation for a series machine running under co stant-torque conditions.

THEATRE DIMMERS

200. Theatre dimmers are made of a number of plates mounted in bank and each plate controlled by its own lever. **A master lever** is usuall arranged with cams so that it may control all or any number of the plat

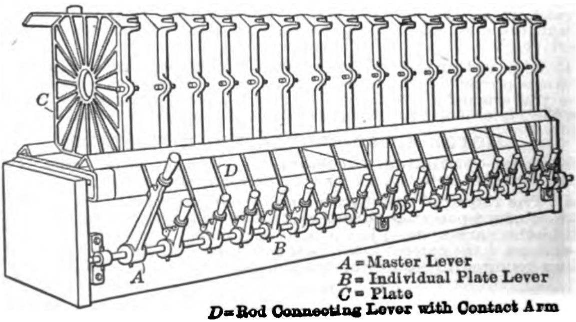


Fig. 54.—Bank of theatre dimmers.

at once. A typical bank is shown in Fig. 54. The circuit operated by o plate seldom carries more than 50 amp. except in the case of the dimm for the auditorium lights. The latter often carries 300 to 400 amp.

201. For dimming carbon-filament lamps a resistance equal to abo 3.4 times that of the lamps in the circuit at full candle-power will dim su ciently so the lamps have no illuminating power. In order that the dimmi may be done smoothly and without flicker, 50 steps are required.

202. For dimming tungsten-filament lamps a resistance equal to times that of the circuit at full candle-power should be used. In order th

212. Starters for series motors. When the resistance is reduced by cutting out a step, the current increases from I to I_{max} as in the case of the shunt motor (Par. 206). At once the counter-e.m.f. increases due to the increase in the field current. Consequently, if the same I_{max} is to be used as in the case of shunt motors, the decrease in resistance as a step is cut out, must be larger than in the case of the shunt motor.

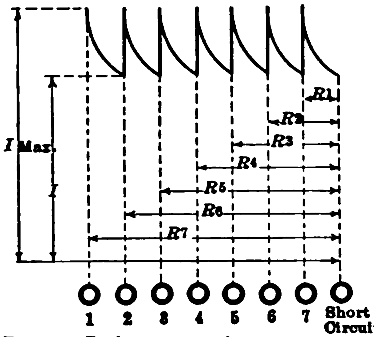


Fig. 55.—Resistance steps for motor starters.

In calculating resistance steps for a series motor which will give the same current curve as shown in Fig. 55, the characteristic curves of the motor must be known. The counter-e.m.f. for any given current is directly proportional to the speed and *vice versa*. In general, however, a starting rheostat that is properly proportioned for a shunt motor may be satisfactorily used with a series motor of the same horse power and voltage.

BATTERY-CHARGING RHEOSTATS

213. The resistance of a battery-charging rheostat, for charging storage batteries from a constant-potential source, may be determined as follows: If E is the e.m.f. of the charging circuit (volts), E_{min} the lowest e.m.f. of the battery during charge (volts), I_{min} the lowest value of charging current, then the total rheostat resistance R will be

$$R = \frac{E - E_{min}}{I_{min}} \quad \text{(ohms)} \qquad (67)$$

A certain amount of this resistance must carry the maximum charging current I_{max}; this amount is

$$R = \frac{E - E_{min}}{I_{max}} \quad \text{(ohms)} \qquad (68)$$

The balance of the resistance will have a current carrying capacity varying from I_{max} to I_{min}.

MISCELLANEOUS RHEOSTATS

214. Wire rheostats. Wire can be wound in coils, or stretched over insulated frames. Wires larger than No. 6 A.W.G. are difficult to wind in spiral form and wires smaller than No. 21 A.W.G. must be wound upon an insulating core. When it is desired to increase the current capacity of a coil resistor beyond that of No. 6 wire, several coils may be connected in multiple. The table in Par. 215 gives the mechanical dimensions of coils made of different sized wires.

215. Table of Dimensions of Wire Coils for Rheostats

Size, A.W.G.	Max. mandrel, inches	Feet per turn	Turns per inch	Max. coil length, inches
6–8	1.25	0.38	4.0	18
9–11	1.00	0.30	4.5	12
12–14	0.75	0.23	7.0	12
15–18	0.50	0.16	9.0	12
19–21	0.25	0.082	14.0	6
22–30	Must be wound on insulated core			

Note.—The maximum diameter of mandrel given in the table corresponds to the length given therein, and if a stiffer coil is desired a smaller mandrel must be used.

Ordinary water gives a drop from 2,500 to 3,000 volts per in. gap at this current density.

RESISTANCE UNITS

223. Resistance units are used wherever a resistance that is not variable is desired. These units are made in many forms and types for the use of those who desire to purchase the units and assemble them in rheostats; for use in the speed regulators of desk and ceiling fans; for testing purposes, etc.

224. The resistance material is usually of German silver or some similar material of low temperature coefficient. This is usually wound on tubes and is then covered with a cement-like coating or with a fused vitreous enamel. The tubes on which the wire is wound consist of pottery, asbestos paper, lava, enameled iron, etc. The enameled iron and pottery tubes are used when the resistance wire is to be hermetically sealed in a fused vitreous enamel.

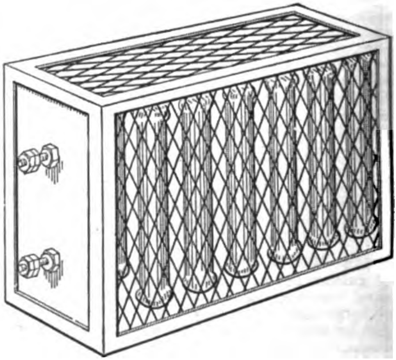


Fig. 57.—Large resistance unit.

225. Carbon resistance units are sometimes used where exceedingly high resistances with a very low watt dissipating capacity are desired.

226. The watt dissipating capacity (I^2R) of such tubular units as are commercially manufactured and listed, varies from 1 to 300 watts. The resistance of these units can be made as high as 16,000 ohms on an enameled wire wound tube 4 in. long and ½ in. diameter.

227. Large resistance units are made of cases enclosing a number of the tubular units described in Par. **224**, or enclosing cast-iron grids, German silver ribbon, etc. (See Fig. 57.)

228. The temperature rise of resistance units is as discussed in Par. **195** and **196**.

229. Mounted resistance units are manufactured with various attachments for readily mounting in special apparatus or for giving various com-

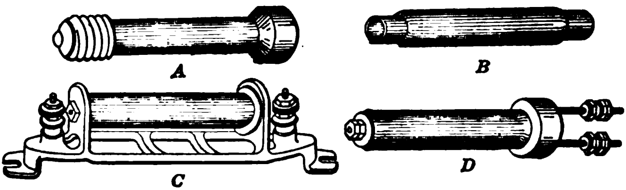


Fig. 58.—Mounted resistance units.

binations, etc. Units designed to replace resistance lamps in order that a resistance may be secured that does not change with time, or on account of heat, are so made as to screw into a standard Edison socket. (See A, Fig. 58.) Other units are made with ferrules on the ends, so they may be readily inserted in the conventional type of fuse clips (See B, Fig. 58); still others are mounted in brackets (See C, Fig. 58); on porcelain bases See D, Fig. 58), etc.

SECTION 6

TRANSFORMERS

INTRODUCTION

1. **A transformer** is a device for transferring energy in an alternating-current system from one circuit to another. It consists essentially of two independent electric circuits linked with a common magnetic circuit. Thus energy at low voltage may be transformed to energy at high voltage, or *vice versa*. In like manner, current of a given value in one circuit may be transformed into current of another value in a different circuit. The winding of the transformer connected to the supply circuit is referred to as the **primary winding**, and those windings of the transformer that are connected to the receiver circuits are referred to as **secondary windings**.

2. **If a transformer with open secondary winding** has its primary circuit connected across alternating-current supply mains, only a small current will flow through the primary. This current is alternating and produces an alternating magnetic flux in the iron core of the transformer, which interlinks both the primary and the secondary windings and by its rate of change induces an e.m.f. in each. If the two windings are closely associated with each other, the e.m.f. induced in each will be proportional to their respective numbers of turns. The e.m.f. induced in the primary winding is known as the **counter e.m.f.** of self-induction of the primary, or **back e.m.f.**, and is equal in magnitude to the e.m.f. of the mains less the IR drop due to the current passing through the winding. Therefore, if the permeability of the magnetic circuit of the transformer is high and the resistance of the primary winding is low, the counter e.m.f. will be very nearly equal in magnitude to the e.m.f. of the supply circuit, and it follows also that the secondary induced e.m.f. will be nearly equal to the e.m.f. of the supply circuit multiplied by the ratio of the number of turns in the secondary winding to that of the primary winding.

3. **If the secondary circuit is completed through an impedance** or load, current will flow through the secondary and the load; this will tend to demagnetize the core, so that the effective impedance of the primary winding is at once lowered and more current flows into it. The extra current, being just sufficient to overcome the demagnetizing effect of the current flowing in the secondary winding, will have the same time-phase as the secondary current and the ratio of the magnitudes of the two currents will be equal to the reciprocal of the ratio of the numbers of turns in the respective windings.

4. **The secondary current causes a drop in e.m.f. in the secondary winding**, partly due to the resistance of the winding and partly due to magnetic leakage caused by the fact that all of the flux which interlinks the primary turns does not interlink all the secondary turns.

5. **The primary current likewise produces a drop of e.m.f. in the primary winding**, due to the resistance of the primary winding and to the fact that there is a portion of the magnetic flux which interlinks some of the primary winding without interlinking any of the secondary winding.

6. **The induced e.m.f.** will therefore be proportional to the e.m.f. of the supply circuit, less the drop in the primary winding; and the secondary terminal e.m.f. will be equal to the secondary induced e.m.f. less the drop in the secondary winding, the drops being taken in their proper phase relations. The total drop from supply e.m.f. to secondary terminal e.m.f. is usually quite small in power transformers, so that the product of the secondary current and terminal e.m.f., measured in kilovolt-amperes, differs from that of the primary by 2 or 4 per cent., only, at full load, while the ratio of the output

a magnetic circuit of uniform cross-section and infinite permeability, and that e_1, the instantaneous value of the e.m.f. impressed on the primary, is a simple harmonic time-function of the form

$$e_1 = 10^8 \times \sqrt{2} E_1 \cos \omega t \qquad (2)$$

where E_1 is the root-mean-square or effective value of the impressed voltage and ω is equal to $2\pi f$ where f is the frequency of the alternating e.m.f.; i_0 becomes zero, and the resulting solution of these equations will give

$$\begin{aligned} (L_1 i_0) &= n_1 A_1 B \sin \omega t \\ (M i_0) &= n_2 A_1 B \sin \omega t \\ E_2 &= -\frac{n_2}{n_1} E_1 \end{aligned} \qquad (3)$$

where n_1, n_2 are the number of turns in the primary and secondary windings respectively, E_2 is the effective value of the secondary voltage, A_1 is the cross-sectional area of the magnetic circuit and B the maximum instantaneous value of the induction in C.G.S. lines per unit area. The relations between E_1 and B are given by

$$\left.\begin{aligned} B &= \frac{\sqrt{2} E_1 \times 10^8}{\omega n_1 A_1} = \frac{E_1 \times 10^8}{4.44 f n_1 A_1} \text{ (c.g.s. lines per unit area)} \\ E_1 &= \frac{\omega n_1 A_1 B}{\sqrt{2} \times 10^8} = 4.44 \frac{f n_1 A_1 B}{10^8} \quad \text{(volts)} \end{aligned}\right\} \qquad (4)$$

These are the equations used to determine the value of the open-circuit secondary voltage and the induction in power transformers. Even if the reluctance of the magnetic circuit be taken into account the value of B is not materially altered, and since exigencies of manufacture may cause larger errors in this quantity than that due to the assumption of infinite permeability, greater refinement is useless. The error in the value of E_2 due to this assumption is not of consequence in most commercial transformers.

16. The primary open-circuit characteristics of power transformers may be obtained with sufficient accuracy by means of a curve giving the **loss per unit mass** of iron at different inductions (Sec. 4), and another giving the **exciting volt amperes per unit mass** at different inductions. The latter curve is preferably obtained from the average of tests on a number of transformers. Sometimes tests are made on different sizes of transformer cores and the resulting curves plotted separately; this is done to take care of the variations due to building, which are greater in small transformers than in large ones. The value of the exciting current obtained in this manner is known as the **equivalent sine-wave value**. The relations between these equivalent sine-wave values of core-loss current and exciting current as obtained above is shown by vector diagram Fig. 1. Typical core-loss and exciting volt-ampere curves are shown in Fig. 2 and Fig. 3, respectively.

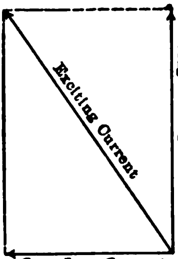


Fig. 1.—Vector diagram of equivalent sine-wave exciting current.

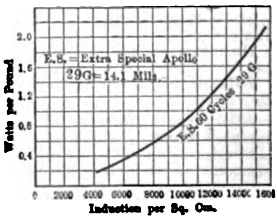


Fig. 2.—Core-loss curve.

17. The current in the primary winding of an unloaded transformer, which has a sine-wave e.m.f. impressed across its terminals, is not a

20. The short-circuit characteristics of a transformer are obtained from those of the loaded transformer by making R_0 and L_0 equal to zero. It is usual to consider the quantity ωM in the resulting equation as infinite in which case the short-circuited transformer may be treated as a simple impedance so that the effective reactance of a transformer of unity ratio when short-circuited is the sum of $\omega(L_1-M)$ and $\omega(L_2-M)$. Moreover under load conditions the effective transformer impedance differs from the short-circuit value only on account of the influence of the normal induction on the permeability of the core, and since the effect of ωM may be ignored in the short-circuit reactance, the effect due the difference of ωM under short circuit and when there is normal induction in the iron being of still smaller order of magnitude may also be ignored. The quantities which in transformers under load are the equivalents of the short-circuit copper loss and impedance have been measured with varying inductions in the iron and have been invariably found to be practically constant.

21. The current in the secondary winding of a transformer supplying a load may be obtained by means of the simple alternating-current circuit shown in Fig. 4. But since the admittance Y is not readily expressible, it is inconvenient to use this circuit. Moreover the quantity (L_1-M) cannot be evaluated very exactly and therefore more or less error is introduced when it is used. The following formula derived mathematically from Eq. 6 and 7 with the assumption made in the preceding paragraph has the advantage of great simplicity

$$e_2=R_0i_2+L_0\frac{\partial i_2}{\partial t}+\left(R_si_2+L_s\frac{\partial i_2}{\partial t}\right) \tag{9}$$

where R_s and L_s are the effective resistance and effective inductance when load current is circulated in the secondary with the primary short-circuited.

22. With sine-wave secondary open-circuit voltages Eq. 9 becomes that of a simple reactive circuit having resistance equal to the sum of the load resistance and the secondary effective short-circuit resistance and having reactance equal to the sum of the load reactance and the secondary short-circuit reactance. The secondary current may then be multiplied by the ratio of transformation to obtain the primary load current, and from this the primary current is obtained by adding the equivalent sine-wave exciting current in proper phase relation. Eq. 9 under these circumstances may be represented symbolically as follows:

$$\dot{E}_2=\{(r_0+r_s)+j(x_0+x_s)\}\dot{I}_2 \tag{10}$$

where E_2 and I_2 are both vectors. The vector diagram and current loci for all loads are given in Fig. 6.

23. The construction of Fig. 6 may be explained as follows: $OA = -E_1$ or the primary impressed e.m.f., reversed in time phase. $OB = E_2$, or the secondary open-circuit e.m.f. The radius of the heavy-line circle with B as centre represents the secondary short-circuit impedance of the transformer, drawn to the same scale as OB. To obtain the loci of the secondary terminal e.m.f. for any load, bisect OB, at C_1 and draw the line C_1, C_2, C_3 at right angles. The locus of all loads having a given power-factor is a circle passing through B with its centre at some point on the line C_3, C_1, C_2. The unity-power-factor centre C_2, is obtained by making C_1, C_2 equal to C_1B multiplied by the ratio of the secondary short-circuit resistance to the secondary short-circuit reactance; the centres C_3, C_4, C_1, etc., for loads of other power-factor are obtained by making cos α_3, cos α_4, etc., equal to the respective power-factors, making the angle lag behind or lead the phase of BC_2, according as the power-factor is lagging or leading. The loci are then obtained by describing circles passing through B with these centres. The loci for different load currents are concentric circles having B as centre and radii proportional to the respective short-circuit impedance drops at these loads. Thus the secondary terminal e.m.f. with full-load secondary current and 90 per cent. leading power-factor is represented in time-phase and magnitude by the vector drawn from O to the point C where the 90 per cent. leading-power-factor circle intersects the full-load impedance-drop circle. To obtain the loci of the current vectors, describe with centre O a circle of radius to represent the effective full-load secondary current on any suitable scale; with the same centre draw another circle of radius equal to that of the voltage, expressed as a percentage of the full-load secondary voltage, which is also the rated voltage. If IR/E and IX/E are respectively the effective short-circuit ohmic and the reactance drops expressed as fractions of the rated voltage, then

$$\text{Regulation} = \frac{IR}{E}\cos\theta + \frac{IX}{E}\sin\theta + \frac{\left(\frac{IX}{E}\cos\theta - \frac{IR}{E}\sin\theta\right)^2}{2} \qquad (13)$$

GENERAL DESIGN

27. The design of successful commercial transformers requires the selection of a simple form of structure, so that the coils may be easy to wind and the magnetic circuit easy to build. At the same time the mean length of the windings and of the magnetic circuit must be as short as possible for a given cross-sectional area, so that the amount of material required and the losses shall be as low as possible. The form of construction should permit of the easy removal of heat by means of ventilating ducts, it should admit of being insulated in a simple and economical manner, and the windings should be of such forms as may be easily reinforced to withstand mechanical stresses.

28. Two types of transformers are in common use. When the magnetic circuit takes the form of a single ring encircled by two or more groups of primary and secondary windings distributed around the periphery of the ring, the transformer is termed a core-type transformer. When the primary and secondary windings take the form of a common ring which is encircled by two or more rings of magnetic material distributed around its periphery, the transformer is termed a shell-type transformer.

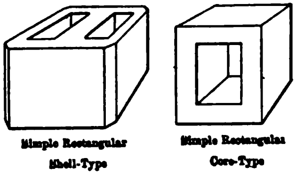


FIG. 7.—Forms of magnetic circuits of transformers.

29. The characteristic features of the **core-type** transformer are a long mean length of magnetic circuit and a **short** mean length of windings; those of the **shell-type** are short mean length of magnetic circuit and long mean length of windings. The result of these features is that for a given output and performance the core-type will have a smaller area of core and larger number of turns than the corresponding shell-type. As a general rule the core-type construction is more economical for small high-voltage transformers than the shell-type construction, the dividing line for size being dependent on the voltage. In the matter of relative weights of iron and copper, the two types tend to merge into each other if steps are taken to alter the construction so that their features are more nearly alike. Fig. 7 and Fig. 8 illustrate the forms of magnetic circuits that have been found to result in the most economical and satisfactory designs.

30. Electrical design. The fundamental formulæ in the electrical design of a transformer are those given under "General Theory," Par. 15, Eq. 4. If a certain current-density and induction be assumed, the allowable thickness of the coils for the proper cooling may be predetermined. The electrical stress between layers and between adjacent coils may also be predicted with sufficient accuracy to specify the amount of insulation that it will be necessary to use in each case.

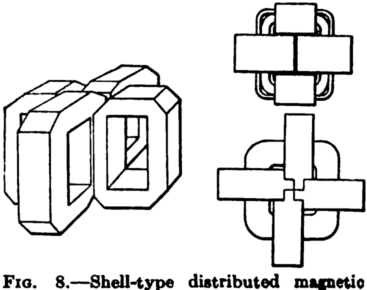


FIG. 8.—Shell-type distributed magnetic circuit.

31. The area occupied by a primary or a secondary

33. Core material. Silicon steel is used almost entirely for power and distributing transformers. For the first class of transformers chiefly on account of its non-ageing characteristics. For the second class on account of its extremely low hysteresis and eddy current loss. A great deal of investigation is being carried on by various manufacturers with a view of producing steels having characteristics suitable for different classes of work. A complete discussion of various classes of sheet steel for electrical apparatus will be found in Sec. 4.

34. Insulation, cooling and mechanical stresses. These factors will have a large influence on the form and dimensions of transformer and are taken up in detail under separate headings below.

DESIGN OF INSULATION

35. High insulation strength is one of the most important requirements of a well-designed transformer. However, provided that the proper strength is obtained at every point, the less insulating material used the better, because the insulating material is the chief factor, limiting the temperature at which it is permissible to operate and it is also the main factor in producing the rise of temperature of the windings.

36. The electric stresses to which a transformer is subjected in service may be transient in nature, or they may be steady. Belonging to the former class are surges set up by switching, breaking down of line insulators, arcing grounds, and short-circuits. Steady electric stresses are caused by such accidents as the grounding of one line of a transmission circuit, and will be preceded by a surge or transient wave due to the change in the electric field brought about by the new condition of stress. Thus high electric stress to ground, in a transformer, may be preceded by high stresses between coils and turns of the high-potential parts of the windings. A breakdown between turns in a high-voltage transformer may therefore be due to a combination of the two forms of stress. Another form of stress that may cause breakdown of the low-tension winding is likely to occur when the electrostatic capacity between the high-tension and low-tension windings is high in comparison with that of the low-tension winding to ground, in which case a dissymmetry of the high-tension circuit such as that due to a ground on one line may cause a potential elevation of the low-tension winding sufficient to break down the insulation, or to cause loss of life.

37. The transient stresses are difficult to estimate with any degree of certainty and the designer usually has to satisfy himself with results obtained by experience with transformers in service.

38. The steady stresses may be easily calculated, and the usual practice is to design the insulation so that it will withstand a difference of potential between the low-tension and high-tension windings and between case and high-tension winding, ranging from two to two and one-half times the possible steady stress under service conditions.

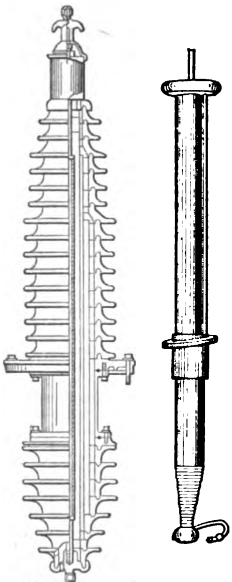
39. The insulation between adjacent coils and adjacent turns of the transformer must be capable of withstanding with an ample margin of safety the normal and transient stresses that occur. It is customary in large transformers to give an overpotential test of double voltage, mainly for the purpose of making sure that there are no weak spots in the coil insulation.

40. Effect of polarity of windings. Polarity in a transformer depends upon the relative direction of the induced electromotive forces in the primary and secondary windings considered with respect to the two adjacent ends of the two windings.* In a single-phase transformer under normal conditions of service, the middle points of both primary and secondary windings are at ground potential; but the maximum difference between adjacent primary and secondary coils may be half the sum of the primary and secondary voltages or half their differences according to the polarity. This factor becomes of extreme importance in the design of transformer for interlinking two high voltage systems.

* A full discussion of this question will be found in an article by C. Fortescue, *Electric Journal*, 1907, and also one by Wm. McConahy, *Electric Journal*, 1910.

48. Outlet terminals. One of the most difficult problems encountered in high-voltage insulation design in the past was the provision of a suitable outlet lead. This problem has been solved in two different ways: one is by the use of the condenser-type terminal (Par. 49), and the other is by the use of an oil-filled bushing (Par. 50).

49. The condenser-type terminal consists (Fig. 9) of alternate cylinders of thin tin-foil and shellac-treated paper, rolled hot on a central brass rod of the proper diameter: they are so arranged that the capacities between adjacent tin-foil cylinders are the same throughout, and the tin-foil cylinders differ in length by equal steps. The potential stress is distributed evenly over the whole length of the terminal. The addition of a disc at the top of the terminal and an external cylinder of insulating material extending between the flange and the disc, the space between the condensers and the cylinder being filled with gum, complete the outlet lead.



Oil-filled terminal   Condenser type terminal

FIG. 9.—Oil-filled and condenser-type terminals.

50. The oil-insulated terminal (Fig. 9) depends upon oil as an insulator and as a means for insuring equal distribution of heat in the terminal. It consists of segments of porcelain or moulded material cemented together to form an enclosure for the oil; a conducting rod extends from top to bottom of this enclosure. The oil space is subdivided by insulating cylinders to prevent lining up of particles in the oil.

51. In transformers for high-voltage transmission the coils adjacent to the line terminals are more heavily insulated from one another than the rest of the coils. In large transformers the normal stress between adjacent coils is seldom permitted to exceed 15,000 volts. As the size of a transformer is increased, keeping the current density and the coil thickness the same the voltage per coil will vary inversely as the fourth power of the output. Since the thickness of the coils and the spacing between them are usually determined by the cooling requirements, a large transformer is more easily insulated than a small one.

52. Grounding of the neutral point. A considerable saving in cost of insulation may be obtained if transformers are designed for operation with the neutral point of the line-circuit grounded. The insulation stresses to which a transformer may be subjected in service are thereby greatly reduced and the danger of breakdown of low-tension insulation due to the effect described in the latter part of Par. 36 is entirely eliminated, in polyphase transformations.

53. The effect of insulation on cooling is negligible except in small transformers where the heat has to be conducted through thick insulating barriers, tape on the coils, and heavy layer-insulation; and in air-blast transformers where the temperature gradient through the heavily taped coils may be very large.

COOLING SYSTEMS

54. The losses in a transformer appear as heat in the windings and the core. Means must therefore be provided for removing it; otherwise high temperature will result, which will destroy the fibrous materials used for insulating the various parts of the transformer. **Methods of removing heat** may be classified as follows:

(a) **By natural convection of air and radiation.** This method is employed in certain special cases for small distributing transformers up to

The reason for most of these requirements are obvious, but (b), (c), (d) and (e) require some explanation, which is given in the next paragraph.

61. Explanation of heat transfers in cooling fluid. Consider two adjacent surfaces of a winding taking the form of two parallel planes a small distance apart, and assume that all the heat is emitted in a direction normal to the planes. The fluid directly in contact with the surface will first become heated and expand, thereby becoming lighter and rising. It will thus at every point of its passage assume a temperature which will increase progressively along the vertical. At the lowest point of the coils the oil nearest the surface will perform all the cooling, but as it rises the temperature gradient through the fluid normal to the surface will increase, thus permitting the conduction of heat to the fluid further removed from the surface. The temperature gradient through the oil at the top of the coils will therefore depend upon the velocity of the fluid and its distance from the surface. The more nearly uniform the velocity of the fluid at each point, the less will be the temperature gradient. The velocity of the fluid at each point depends among other things upon the viscosity of the fluid being more uniform the lower the viscosity. High specific heat is important because it permits a given amount of heat to be removed per unit time at lower velocity and lower temperature rise along the surface. High thermal conductivity is necessary so that heat may be transmitted through the fluid normal to the surface with a small temperature gradient. It should be noted that where the fluid is a gas, a certain amount of work is absorbed during expansion, so that the specific heat at constant pressure should be used.

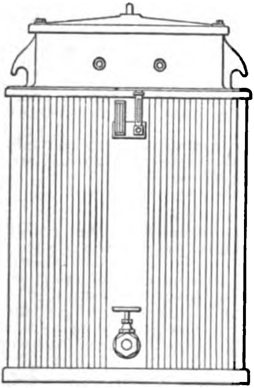


FIG. 10.—Oil-insulated self-cooled transformer.

62. The temperature difference between the fluid at the top of the coil and that at the bottom is a measure of the force required to circulate the fluid. Part of this force is used up in overcoming the friction offered by the surfaces and the viscosity of the fluid.

63. In transformers cooled by free convection in air the remainder of this force is that necessary to bring the velocity of the air up to the required value to effectively remove the losses. **In oil-insulated self-cooled types** (Fig. 10), where the transformer is immersed in a liquid which circulates by free convection, cooling the surfaces of the windings and being cooled in turn at the surface of the container by convection of the air, the hydraulic force or head developed in the windings due to the difference in temperature has to overcome not only the resistance to flow within the windings themselves, but also that external to the windings due to the sides of the case. In addition to this there is a back pressure or counter-head which represents the force required to overcome the friction resistance of the external surface of the case to the convection currents of air and that required to set them in motion.

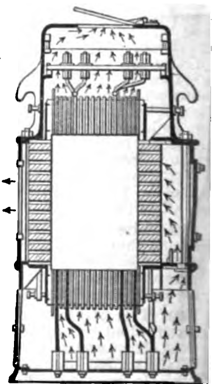


FIG. 11.—Air-blast transformer.

64. In the air-blast method of cooling (Fig. 11), instead of depending solely on free convection of air to cool the transformer, pressure is used and air is forced through the windings. The temperature rise of the hottest part of the surfaces, above approximately proportional to the one-fourth power of the output while the losses increase as its three-fourth power, the additional surface necessary to dissipate the heat must be obtained by corrugating the tank surface. The air flow has therefore to encounter a more constricted area of entry and a longer path of higher resistance. The volume of air per watt lost will consequently decrease and the average temperature of the air flowing over the surface increase, resulting in a higher average temperature of the oil, unless the gradient between the oil and cooling air has been sufficiently decreased by increasing the tank area per watt lost. The maximum temperature of the oil will tend to be higher, and therefore the maximum temperature of the windings which is the limiting factor in any electrical apparatus will also tend to be higher. Accordingly in large transformers the difference between the average temperature of the air flowing over the surface and the average temperature of the oil must be kept lower for a given temperature rise in the coils than in small transformers, and therefore a larger tank area per watt lost, will be required, or else the temperature gradient through the coils themselves must be decreased.

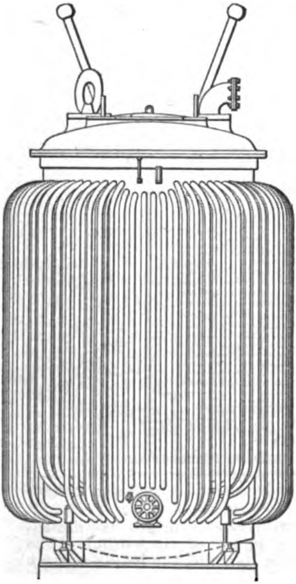


FIG. 14.—Oil-insulated self-cooled transformer (tubular type).

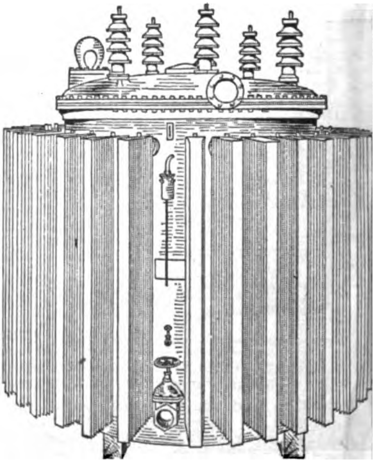


FIG. 15.—Oil-insulated self-cooled transformer (radiator type).

70. The usual course is a compromise between these two methods of keeping down the temperature rise in the coils, but with very large transformers this becomes costly and more efficient cooling tanks must be used, good examples of which are the tubular and radiator types of tanks (Figs. 14 and 15) or else recourse must be had to artificial methods of cooling such as water cooling, forced circulation, etc.

71. The watts lost per sq. in. of coil surface for cylindrical coils of large radius and for discoidal coils, may be obtained by very simple formu-

The same equations apply to θ_a, and θ_b if we substitute these values for θ_0 and θ_1 respectively; and also substitute P, A_s, σ_s, G, and α_s for $P_0 A_0$, σ_0, G_0, and α_0 respectively; we shall then have the temperature rise of the coils above the oil at the end of an interval t_1, starting with a temperature rise θ_b.

75. In water-cooled transformers the length of cooling coil required will depend upon the rate of flow of the water. Using the same symbols as before, except that the temperature rises will be measured above the incoming water, we shall have, if radiation from the surface of the tank is negligible and taking θ_w as the temperature rise of the water, F as the flow in gallons per min., L as the length of cooling coil in feet and α_w the emissivity of the surface of the cooling coil in watts per ft. per deg. cent.,

$$\theta_w = \frac{0.0038P_0}{F} \qquad (28)$$

$$L = 606\frac{F}{\alpha} \log_{10} \frac{\theta_0}{\theta_0 - \theta_w} \qquad \text{(feet)} \qquad (29)$$

$$\left.\begin{array}{l}\text{Temperature rise above}\\ \text{entering water under}\\ \text{steady conditions}\end{array}\right\} = \frac{0.0038P_0}{F\left[1 - \dfrac{1}{10^{\left(\frac{0.00165\alpha_w L}{F}\right)}}\right]} \qquad \text{(deg. cent.)} \qquad (30)$$

Denote the bracketed portion of the denominator of the above fraction by C; then,

$$\theta_1 = \frac{\theta_w}{C} - \frac{\dfrac{\theta_w}{C} - \theta_0}{10^{\left(\frac{2165FCt_1}{G_0\sigma_0}\right)}} \qquad \text{(deg. cent.)} \qquad (31)$$

$$t = \frac{G_0\sigma_0}{2165FC} \log_{10} \frac{\dfrac{\theta_w}{C} - \theta_0}{\dfrac{\theta_w}{C} - \theta_1} \qquad \text{(hours)} \qquad (32)$$

C is constant for a given length of pipe and flow of water. The temperature rise of the coils above the oil may be obtained by the formulas given in the last paragraph. The above formulas with some modification may be used for forced circulation.

76. The cooling surface required for a transformer having a rise of 40 deg. cent., based on a room temperature of 25 deg., will vary from 4 sq. in. per watt lost, to 8 or 9 sq. in., according to the size of the transformer. The value of α_0 will vary from 0.008 to 0.004 watts per sq. in. per deg. cent.

77. The following relations will be found useful to transformer designers. Energy dissipated in 1 lb. of copper at the rate of 1 watt will raise the temperature of the copper at the rate of ⅓ deg. cent. per min. if no heat be permitted to escape. Water flowing at the rate of 3.8 gal. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent. Air at atmospheric pressure, flowing at the rate of 1,650 cu. ft. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent.

MECHANICAL DESIGN AND COIL GROUPING

78. Mechanical stresses in service are due to the heavy currents developed in electrical apparatus under short-circuit, caused by the tremendous amount of energy developed in modern electrical systems. Reactance in a transformer, on account of the great length of the leakage paths in air, furnishes practically the same protection to connected apparatus as an air reactance.

79. Coil grouping and reactance. The reactance of a transformer depends on the grouping of the high-tension and the low-tension windings. The same general principles apply to the grouping of the windings of any type of transformer. The element of a given grouping is formed by a set of high-tension and low-tension coils of equivalent number of turns, generally an even submultiple of the total number of turns, placed as near together as

N is the number of HL groups, c is the space between adjacent high-tension and low-tension windings, and a_1, a_2, b_1, b_2, b and d are as shown in Figs. 16 to 18.

82. Formulas for mechanical force exerted on coils. In a transformer the electrokinetic energy is given by

$$W = \frac{1}{2} L I_1^2 \qquad \text{(Joules)} \qquad (36)$$

where I_1 is the primary current, and therefore since $F = \frac{\partial w}{\partial x}$

$$F = \frac{1}{2} I_1^2 \frac{\partial L}{\partial x} \times 10^7 \qquad \text{(dynes)} \qquad (37)$$

x being in the direction of the maximum force, that is, at right angles to the surface of the coils. For shell-type transformers with discoidal coils,

$$F = \frac{1}{2} I^2 \left[\frac{4\pi n^2 (l_1 + l_2)}{4.45 \times 10^7 N^2 (a_1 + a_2)} \right] \qquad \text{(lb.)} \qquad (38)$$

83. Mechanical design of cases. Where fluted cases are used they should be made of ingot steel at least 0.079 in. thick, except for transformers below 100 kw., then $\frac{1}{16}$ in. may be used. Cases for oil-insulated self-cooled transformers have the sides cast in a base of cast iron. Boiler-iron cases such as are used for water-cooled transformers are usually guaranteed to withstand a pressure of 50 lb. per sq. in. The covers of large transformers are provided with vents to release the pressure if an explosion should take place. The tank is provided also with a large gate valve, so that the oil may be drawn off very quickly. The cases of large transformers should be made as nearly air-tight as possible, as this prevents dirt or moisture finding its way into the tank.

84. In the design of end-frames for large transformers there is a tendency to replace cast iron by structural and cast steel; the weight of the end-frame is thereby much reduced for a given strength; moreover, when structural steel is used, or a combination of structural steel and steel castings a much greater latitude is given the designer, as he then has freedom to make the proportions of the core anything he pleases. The cooling coils of water-cooled transformers are usually made of $\frac{3}{4}$- to 1-in. brass or iron pipe and are tested up to 250 lb. per in. hydraulic pressure.

TRANSFORMERS FOR POWER SERVICE

85. General consideration in design. The most important quality in a power transformer is **durability**; it should be able to withstand the most exacting conditions to be met in service without being sensibly weakened. It is important that the insulating material shall not be subjected to excessive temperatures, and therefore every portion of the coil surfaces should be well exposed to the cooling medium. The coils directly connected to the lines in high-voltage transformers should have reinforced insulation.

86. The cheapest transformer consistent with durability that has a reasonably good performance, is what is generally required. Such features as efficiency and regulation are usually of secondary importance. The flux-density in the iron of such a transformer will be made as high as consistent with a reasonable exciting current; the loss per lb. at commercial frequencies in silicon steels is so low that the core-loss is seldom a limiting feature. The current-density, on the other hand, is limited chiefly by considerations of cost, because when the density is increased beyond a certain point, for a transformer designed to operate at a given temperature rise, the cost begins to increase again.

87. Types and characteristics. Power transformers differ mainly in the methods used to cool them: the characteristics pertaining to different methods of cooling are taken up under "Cooling" (Par. 54 to Par. 77). Transformers cooled by natural circulation of oil and air must be designed on a more liberal scale than water-cooled transformers, or those cooled by forced oil circulation, and therefore the losses will be lower in the former than in the latter. Air-blast transformers, on account of the heavy insulation and large insulation clearances needed, are not as efficient as other power transformers of the same voltage-class.

so that they may be used for lower voltages. The usual secondary distributing voltages are considered standard. Transformers used for interconnecting two high-voltage systems are considered special.

93. A standard transformer is completely specified when the method of cooling, the frequency of the circuit (either 25 or 60 cycles), the voltage class, and low-tension voltages are given. Manufacturers have type numbers or letters for their standard lines, and in some cases they have two lines to offer, or two different lines may overlap for a few sizes. In general, however, no ambiguity will exist if the method of cooling is specified with the other data required.

94. Tables giving ratings, efficiencies, regulation and weights typical of standard single-phase oil-insulated air-cooled transformers. These transformers have a guaranteed temperature rise not exceeding 40 deg. cent. at continuous full-load rating. When run continuously at one and one-fourth load the guaranteed rise is 55 deg. cent. above the air; room temperature to be 25 deg. cent. The insulation tests are in accordance with the Standardisation Rules of the A. I. E. E. The tables follow in Par. 95 to Par. 102.

95. Single-phase—60 Cycles—11,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight including oil
	¼ load	½ load	¾ load	Full load	1¼ load	100 % p. f.	80 % p. f.	
100	94.9	96.9	97.5	97.6	97.5	1.55	3.55	3,800 lb.
150	95.5	97.3	97.8	97.9	97.8	1.3	3.6	5,200 lb.
200	95.8	97.4	97.9	98.0	97.9	1.2	3.6	6,100 lb.
300	96.2	97.7	98.2	98.3	98.2	1.1	3.6	8,300 lb.
500	96.6	98.0	98.4	98.5	98.5	0.9	3.6	12,800 lb.
750	97.1	98.2	98.5	98.6	98.6	0.8	3.75	18,500 lb.

96. Single-phase—60 Cycles—22,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight including oil
	¼ load	½ load	¾ load	Full load	1¼ load	100 % p. f.	80 % p. f.	
100	94.4	96.7	97.3	97.4	97.3	1.6	3.7	4,800 lb.
150	95.0	97.1	97.6	97.7	97.6	1.4	3.7	6,100 lb.
200	95.4	97.3	97.8	97.9	97.8	1.3	3.75	7,000 lb.
300	96.1	97.7	98.1	98.2	98.1	1.1	3.8	10,000 lb.
500	96.5	97.9	98.3	98.4	98.4	0.9	3.8	13,500 lb.
750	96.9	98.1	98.5	98.6	98.6	0.8	3.9	19,000 lb.

97. Single-phase—60 Cycles—33,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight including oil
	¼ load	¾ load	½ load	Full load	1¼ load	100 % p. f.	80 % p. f.	
100	93.8	96.4	97.1	97.3	97.3	1.6	4.8	6,200 lb.
150	94.9	97.0	97.6	97.8	97.8	1.4	4.6	6,600 lb.
200	94.9	97.0	97.6	97.8	97.8	1.3	4.4	8,000 lb.
300	95.7	97.4	97.8	97.9	97.8	1.2	4.2	11,000 lb.
500	96.4	97.8	98.2	98.3	98.3	1.2	4.2	16,000 lb.

103. Tables giving ratings, efficiencies, regulation and weights typical of standard single-phase oil-insulated water-cooled transformers. The temperature guarantees of these transformers are usually 40 deg. cent. above incoming water with continuous full load, and 55 deg. cent. above incoming water with a continuous load one and one-fourth times full-load. The insulation tests are made in accordance with the Standardisation Rules of the A. I. E. E. The tables follow in Par. **104** to Par. **113.**

104. Single-phase—60 Cycles—22,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
500	96.7	97.9	98.2	98.3	98.2	1.2	4.1	6,900 lb.	3½	4
1,000	97.3	98.3	98.6	98.6	98.6	1.1	4.0	10,400 lb.	5½	6½
1,500	97.4	98.4	98.7	98.7	98.7	0.95	3.9	13,500 lb.	7	8½
2,500	97.7	98.6	98.8	98.9	98.8	0.85	3.8	20,400 lb.	9½	12½
4,000	98.0	98.8	98.9	99.0	98.9	0.75	3.8	26,000 lb.	13½	16½

105. Single-phase—60 Cycles—44,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
500	95.9	97.5	97.9	98.0	97.9	1.3	4.5	8,600 lb.	4	5
1,000	96.8	98.1	98.4	98.4	98.4	1.2	5.2	12,500 lb.	6	7
1,500	97.2	98.3	98.6	98.6	98.5	1.0	3.4	17,000 lb.	8	10
2,500	97.5	98.5	98.7	98.8	98.7	0.9	3.9	20,000 lb.	11	12
4,000	97.8	98.6	98.8	98.9	98.8	0.75	3.7	29,000 lb.	14½	17½

106. Single-phase—60 Cycles—66,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
500	95.3	97.2	97.6	97.7	97.7	1.6	6.7	11,500 lb.	4½	5½
1,000	96.1	97.6	98.0	98.1	98.1	1.2	4.6	16,500 lb.	7	8
1,500	96.7	97.9	98.3	98.3	98.3	1.05	4.6	21,000 lb.	9½	11
2,500	97.2	98.3	98.6	98.6	98.6	0.95	4.7	26,500 lb.	12	15
4,000	97.7	98.5	98.7	98.8	98.7	0.85	4.9	32,000 lb.	16	19

111. Single-phase—25 Cycles—66,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
750	96.6	97.6	97.8	97.7	97.5	1.92	5.6	21,500 lb.	5½	6½
1,000	96.8	97.8	97.9	97.9	97.7	1.7	5.7	23,000 lb.	8	9½
1,500	97.0	98.0	98.1	98.0	97.9	1.6	5.3	28,000 lb.	10½	12½
2,500	97.4	98.2	98.3	98.2	98.1	1.4	6.0	34,500 lb.	15½	18½
4,000	97.6	98.3	98.5	98.4	98.3	1.2	5.2	49,000 lb.	21½	26

112. Single-phase—25 Cycles—88,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
750	96.2	97.4	97.6	97.5	97.3	2.0	6.6	26,600 lb.	7	8
1,000	96.6	97.7	97.8	97.8	97.6	1.9	6.8	28,000 lb.	9½	11
1,500	96.7	97.7	98.0	97.9	97.8	1.65	4.7	35,500 lb.	11	13
2,500	97.2	98.1	98.3	98.2	98.1	1.3	4.6	45,500 lb.	17	19½
4,000	97.4	98.2	98.4	98.4	98.3	1.3	5.0	59,500 lb.	22½	27½

113. Single-phase—25 Cycles—110,000-volt Class

Kv-a.	Efficiencies					Regulation		Net weight incl. oil	Water rates: gal. per min.	
	¼ load	½ load	¾ load	Full load	1¼ load	100% p. f.	80% p. f.		100% load	125% load
1,000	96.3	96.4	97.6	97.5	97.3	1.95	5.8	35,700 lb.	12	14
1,500	96.5	97.6	97.8	97.7	97.6	1.75	5.8	42,800 lb.	13½	15½
2,500	97.1	98.1	98.20	98.10	98.0	1.5	5.7	56,000 lb.	17	19½
4,000	97.3	98.2	98.4	98.4	98.3	1.30	5.9	72,000 lb.	24	27½

114. Efficiencies, regulation and weights typical of three-phase oil-insulated water-cooled transformers may be obtained with reasonable accuracy by taking the values for single-phase transformers of one-third the rating; the water rates and weights being multiplied by three.

TRANSFORMERS FOR DISTRIBUTING SYSTEMS

115. General considerations in design. Transformers for distributing systems should be of high efficiency. Competition has brought about a certain degree of standardization of the losses of each size of transformer. The problem is, therefore, to produce a design having a minimum cost which is durable in service and conforms to definite performance specifications.

116. The relative values of core-loss and copper-loss in lighting transformers have been largely determined by competition, but it is probable that the present values give about the best average results in service.

121. Performances of 25-cycle Transformers; Standard Voltages 2,200–1,100/220–110

Kv-a.	Losses (watts)		Efficiencies				Regulation		Floor space (in.)	Height (in.)	Net weight (lb.)
	Iron	Copper	¼ load	½ load	¾ load	Full load	100 % p. f.	80 % p. f.			
1.0	16	46	92.9	94.8	94.7	94.1	4.60	4.00	13[illegible] × 11[illegible]	15[illegible]	150
1.5	23	72	93.2	94.8	94.7	94.0	4.81	4.80	16[illegible] × 13[illegible]	17[illegible]	200
2.0	23	94	94.6	95.5	95.2	94.5	4.72	4.88	16[illegible] × 13[illegible]	17[illegible]	200
2.5	31	105	94.3	95.6	95.5	94.8	4.21	4.16	16[illegible] × 13[illegible]	20[illegible]	225
3.0	35	125	94.6	95.7	95.6	94.9	4.18	4.14	16[illegible] × 13[illegible]	20[illegible]	225
4.0	45	150	94.8	96.0	95.9	95.3	3.76	3.98	17[illegible] × 15[illegible]	23[illegible]	300
5.0	52	170	95.2	96.3	96.2	95.8	3.41	3.50	18 × 16[illegible]	27[illegible]	375
7.5	72	230	95.6	96.6	96.6	96.1	3.08	3.13	20[illegible] × 17[illegible]	32[illegible]	500
10.0	86	285	96.0	96.9	96.8	96.4	2.87	3.42	25[illegible] × 20	30[illegible]	660
15.0	113	392	96.5	97.2	97.1	96.7	2.63	3.22	29[illegible] × 21[illegible]	36[illegible]	890
20.0	150	430	96.5	97.5	97.4	97.2	2.18	3.08	32[illegible] × 24[illegible]	38[illegible]	1,150
25.0	165	525	96.9	97.7	97.6	97.3	2.13	3.04	32[illegible] × 24[illegible]	46	1,365
30.0	290	580	95.8	97.2	97.3	97.2	1.93	2.62	34[illegible] × 32[illegible]	35[illegible]	1,600
37.5	335	670	96.2	97.4	97.5	97.4	1.78	1.90	37 × 35[illegible]	37[illegible]	2,020
50.0	400	800	96.5	97.6	97.8	97.7	1.60	1.75	37 × 35[illegible]	44[illegible]	2,200

122. Performances of 60-cycle Transformers; Voltages 6,600–6,300–6,000/220–110

Kv-a.	Losses (watts)		Efficiencies				Regulation		Floor space (in.)	Height (in.)	Net weight (lb.)
	Iron	Copper	¼ load	½ load	¾ load	Full load	100 % p. f.	80 % p. f.			
1.0	22	27	91.3	94.5	95.3	95.3	2.71	3.13	16[illegible] × 11[illegible]	18[illegible]	133
1.5	27	39	92.7	95.3	95.8	95.8	2.61	2.95	16[illegible] × 11[illegible]	18[illegible]	140
2.0	34	46	93.1	95.6	96.2	96.2	2.32	3.04	18[illegible] × 12[illegible]	21[illegible]	176
2.5	38	55	93.8	96.0	96.5	96.4	2.23	3.14	18[illegible] × 12[illegible]	21[illegible]	190
3.0	40	68	94.5	96.3	96.6	96.5	2.29	3.26	18[illegible] × 12[illegible]	21[illegible]	192
4.0	45	81	95.2	96.8	97.0	96.9	2.04	2.27	19[illegible] × 13	23[illegible]	230
5.0	50	105	95.7	97.0	97.2	97.0	2.11	2.29	19[illegible] × 13	23[illegible]	240
7.5	70	142	96.0	97.3	97.4	97.3	1.91	2.29	22[illegible] × 15[illegible]	25[illegible]	346
10.0	90	162	96.1	97.4	97.6	97.6	1.63	1.99	22[illegible] × 15[illegible]	25[illegible]	380
15.0	118	235	96.6	97.7	97.8	97.7	1.58	2.06	24[illegible] × 17	31	543
20.0	147	295	96.8	97.8	97.9	97.8	1.49	2.11	30[illegible] × 21[illegible]	32	748
25.0	166	360	97.1	98.0	98.1	98.0	1.46	2.21	30[illegible] × 21[illegible]	36	853
30.0	183	420	97.3	98.1	98.2	98.0	1.42	2.23	33 × 22[illegible]	36[illegible]	957
37.5	220	490	97.4	98.2	98.3	98.1	1.33	2.32	33 × 22[illegible]	42	1,081
50.0	267	620	97.6	98.3	98.4	98.3	1.27	2.39	35[illegible] × 24[illegible]	48	1,390

125. Performances of 60-cycle Transformers; Voltages 16,500–15,750–15,000/220–110.—(*Continued*)

Kv-a.	Losses		Efficiencies				Regulation		Floor space (in.)	Height	Net weight (in.)
	Iron	Copper	¼ load	½ load	¾ load	Full load	100 % p. f.	80 % p. f.			
37.5	325	550	96.3	97.6	97.8	97.7	1.52	2.97	35¾×24¾	48	1,320
50.0	370	700	96.8	97.9	98.0	97.9	1.45	2.92	37¼×30⅝	44⅜	1,450
75.0	600	840	96.6	97.9	98.1	98.1	1.20	2.70	40½×34 1/16	51	1,965
100.0	800	980	96.7	98.0	98.2	98.2	1.05	2.60	40⅝×34 1/16	56½	2,225

126. Manhole transformers. It is the general practice in large cities to supply energy for lighting by means of underground cables. Manhole transformers are simply lighting transformers fitted with cases of a type suited for operation in a manhole. These cases are rendered water-tight and air-tight and have an extra amount of radiating surface. The cover is provided with a vent covered by a thin air-tight metal diaphragm, so that if the pressure in the case becomes excessive the diaphragm will rupture. The outlet bushings should be so designed that they are moisture proof and yet admit of ready disconnection of the transformer. The rating, efficiency and regulation are the same as for standard distributing transformers.

MULTIPLE OPERATION

127. General principles. In Par. **19** of this section it is shown that the transformer of unity ratio may be represented by a simple alternating-current circuit shunted by an admittance *Y*. Where the ratio is not unity, this equivalent circuit still holds, if one winding is taken as the reference winding and all admittances are reduced to terms of this winding; this may be done by multiplying (or dividing) all these quantities in the other winding by the square of the ratio. The admittance *Y* does not enter the problem of relative division of the load and may therefore be ignored; the effective impedance of the transformer with respect to the reference winding will then be the same as the short-circuit impedance with that winding considered as the primary and the other short-circuited.

It is shown in Sec. 2, that in a branched circuit the current in each branch will be inversely proportional to the impedance of the branch. Since the effects of the primary and the secondary resistance and the magnetic leakage of the transformer may be represented by a simple impedance, the rule of branch circuits will also apply to parallel operation of transformers. In actual calculations the problem is usually to determine how a given number of transformers will divide a load of given kv-a. and power-factor. It will be found convenient in most cases, instead of using actual impedances or admittances, to use the ohmic and reactance drops expressed as fractions of the secondary voltage. Admittances derived from these are proportional to the actual admittance.

128. Formulas. Let the kv-a. rating of the transformers be P_1, P_2, P_3, etc., and let the impedance volts of each, expressed as a fraction of the rated voltage, be (c_1+jd_1), (c_2+jd_2), (c_3+jd_3), etc., respectively, then the admittances (g_1-jb_1), (g_2-jb_2), (g_3-jb_3), etc., will have the following values;

$$\left.\begin{aligned} g_1 &= \left(\frac{c_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right); \quad b_1 = \left(\frac{d_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right) \\ g_2 &= \left(\frac{c_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right); \quad b_2 = \left(\frac{d_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right) \\ g_3 &= \left(\frac{c_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right); \quad b_3 = \left(\frac{d_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right) \end{aligned}\right\} \quad (39)$$

fraction of AB that the resistance drops of the respective transformers bear to their impedance drops. AC_1 is taken equal to the current that will produce the drop AD_1 in one transformer, and AC_2 is taken equal to the current that will produce the drop AD_2 in the other transformer. The resultant AC is the combined current. The corresponding combined resistance drop is AD. The line AC will then represent the combined load current on a certain scale, and AC_1 and AC_2 will represent the currents in the respective transformers, in magnitude and phase, on the same scale. Since the currents are known, the value of the impedance drop is known, and therefore the scale on which AB represents the impedance drop is known also: we may take a certain length to represent the magnitude of the secondary open-circuit voltage on the same scale, and with B as a centre strike an arc EOF; then, extending CA to E, draw AO, making the angle α with AE, where $\cos \alpha$ is the power-factor of the load. OA represents the secondary terminal voltage and OB represents the secondary open-circuit voltage, or approximately the primary e.m.f. multiplied by the ratio of transformation, and with phase reversed.

POLYPHASE TRANSFORMATIONS

132. General considerations. Polyphase systems may be classified as **symmetrical** and **unsymmetrical.** A symmetrical system may be defined as follows: if the system be n-phase, it will then consist of n e.m.fs. of equal intensity differing from each other in phase by $\frac{1}{n}$th of a period. If $\dot{E}_1 = E_1 \epsilon^{j\omega t}$ is one of the e.m.fs. and if 1, α_1, α_2, α_{n-1} are the n roots of the equation $x^n - 1 = 0$, we may write the n e.m.fs. symbolically as follows:

$$\dot{E}_1 = \dot{E}_1, \quad \dot{E}_2 = \alpha_1 \dot{E}_1, \quad \dot{E}_3 = \alpha_2 \dot{E}_1, \quad \dot{E}_n = \alpha_{n-1} \dot{E}_1 \qquad (45)$$

In such a system we shall have

$$\dot{E}_1 + \dot{E}_2 + \dot{E}_3 + \ldots . + \dot{E}_n = 0 \qquad (46)$$

and the **rules pertaining to branched alternating-current circuits** will also hold true for all polyphase circuits, viz.,

(a) The vector sum of all currents flowing toward a common point is zero.

(b) The vector sum of the electromotive forces taken round any closed circuit is zero, the effect of resistance and reactance being considered as counter e.m.fs.

The directions in the windings of the transformers which are taken as positive must be maintained consistently in the vector diagram, or symbolic representation of the electromotive force.

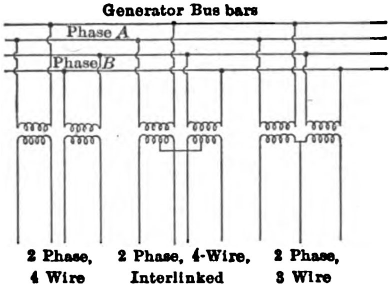


Fig. 22.—Two-phase systems.

133. Two-phase to two-phase transformation. The usual transformation is effected by transforming each phase independently by means of a transformer; the four secondary leads are independent, forming the terminals of a four-wire non-interlinked two-phase system. If the middle points of the secondary bindings be connected together the four-wire symmetrical interlinked two-phase system is obtained. If two ends of the secondary winding be connected together the result is the two-phase three-wire system which is an unsymmetrical interlinked polyphase system and therefore not suitable for long distance transmission. In this system the e.m.f. between the other two ends of the windings is $\sqrt{2}$ times the e.m.f. across the windings. Fig. (22) illustrates these systems.

where $\dot{I}_1$ and $\dot{I}_2$ are the two-phase currents, the corresponding relations for three-phase to two-phase transformation are obtained.

When the currents $\dot{I}_A$, $\dot{I}_B$ and $\dot{I}_C$ are balanced,

$$\dot{I}_C - \dot{I}_B = j2\left(\frac{m_1}{m_2}\right)\dot{I}_A \tag{51}$$

and therefore in order that the three-phase e.m.f. may be balanced independently of the load,

$$\dot{Z}_2 = \left(\dot{Z}_1 + \dot{Z}_4\right)\left(\frac{m_2}{m_1}\right)^2 \tag{52}$$

$$\left.\begin{aligned} \text{or } r_2 &= (r_1 + r_4)\left(\frac{m_2}{m_1}\right)^2 \\ \text{and } x_2 &= (x_1 + x_4)\left(\frac{m_2}{m_1}\right)^2 \end{aligned}\right\} \tag{53}$$

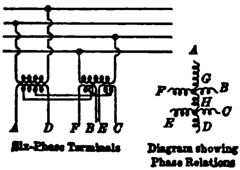


Fig. 24.—Two-phase to six-phase transformation.

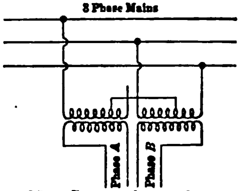
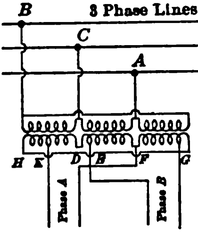


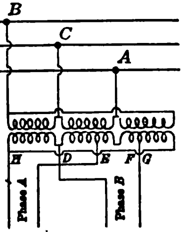
Fig. 25.—Scott three-phase to two-phase transformation.

The necessary adjustment must be made to the two-phase side of the bank of transformers. As a general rule no compensation is needed in practical work, as the unbalancing due to the transformer is trifling compared with that due to other causes. The ratio m_1/m_2 for symmetrical two-phase to three-phase transformation is $\sqrt{3}/2$ so that $(m_2/m_1)^2$ is 1.33.

137. Two-phase to six-phase transformation. This transformation may be accomplished by using two Scott-connected banks of transformers, but a more satisfactory method is that shown in Fig. 24 in which two transformers are used. Referring to Fig. 24, *FB* and *EC* represent two secondary windings of one transformer, supplied by one phase; *AD* represents the secondary of the other transformer supplied by the other phase. The currents in *GA*, *GB*, *HC*, *HD*, *HE*, and *GF* are the six-phase line currents. The current in *GH*, when the load is balanced, is equal to twice that in *GA*, *GB*, etc. The magnitude of the voltage that must be developed in *FB* is $\sqrt{3}/2$ times that in *AD*. *AG* and *HD* contain one-fourth the number of turns that are in *AD*.



Taylor Connection
3 Phase to 2 Phase with
3 Transformers
Fig. 26.



3 Phase to 2 Phase
with
3 Transformers
Fig. 27.

Figs. 26 and 27.—Three-phase connections using three transformers.

138. Three-phase to two-phase transformation with three transformers. These methods of transformation offer some advantages in small installations where the cost of a spare unit is prohibitive, and it is desired to provide against the possibility of complete interruption of service due to ment of the windings is such that the third-harmonic components of the exciting currents of the three transformers cannot flow therein, consequently a third-harmonic component appears in the wave-form of each e.m.f. between the neutral and line. Since the impressed e.m.f. between any two terminals cannot have a third-harmonic component, and since this e.m.f. must be equal to the vector difference of the e.m.fs. between neutral and the two terminals across which the e.m.f. is impressed, these third-harmonic components in the two e.m.fs. from *O* to *A* and from *O* to *B* (Fig. 29) must be equal and in phase. The same statement applies to the third harmonic of the e.m.f. between *O* and *C*. There is therefore in each of the e.m.fs. *OA*, *OC* and *OB* a third-harmonic component of a value depending on the saturation of the core, and having exactly the same time phase. This triple frequency e.m.f. while not in itself serious, becomes so if the neutral of the secondary windings be grounded for then it sets up a triple frequency charging current through ground which interferes with neighboring telephone circuits.

143. Another defect of this connection (Par. **142**) is instability of the neutral point which renders it unsuitable for four-wire three-phase distribution; furthermore if one transformer becomes short-circuited an overvoltage of 73 per cent. is impressed on the remaining two transformers. This defect may be overcome by connecting the primary neutral point to that of the generator, but this will not generally permit grounding the secondary neutral point because there is usually a third harmonic in the generator wave between neutral and ground.

144. There are several ways in which the triple-frequency pulsation in the secondary may be removed. One of them is to **interconnect the secondaries** of the three transformers as shown in Fig. 34. Another method is to provide a small delta winding for the purpose of supplying the necessary triple-harmonic component of the exciting current; this action of the delta connection in combination with the star is discussed under delta-star connections, Par. **148**. All of these schemes add to the cost, and more than counter-balance any gain that might be derived from using this (star-to-star) connection.

145. In star-star connected three-phase core-type transformers the third harmonic component of the e.m.f. between neutral and lines does not occur on account of the mutual inductance between phases.

146. Delta-delta connection. This connection is widely used. Each transformer has its exciting current directly supplied by the generator so that there is no e.m.f. wave distortion. The load taken by each transformer in this connection will depend upon its impedance, so that transformers of different characteristics should not in general be connected together to form a delta-connected bank. If I_A, I_B and I_C are the secondary line currents and I_{AB}, I_{BC} and I_{CA} are the currents in the transformer secondaries, Fig. 29, and Z_1, Z_2, Z_3 are the impedances of the different transformers we shall have the following relations:

$$\left.\begin{aligned} I_{AB} &= \frac{Z_2 I_B - Z_3 I_A}{Z_1 + Z_2 + Z_3} \\ I_{BC} &= \frac{Z_3 I_C - Z_1 I_B}{Z_1 + Z_2 + Z_3} \\ I_{CA} &= \frac{Z_1 I_A - Z_2 I_C}{Z_1 + Z_2 + Z_3} \end{aligned}\right\} \quad (54)$$

147. Delta-star and star-delta connections. These methods of connecting a bank of transformers are the best for **high-voltage transmission**, the delta-star connection being used for stepping-up and the star-delta for stepping-down. When the voltage is stepped-up with a delta-star connection, the neutral of the star may be grounded without introducing any trouble, because the third-harmonic e.m.f. and its multiples, which are the

152. Formulas for "V"-connected transformers. Taking $\dot{Z}$ as the transformer impedance and $\dot{Z}_0$ as that of the load on each phase, and $\dot{E}_A$, $\dot{E}_B$ and $\dot{E}_C$ as the primary star-e.m.fs., and assuming the ratio of transformation to be unity, the primary currents will be

$$\left.\begin{aligned} \dot{I}_{AB} &= \frac{\dot{E}_B}{\frac{\dot{Z}}{3}+\frac{\dot{Z}_0}{3}} + \frac{\dot{E}_C}{\dot{Z}+\frac{\dot{Z}_0}{3}} \\ \dot{I}_{BC} &= -\frac{\dot{E}_B}{\frac{\dot{Z}}{3}+\frac{\dot{Z}_0}{3}} - \frac{\dot{E}_A}{\dot{Z}+\frac{\dot{Z}_0}{3}} \end{aligned}\right\} \quad (59)$$

If we place in the primary, at B, a reactance equal to $\frac{2}{3}Z$ (Fig. 30), the ratio being assumed to be unity, we shall have

$$\left.\begin{aligned} \dot{I}_{AB} &= \frac{\dot{E}_B+\dot{E}_C}{\dot{Z}+\frac{\dot{Z}_0}{3}} = -\frac{\dot{E}_A}{\dot{Z}+\frac{\dot{Z}_0}{3}} \\ \dot{I}_{BC} &= -\frac{\dot{E}_B+\dot{E}_A}{\dot{Z}+\frac{\dot{Z}_0}{3}} = \frac{\dot{E}_C}{\dot{Z}+\frac{\dot{Z}_0}{3}} \end{aligned}\right\} \quad (60)$$

The connection is now balanced and gives exactly the same secondary e.m.fs. at a load of any impedance as a bank of delta-connected transformers having equal impedances of value $3Z$.

153. The "T"-connection is economical in first cost. It consists of two transformers, one of which has both its primary and secondary wind-

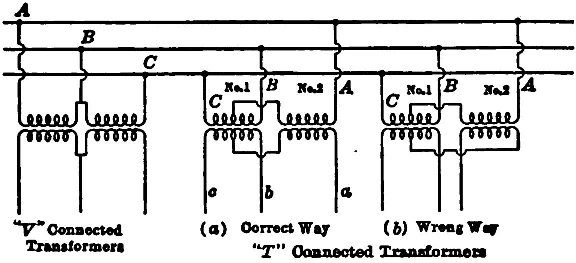


FIG. 30.—Unsymmetrical three-phase to three-phase transformations.

ings designed for 87 per cent. of the three-phase voltages; the other is designed for the full voltage, and both primary and secondary windings are provided with taps at the middle points. The transformers are connected as shown in Fig. 30.

154. Formulas for "T"-connected transformers. Assuming unit ratio the currents in the primary winding will be equal in magnitude and opposite in time-phase to the line currents in the secondary. If $\dot{Z}_1$ is the impedance of the 87 per cent. transformer and Z_2 is the impedance of one-half of the primary of the other transformer, with the corresponding half of the secondary short-circuited, and if $\dot{E}_{AB}$, $\dot{E}_{BC}$ and $\dot{E}_{CA}$ are the primary impressed e.m.fs., the secondary e.m.fs. will be

161. The interconnected-star connection shown in Fig. 34 is used in connection with direct-current three-wire distributing systems. This connection permits continuous current in the neutral wire to flow through the transformers without magnetising them.

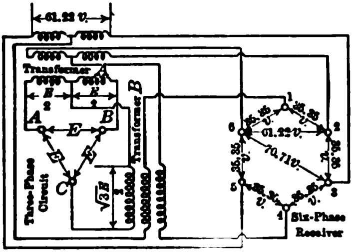


Fig. 33.—Three-phase to six-phase transformation, double tee.

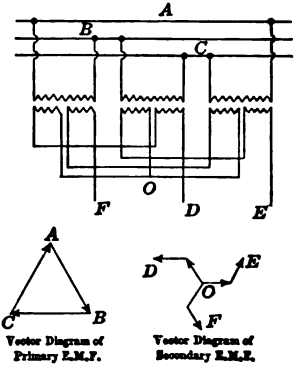


Fig. 34.—Interconnected star connection.

CONSTANT-CURRENT TRANSFORMERS

162. The constant-current transformer depends for its regulation on the force of repulsion between the primary and the secondary coils which carry currents that are in opposite time-phase. Referring to Fig. 35 and Fig. 4, as the load impedance decreases, the current will first increase, if the quantities $(L_1 - M)$ and $(L_2 - M)$ remain constant, but if the latter increases in the right proportion the current will remain constant. As the load impedance $r_o + jx_o$ is decreased, the total reactance in the secondary circuit will decrease, and the short-circuit reactance of the primary circuit will increase a corresponding amount. The ratio of current transformation will therefore remain practically constant throughout the range. The apparatus may thus be considered as a device to maintain a constant effective primary impedance, independent of the load. The short-circuit impedance with full-load coil separation should be as low as consistent with a reasonable cost or satisfactory operation, but with no-load separation it should be high enough to limit the current to its normal value. Sometimes the transformer is designed with regulation to take care of the cutting out of a portion, only of the load impedance, in which cast the short-circuit impedance voltage of the primary circuit for normal current will be less than the primary impressed voltage.

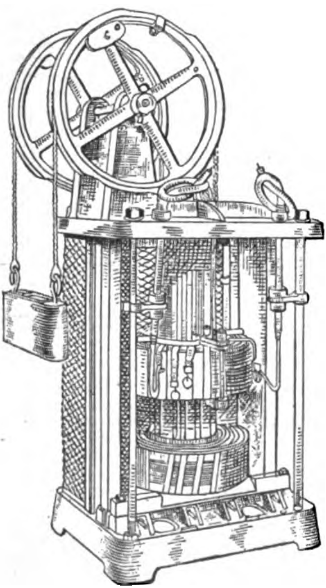


Fig. 35.—Constant-current regulator transformer.

The inductance for a cruciform-core regulator is

$$L = \frac{4\pi C N^2}{10^9}\left(\frac{7.6}{0.23 + \log \frac{r_a}{r_b}}\right) \qquad \text{(henrys)} \qquad (63)$$

For each case the repulsive force F is

$$F = \frac{1}{2} I_1^2\left(\frac{100L}{4.45 \times 2.54 \times C}\right) \qquad \text{(pounds)} \qquad (64)$$

The value of C is obtained by adding to the coil separation the insulation clearance between coils plus 0.45 times the length of each coil. All dimensions are to be measured in inches.

168. Regulation, of constant-current transformers for arc-lighting is usually guaranteed over a range from full load to no load. If properly adjusted, the current should be within 0.1 amp. of the normal value of current for any number of lamps between full load and no load.

169. The satisfactory working of alternating-current arc lamps demands a certain amount of reactance in the lamp circuit. This is provided in the transformer by its own effective reactance. The full-load operating power-factor of an alternating-current arc-lamp system seldom excells 70 per cent.; at small loads the power-factor is very much less. A table of efficiency and rating is given in Par. **171**.

170. Constant-current regulators for series tungsten lamp lighting are similar in design to the alternating-current series arc lamp constant-current transformer, except that the dashpot is omitted. Ratings and efficiencies are given in Par. **172**.

171. Constant-current Transformers for Arc-Lighting; Ratings and Efficiencies

60 Cycles

	Secondary amp.			Full-load efficiency
	6.6	7.5	10.0	
No. of lamps	6	5	6	90.2
No. of lamps	13	11	12	92.5
No. of lamps	20	17	18	92.7
No. of lamps	27	24	25	93.3
No. of lamps	38	34	35	93.9
No. of lamps	55	48	50	94.6
No. of lamps	83	72	75	95.3
No. of lamps	110	96	100	95.7

172. Ratings, Power-factors and Efficiencies of Constant-Current Transformers for Operating Series Tungsten Lamps

60 Cycles

Kw.	Efficiency per cent.				Primary power-factor per cent.			
	¼ load	½ load	¾ load	full load	¼ load	½ load	¾ load	full load
4.0	73.7	86.5	90.5	91.7	22.9	50.6	75.6	83.7
8.0	78.7	89.2	92.5	93.65	23.1	51.8	77.4	84.9
12.0	79.7	89.8	93.0	93.8	23.3	52.3	78.1	85.2
17.0	81.2	90.7	93.5	94.5	23.6	52.5	78.5	85.4
24.0	82.8	91.6	94.2	95.0	23.8	52.7	79.0	85.6
25 Cycles								
4.75	71.9	86.0	90.3	91.0	24.5	51.2	76.8	84.2
7.0	74.5	87.6	91.3	92.0	24.9	52.7	78.3	85.7
10.0	76.4	88.7	92.0	92.3	25.3	53.6	79.8	87.0
14.0	77.0	89.1	92.5	93.1	25.6	54.3	80.7	88.1
20.0	79.1	90.3	93.3	94.0	25.8	54.8	81.3	88.6
28.0	82.6	92.0	94.5	96.0	25.9	55.1	81.4	88.7

178. Auto-transformers for producing a proper division of the load between transformers operating in parallel. There are several ways in which auto-transformers may be used for this purpose; one of these, by which a group of any number of transformers of one design may be connected so as to operate in multiple with a group of any number of transformers of another design, is illustrated by Fig. 39. The illustration shows only single-phase groups, but polyphase groups may be paralleled in a similar manner.

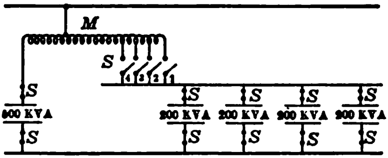


Fig. 40.—Use of auto-transformers for paralleling transformers.

Another method of paralleling two groups of transformers is illustrated in Fig. 40. In this method it is necessary to have an auto-transformer with a number of taps, so that the proper tap may be used for each combination of groups. When paralleling two transformers of unequal impedance drop at their rated currents, the voltage across the whole winding of the auto transformer will be

$$\sqrt{(I_1r_1 - I_2r_2)^2 + (I_1x_1 - I_2x_2)^2} \qquad (64)$$

The winding should be designed to have the turns in each portion inversely proportional to the rated current of the transformer connected to it.

179. The regulation of an auto-transformer is illustrated most clearly by means of a vector diagram. Fig. 41 shows the vector diagram of a step-down auto-transformer. Fig. 42 shows that of a step-up auto-transformer.

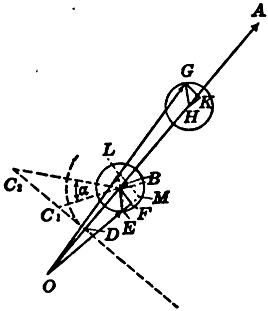


Fig. 41.—Step-down.

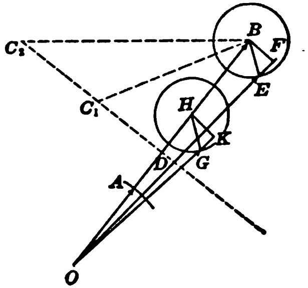


Fig. 42.—Step-up.

Figs. 41 and 42.—Vector diagrams of voltage relations in step-down and step-up auto-transformers.

The construction is as follows: *OA* is the primary counter e.m.f. *OB* is equal to *OA* multiplied by the ratio of transformation. The impedance drop *BE*, in the case of the step-down auto-transformer (Fig. 41) is equal to $(1-m)$ times the short-circuit impedance voltage of the auto-transformer considered as a transformer with the primary short-circuited, the secondary of the transformer being that portion of the winding which forms the secondary of the auto-transformer, the primary being the remaining portion, 'm' being the ratio of transformation. In the vector diagram for the step-up auto-transformer (Fig. 42) the impedance drop *BE* is equal to the short-circuit impedance of the secondary with the primary winding short-circuited, the secondary being that of the auto-transformer considered as a

The mean induction in the core will depend on this e.m.f. and may be found by means of Eq. 4. Let the angle of lag of the exciting current behind the induced e.m.f. be α and let its value considered with reference to the secondary winding be I_m; then if the angle of lead of the induced e.m.f. over I be θ, determined by the formula,

$$\tan\theta = \frac{\omega(L_2 - M) + \omega L_0}{R_2 + R_0} \qquad (67)$$

we shall have

$$\dot{I}_1 = \dot{I}_2\left[\sqrt{1+\left(\frac{I_m}{I_2}\right)^2 + 2\frac{I_m}{I_2}\cos(\theta-\alpha)}\right]\epsilon^{j\theta_1} \qquad (68)$$

where θ and α are already defined, and the value of θ_1 is found from the formula

$$\tan\theta_1 = \frac{\frac{I_m}{I_2}\sin(\theta-\alpha)}{1+\frac{I_m}{I_2}\cos(\theta-\alpha)} \qquad (69)$$

The quantity under the radical in Eq. 67 is the factor by which the ratio turns must be multiplied in order to get the ratio of transformation, and θ_1 is the lead of the primary current over the secondary current.

187. The important factors in the design of series (current) transformers are the load impedance and the effective secondary impedance for these together determine the mean induction in the iron for a given secondary current. These factors being fixed the excellence of the design will depend on the quality of the iron and the care taken in building which should be such as to make I_m as small as possible. Care should be taken in the mechanical design to avoid eddy currents in the end frames, and in the electrical design that in the endeavor to make the induction low by using a large number of turns this purpose is not defeated by the large increase in secondary reactance produced thereby.

188. The effect of these factors and of different qualities of iron may be studied by means of curves of ratio and phase displacement, such as that shown in Fig. 43 which was made by a method similar to those recommended by Crawford and Sharp, Agnew and others (see Sec. 3).

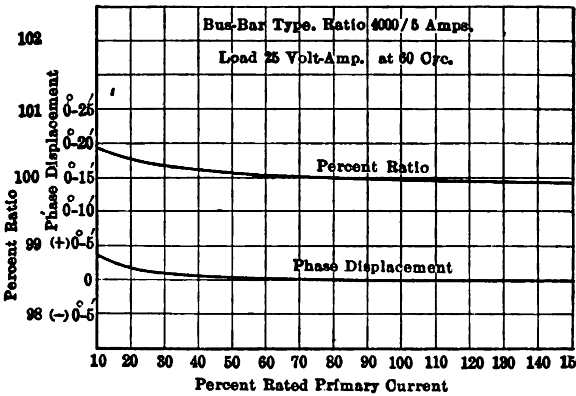


Fig. 43.—Calibration curve of a standard bus-bar type series transformer.

189. Series (current) transformers for high-voltage circuits are generally costly on account of the necessity of insulating them heavily and if they are oil-immersed they require in addition a high-voltage terminal.

of the dials the voltmeter or potential relay will indicate the voltage at the desired point of the feeder or line for any load.

195. Theory of line-drop compensators. Refer to Fig. 6 (under "General Theory"). The voltage at the station is represented by the secondary open-circuit voltage, and the voltage at the end of the line or centre of distribution is represented by the secondary full-load voltage; the reactance drop and the ohmic drop of the compensator are represented by the secondary short-circuit reactance drop and resistance drop, respectively.

196. In order to obtain the highest accuracy with line-drop compensators, it is necessary that the voltmeter operate on a small current compared with that passing through the compensator. Compensators for use with potential regulators, should be designed for larger currents than those for use with indicating instruments.

197. Compensating transformers for neutralizing inductive disturbances in telephone and telegraph lines. Where telephone or telegraph circuits parallel an alternating-current traction system, high voltages may be induced in them due to electromagnetic induction from the railway system. To overcome this trouble, a number of extra pairs of wires are placed among the other telephone wires so that their mutual inductance to the railway circuits is the same as those of the regular telegraph or telephone wires. These extra wires are grounded at various points, and connected to the primary windings of a special transformer, so that the e.m.fs. induced in them magnetize the transformer in the same direction. The telephone or telegraph wires are then connected to secondary coils of this transformer, so that the induced e.m.f. of the transformer opposes and neutralizes the induced e.m.f. due to the railway system. Since the two wires of any pair encircle the core in the same direction, the secondary windings are practically non-inductive, as far as the telephone currents are concerned. The transformers are usually of the core-type construction and differ from ordinary transformers only in the large number of secondary coils and the manner in which they are wound so as to obtain freedom from cross talk.*

198. Insulating transformers for telephone lines are designed to protect both the telephone and the user from high voltages, due either to induction or accidental contact with a high-tension line. This device consists of a shunt transformer provided with a condenser across the primary terminals, the purpose of the condenser being to supply the greater portion of the magnetizing current of the transformer under normal operation. The secondary terminals are connected to the telephone in the usual way. Such transformers are usually built to stand a 25,000-volt test, for 1 min., between the windings, and between windings and case. A lightning arrester and special fuses are generally provided for the primary circuit. The secondary may be grounded if desired, or an insulated stool provided for the user to stand upon.

199. Extra-high-voltage testing transformers. Test voltages as high as 375,000 volts above ground potential are becoming common, such a test voltage requires a testing transformer equivalent in insulation strength to one designed for 750,000 volts with the middle-point grounded. In the testing of insulators an artificial ground is commonly used for the higher voltages. This method of testing is economical in the respect that it requires a transformer insulated for only one-half the potential necessary when test specifications require that one terminal be grounded; but it is open to doubt whether tests made in this manner are as exacting as those made with one side of the circuit grounded. Testing transformers may now be obtained suitable for intermittent testing up to 600,000 volts with one terminal grounded, and up to 750,000 volts with the middle-point grounded. One testing transformer in present service has been tested up to 720,000 volts, effective (by spark-gap measurement), with one end grounded; another has been tested momentarily up to 900,000 volts, effective (by spark gap), with the middle-point grounded. The voltage impressed on the primary is raised either by cutting out resistance as in the potentiometer method of controll or by employing a dial and a separate regulator transformer.

200. Bell-ringing transformers. The bell-ringing transformer, connected to a 110-volt, 60-cycle, lighting circuit, produces at its secondary

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* See article in *Electric Journal* for October, 1914, by Shaw.

rises under certain specified conditions must meet the guaranteed values, Par. 212 to 216.

(e) Insulation tests. These comprise the overpotential test which is made for the purpose of exposing any defect or injury in the insulation between turns, between layers, and between coils; the disruptive test for determining whether the insulation between the primary and the secondary windings and between these two windings and ground is sufficiently strong. Par. 217 to 220.

(f) Tests on instrument transformers; calibration.

206. Shop tests. In the case of large power transformers these tests are sometimes omitted, but in their stead each coil is very carefully inspected during the course of winding and insulating. The tests to determine any defects in winding are made by placing each coil on a core which is furnished with a removable yoke, and inducing in each turn of the coil a specified e.m.f. A test to determine whether the insulation is intact after the coils are assembled and the iron built in, is made by subjecting the insulation between the primary and the secondary windings, and between each of these windings and ground, to a test of several thousand volts. The transformer is then ready for the testing department.

207. Tests to determine whether the transformer is correctly wound and assembled. The first test to make is the **ratio test.** This determines whether the transformer has been wound correctly and the leads and tap brought out in the right places. The methods used in making this test will depend upon the transformer to be tested. Large power transformers are tested for ratio by having a fraction of the normal voltage impressed on a winding while the voltage between taps is measured by means of a voltmeter, and the ratio of the tap voltage to the total is thus obtained. The ratio of the primary voltage to the secondary voltage is obtained in the same manner. Small transformers for lighting and small power service may be tested by balancing against a standard of known ratio. The same method applies to shunt-type (potential) transformers for instruments.

208. Polarity test. In power transformers this test follows the ratio test, and is made by connecting two adjacent primary and secondary

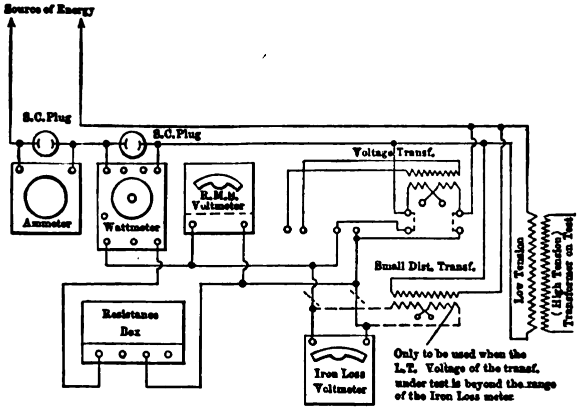


FIG. 44.—Connection for making iron-loss test.

leads together and noting whether the secondary e.m.f. is thereby added to the primary e.m.f., or subtracted from it. In the case of small transformers, the ratios of which are tested by comparison with a standard, the polarity is given at once by reference to that of the standard. Thus the apparatus for testing may be so arranged that if the polarity of the trans-the ammeter reading, and the true-watts component is obtained by dividing the observed core-loss by the value of rated secondary voltage plus the secondary *IR* drop.

211. Copper-loss and impedance volts. This measurement is made by short-circuiting one winding (properly it should be the primary winding) and circulating rated full-load current in the other, observing the loss in watts and the impressed voltage. The connections for the test should be made as shown in Fig. 45. The current should be adjusted with the voltmeter and the wattmeter shunt winding disconnected. The wattmeter may then be read first, followed by the voltmeter. If the exciting current of the transformer is high, a correction, obtained from Eq. 11, Par. **24**, must be added to the copper-loss measured as above. The copper-loss so obtained will be the true copper-loss of the transformer and includes the eddy-current loss in the conductors. By dividing the copper-loss by the rated output, the effective *IR* drop, expressed as a fraction of the rated voltage, will be obtained. Divide the observed voltage by the rated voltage, and the effective impedance-drop, expressed as a fraction of the rated voltage, will be obtained: the effective reactance drop, expressed as a fraction of the rated voltage, may then be obtained by taking the square root of the difference of the squares of these two quantities. Efficiencies and regulation may then be computed from these results by the usual formulas, which are given under "General Theory," Par. **24** to Par. **26**.

212. Tests for efficiency of cooling include the measurement of temperature rise above the cooling medium at various loads. Resistance measurements are also included, because they are necessary to determine the rise in temperature of the copper.

213. Resistance measurements may be made with a Wheatstone or a Kelvin bridge of the proper range. The conditions for measuring the cold resistance should be carefully prepared, so that the apparatus whose resistance is under determination will be at the temperature of the surrounding air. If the temperature of the room fluctuates, it is recommended that an idle unit be employed, of the same design as those on test. The resistance of the winding of the idle transformer may then be used as a basis from which to measure the temperature, by increase of resistance of the loaded transformer.

214. Methods of loading. There are various methods of artificially loading transformers. The best method, where two or more transformers

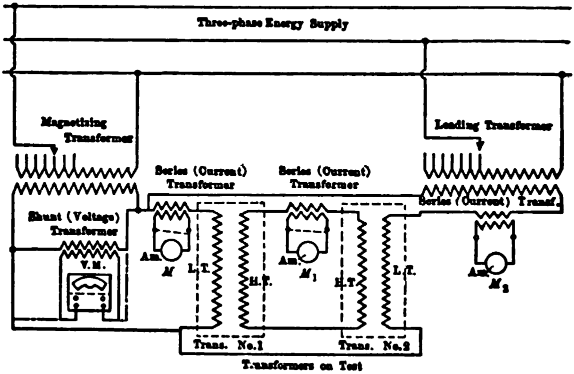


Fig. 46.—Method of artificially loading a transformer (opposition method).

are obtainable, is the **opposition method.** The simplest arrangement of this method is illustrated in Fig. 46. Two transformers are connected as if for multiple operation; then one of the connections of one set of windings is

223. Shipping and unpacking. Before leaving the factory, transformers are carefully packed. They are now generally shipped in their tanks with oil, and are ready for operation as soon as they arrive; but it is always a wise precaution, particularly with high-voltage transformers, to draw off from the bottom of the tank some of the oil and give it the usual disruptive test. If the dielectric strength is not high enough the oil should be dehydrated (Par. 232). This may be done without removing the transformer from the tank, by drawing the oil from the bottom of the tank through the dehydrating outfit and returning it at the top; this should be continued until repeated tests show the oil to be in good condition. If the transformer has been shipped in a packing case, and is one of a high-voltage type, it should **be dried** out before installation, unless it is hermetically sealed in an air-tight metal casing. The safest and best method that can be used to dry out a transformer is to force dry air at a temperature of 90° C. through the windings. Grid resistances may be used for heating the air, and it may be forced through the windings by a blower.

224. Precautions in making connections. When installed ready for operation the transformers should be carefully inspected to see that they are all connected properly, both internally and externally; that all switching apparatus is in good working order; and if new banks are to run in multiple with previously installed banks, it should be noted that they are connected at the proper operating taps, and so as to have the same polarity as the older banks. If the new transformers are of the same manufacture as the old, the polarity will be the same as that of the old, if the banks are similarly connected. If they are of different manufacture from the old, the polarity when similarly connected may be such as to make parallel operation impossible. It is therefore a wise precaution to check up the relative polarity of the old and the new banks before connecting together. This may be done by connecting the new bank on the high-tension side and connecting one of the low-tension terminals to the common bus bar; then, with a voltmeter, and if necessary with the aid of a shunt (potential) transformer, measure the voltage between the other two terminals and the respective busses with which they are to connect (a bank of lamps may be used instead of a voltmeter, with 110- or 220-volt connections) and observe the following **rules:**

(a) **If the polarities are alike** the voltmeter will read zero, in each case.

(b) **If the polarities are reversed** the voltmeter will read, in each case, double the secondary voltage. The remedy is to reverse the connections of the low-tension leads of each transformer in the new bank. (In three-phase transformers it may be found more convenient to reverse the connections of the high-tension coils.)

(c) **In three-phase transformers** the following cases may be met, in addition to the above. Having two similarly located low-tension terminals, of the old and new banks, connected together, the high-tension terminals of each bank being similarly connected to the same source of e.m.f., measure the voltage between corresponding free low-tension terminals.

(c-1) **If one voltmeter reads the secondary voltage correctly and the other reads double this value,** the external polarity of the two transformers is the same, but the terminals are in different order. The remedy is to interchange the internal low-tension connections to the terminals of the new transformers, so that the lead connected to the terminal for which the voltmeter reads double voltage will take the place of the lead connected to the terminal tied to the corresponding terminal of the old transformer. Equivalent external transposition may be made instead.

(c-2) **If one voltmeter reads zero and the other reads 1.73 times the secondary voltage,** then we have a case of reversed external polarity and transposition of terminals, combined. The remedy in the case of a delta connection is to disconnect the ends of the two coils from the terminal showing high voltage and connect the other ends of these two coils to this terminal; the ends previously removed should then be connected to the two remaining terminals, so that a coil that was originally connected to any one of these two terminals will now be connected to the other one. An equivalent change of connections must be made in the case of a star connection.

225. Multiple connections. Transformers having like primary and secondary connections may be run in multiple with one another, but transformers having unlike primary and secondary connections cannot be made to run in multiple with the former except by the use of auxiliary devices, thicknesses of a blotting paper. When using this apparatus it should b seen that the paper is carefully dried, and it is better to soak it, first of al in clean oil that is perfectly dry. Fig. 47 shows this form of oil dehydrato When the oil is in very bad condition, the paper should be changed from tim to time, as often as found necessary. Oil in first-class condition should brea down at not less than 40,000 volts, with a gap of 0.15 in. between ½-in spheres.

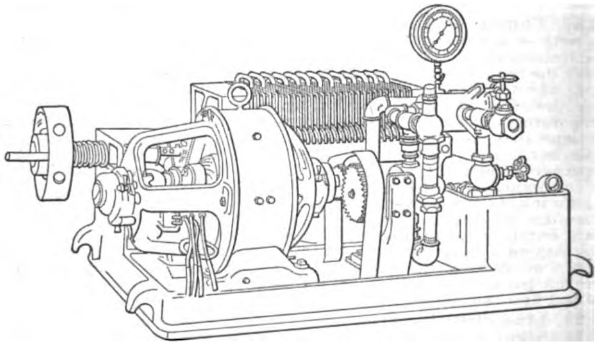


Fig. 47.—Filter press type of oil dehydrator.

233. Regulation of quantity of cooling medium. When water-cooled transformers are subjected to heavy overloads the water rate should be increased correspondingly. Any oil-immersed transformer will withstand a heavy load, for a short period very much better than an air-cooled transformer. Allowance should therefore be made in operation for the cooling characteristics of the transformers, and where artificial means are used for cooling, the cooling may be improved under abnormal load conditions by using more of the cooling medium.

234. The oil-piping layout of transformers when installed should be arranged so that the oil in any unit may be filtered without disturbing the others; there are several obvious methods of accomplishing this. Whatever scheme be used, care should be taken that all the air is removed from the oil in the transformer tanks; this may be done by creating a vacuum under the cover during the process of pumping.*

235. A transformer when burned out or defective should immediately be replaced by a spare unit if one is available. A careful examination should then be made of the windings; if nothing is disclosed, the transformer should be returned to its tank and measurements made of its open-circuit losses. If there are any short-circuited turns or layers, the open-circuit losses will be abnormally high. The location of the trouble can generally be traced by the blackening due to smoke, and by feeling the coils, after first removing the exciting voltage, for the point of highest temperature. If either of these methods fail, measurement may be taken of the resistance of primary and secondary windings; a short-circuit will be indicated by a lower resistance than normal. In many cases, however, a short-circuit which cripples the transformer may involve only a few turns in a large total number, so that the continuous-current resistance measurement may not be sensitive enough to detect it.

236. Formation of scale in cooling coils. A water-cooled transformer may progressively increase in temperature and appear to be defective, due to no apparent cause. In such a case the cause of the trouble can generally be traced to the water supply, which will be found to contain foreign matter in solution, such as lime and carbonates; these impurities, when the water becomes heated in passing through the tubes, are precipitated in the form of

* *Electrical World*, Feb., 1913, p. 360.

which counterbalances the magnetizing or demagnetizing effect of the secondary current.

243. The variation of secondary e.m.f. with change in angular position, for a certain type of single-phase potential regulator is shown in Fig. 49. A vertical cross-section is shown in Fig. 49.

244. The polyphase regulator in every essential detail, is a polyphase induction motor, the polyphase coil-wound rotor of which can be locked in any position desired. The primary windings are connected across the supply lines, precisely like the primary windings of a polyphase induction motor; however, the secondary phase-windings of the induction regulator, instead of being closed upon themselves, as is true of the secondary windings of an induction motor, are separately insulated and separately connected in series with the delivery circuits from the regulator. When polyphase e.m.fs. are impressed upon the primary windings, the e.m.f. generated in each secondary coil is of the same frequency as the primary e.m.f. and its value is entirely independent of the mechanical position of the movable member; the time-phase position of their e.m.fs., however, varies directly with the electrical space position of the movable member. (Compare with the single-phase induction regulator; see Par. **240.**) The resultant delivered e.m.f. is the

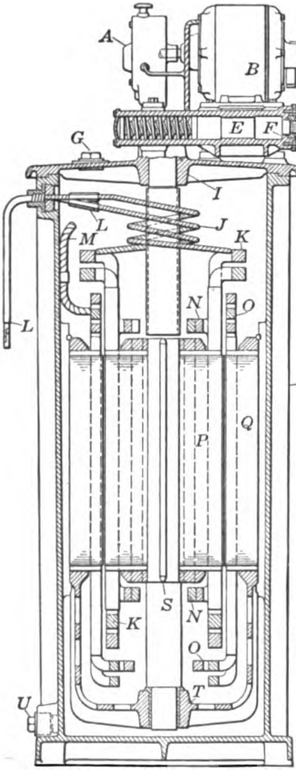


Fig. 49.—Vertical cross-section of single-phase induction regulator.

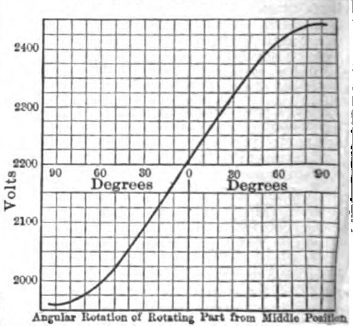


Fig. 50.—Secondary voltage of single-phase potential regulator of varying positions of rotating mauler.

vector sum of (or difference between) the primary and the secondary e.m.fs.; it is not constant in value but varies largely with the position of the movable member.

245. Currents and m.m.fs. in polyphase regulators. The current in the delivery circuit (which is the same as that in the secondary coil) depends directly upon the delivered resultant e.m.f. and the impedance of the delivery circuit. In the polyphase induction regulator there is no special "tertiary" circuit, but each primary phase-winding acts in part as and "all out" will be equal to the value of $\sqrt{1-(\text{power-factor})^2}$, the power-factor being the value with resistance all in. It is evident that if the operating power-factor be made low enough, a series system of incandescent lamps may be operated at constant current, from a constant-potential source, with very little variation in the series reactance.

250. Limitations. The constant-current regulator is manufactured as a standard apparatus by a few companies, but it cannot advantageously take the place of the constant-current transformer, since it requires an additional transformer for insulation purposes (see National Electrical Code); it may, however, be used to advantage instead of the constant-current transformer where it is not required that the receiver circuit be insulated from the supply circuit.

251. Types and characteristics. The usual type manufactured is air-cooled and of the form described in Par. **249**. An automatic constant-current regulator may also be made by connecting in opposition two coils which surround a closed magnetic circuit, using their leakage reactance for the regulating reactance. The two coils are pivoted so as to approach each other at the middle of the core. In action they will repel each other with a force nearly proportional to the current, for any position; with proper counterweight, therefore, the current will automatically be kept constant.

252. A motor-controlled potential regulator may be used as a constant-current regulator by controlling it from a constant-current relay; it is usually, however, too sluggish in operation to give perfect satisfaction.

REACTORS

253. General types. Reactors, choke coils, or reactances for power purposes may be divided into two classes, viz., those in which iron is used and those in which no magnetic material whatever is used. The first type consists of a coil encircling a circuit of iron which is usually broken by an air-gap or a series of air-gaps. The second type is simply a carefully constructed, circular coil of rectangular cross-section, of suitable proportions for cooling, and well supported mechanically.

254. Iron core reactances. The fundamental equations and general design are the same as for constant-potential transformers. The air-gap should be subdivided so as to avoid concentrated leakage, which causes eddy currents in the conductors (which are difficult to eliminate) and also makes it difficult to calculate the reactance accurately. The relative amount of copper and iron will be determined largely by the condition for minimum cost, but where the conductors are very large, it is advisable to increase the area of the core and reduce the number of turns in order to keep down the eddy-current losses in the conductors. In winding with multiple conductors every care should be taken to see that the reactance of each conductor and its resistance is the same; this may be accomplished by properly distributing the "start" and "finish" leads of the conductors.

If the length of the air-gap is l, the required inductance L, the current I, the number of turns n, the effective area of the air gaps must be obtained and it will depend on their number and distribution. The value of $\mathcal{B}$ may then be calculated from this area by Eq. 4, Par. **5**.
Thus the value of l will be

$$l = \frac{4.51nI}{\mathcal{B}} \quad \text{(in.)} \qquad (71)$$

where $\mathcal{B}$ is the induction in lines per sq. in.

255. The current densities and the flux densities will be about the same as for transformers. The methods of insulating the coils are very similar and need no special treatment here, as they are covered under the heading of "Insulation," Par. **41** to Par. **47**.

256. Cooling may be effected by any of the various methods applied to transformers. The problem is the same in every particular and is treated under that heading, Par. **61** to Par. **70**.

257. Applications. Iron reactors for power purposes are mostly used in connection with compound-wound rotary converters to obtain compounding or overcompounding of the voltage at the continuous-current terminals. Iron reactors are also used to shunt the series coils of compound-installing, reactors will be amply strong enough to withstand any stress that may arise in service.

263. Formulas for self-inductance. The inductances of coils at commercial frequencies may be calculated with a high degree of accuracy, provided the proper formula is used. The following formula, which is Lorenz's cylindrical current-sheet formula with a correction for thickness of coil, will be found accurate. Refer to Fig. 53 for dimensions which are assumed to be inches.

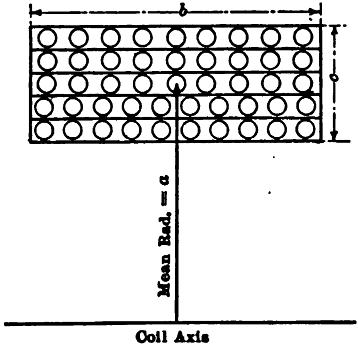


FIG. 53.—Cross-section of reactance coil.

264. Rosa's formula. This is accurate for any shape of coil. For practical work the correction for the form of the conductor is negligible and may be omitted; the formula then becomes

$$L = L_s - \Delta_1 L \qquad (72)$$

To obtain the value of L_s the formula below may be used (Eq. 73):

$$L_s = an^2Q \times \frac{2.54}{10^9} \quad \text{(henrys)} \qquad (73)$$

Where Q is a function of $2a/b$, the values of which for different values of this ratio are given in the table below, in Par. 265. The correction term $\Delta_1 L$ is given by the formula

$$\Delta_1 L = 4\pi a\left(\frac{b}{c}\right)(A_s + B_s) \times \frac{2.54}{10^9} \quad \text{(henrys)} \qquad (74)$$

Where A_s and B_s are given in the tables below (Par. 266 and Par. 267) as functions of c/a.

265. Values of the Constant Q in Eq. 73

$2a/b$	Q	$2a/b$	Q
0.20	3.63240	1.80	19.57938
0.30	5.23368	2.00	20.74631
0.40	6.71017	2.20	21.82049
0.50	8.07470	2.40	22.81496
0.60	9.33892	2.60	23.74013
0.70	10.51349	2.80	24.60482
0.80	11.60790	3.00	25.41613
0.90	12.63059	3.20	26.18009
1.00	13.58892	3.40	26.90177
1.20	15.33799	3.60	27.58548
1.40	16.89840	3.80	28.23494
1.60	18.30354	4.00	28.85335

266. Value of the Constant A_s as a Function of c/a, c being the Depth of the Winding and a the Mean Radius

c/a	A_s	c/a	A_s
0.00	0.6949	0.20	0.6922
0.10	0.6942	0.25	0.6909
0.15	0.6933		

271. The theory of operation. An ionising agent is required to start the electron stream issuing from the cathode. The liberated electrons proceed at high velocity toward the anode ionising molecules of gas on their course thereby producing positively charged bodies and increasing the stream of electrons moving toward the anode. The positive charges are drawn toward the cathode where they become neutralised again or negatively charged; in so doing they further increase the ionization at the cathode, and produce in its neighborhood a high intensity or potential gradient which assists in accelerating the electrons emitted at the surface of the cathode. The neutral or negatively charged molecule is forced back toward the anode, but becomes ionized again by the stream of electrons issuing from the cathode. The negatively charged molecules apparently rarely move far enough away from the cathode, before becoming ionised by collision, and positively charged, so as to come under the influence of the electric field of the inactive electrode. There is, therefore, no leakage or an extremely small one between the active and inactive anode.

272. In the actual design of rectifiers it appears that rectifying power is dependent upon the extent of the dark space surrounding the inactive terminal, which is known as **Crooke's dark space.** This space increases in volume as the vapor pressure decreases. The rectifying power is therefore enhanced by keeping the vapor pressure low, which means operating at low temperature. Another method by which the rectifying power may be increased, is by enclosing the terminals in narrow chambers far removed from the mercury pool; this produces a rectifier much more sensitive to temperature variation than when the terminals are in a common chamber.

273. Auxiliary apparatus. In order to obtain unidirectional current the mercury-vapor rectifier must be provided with a **transformer,** or autotransformer, connected to the anodes so that they will be alternately positive and negative with respect to the mercury pool. The transformer (or autotransformer) must be provided with a middle tap, between the two terminals connected to the anodes; this tap and the cathode of the rectifier chamber form the two terminals of the direct-current circuit. In order to obtain a current whose instantaneous values will fluctuate between narrower limits, some means must be provided to overlap the activities of the two terminals of the rectifier, so that one will become active before the other ceases its activity. This can be accomplished by introducing inductance in the direct-current circuit, or what amounts to the same thing a high magnetic leakage between the two halves of the transformer secondary winding connected to the rectifier. Thus a magnetic field is set up by the current in the anode, which, when the current is decreasing, sets up an electromotive force which tends to hold the anode potential up to the proper value, while the rate of decrease of the current is very much slower than when the inductance is absent; and thus the current is permitted time to build up in the previously inactive anode, before the current has ceased in the other.

274. Formulas for calculation of transformation ratio, induction, etc. The exact calculation of wave form, ratio of direct to alternating current, etc., is a somewhat complex problem involving transient phenomena. For practical work a sufficiently close approximation to exact theory is obtained by considering the ripple in the direct-current wave to be a simple double-frequency harmonic. In the formulas that follow it is assumed that the unidirectional current is represented by a constant average value I_a on which is superimposed a double-frequency simple harmonic current-wave of maximum value I_b: the effective value of the current is $I_e = \sqrt{I_a^2 + I_b^2}$. Let L_a be the effective inductance and let R_a be the effective re-

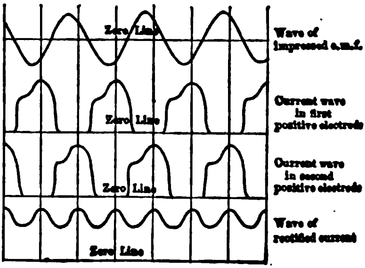
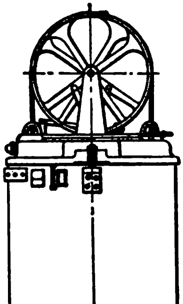


FIG. 55.—Typical wave form of single-phase rectifiers.

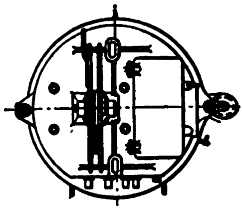
276. A unidirectional current cannot be delivered by the secondary of a transformer except through the medium of the magnetic circuit, which stores the energy during the inactive cycle and delivers it in the form of unidirectional current. The regulation and the power-factor in such cases are necessarily poor. In order to obtain satisfactory operation, two three-phase rectifiers are required which will operate from the secondaries of the three-phase transformer; or three single-phase transformers may be connected to give diametrical six-phase currents, the middle points of the secondaries being connected together. The rectifiers are connected so that there is one anode of each to a single secondary winding. The cathodes are connected together through reactances. In this manner a current may be obtained which is almost perfectly continuous.

277. When mercury-vapor rectifiers are employed for supplying unidirectional current for arc lighting, they require a special form of constant-current transformer provided with a double secondary winding, each portion of which is alternately active and inactive. The two parts of the secondary winding may be so arranged as to supply whatever sustaining reactance is required for satisfactory operation; this is the method adopted by one large company for one of its types of standard rectifier arc-lighting equipments. External reactance may also be supplied through suitable reactance coils; this method is used by another large company, and is also used by the first-mentioned company in another standard type of rectifier arc-lighting equipments.

278. A fifty-light equipment manufactured by the first-mentioned company (Par. 277) makes use of the self-sustaining feature. In the regulator part of the equipment the secondary coils are placed at the top and the bottom of a shell-type core and are so designed as to give the required sustaining inductance, which is the same as the inductance obtained between the middle point of the two coils and the two outer terminals connected together. The primary winding is made up of two coils connected in series, and so arranged by means of wheels and counterweights that they will move in opposite directions from the middle point of the magnetic circuit; under full-load operating conditions they will be as far apart as possible. But under no-load conditions they will be at their minimum separation. In operation, both primary coils are repelled from the active secondary with equal force, but the mutual attraction due to their own currents makes the two coils tend to approach one another; so that with proper counterweights and adjustments, a constant alternating-current may be maintained in the primary, and thus a constant unidirectional-current may be obtained from the secondary. The general appearance of a rectifier equipment for series arc lighting is shown in Fig. 58.



Side Elevation



Plan View

Fig. 58.

279. A one-hundred-light equipment manufactured by the same company (Par. 277) has essentially two separate constant-current regulators, which have a common magnetic circuit. The primary coils are independent and are connected in multiple, so that each primary coil and the adjacent

284. The efficiency of the rectifier is relatively low, seldom exceeding 60 per cent. and frequently averaging much less. The efficiency increases with decrease in the amount of current to be rectified.

285. Heating. Since the efficiency is low, the heat loss in the rectifier is comparatively large, which results in rapid deterioration of the plates. The degree of rectification, as the temperature rises, is much less complete. In other words, the leakage of current becomes excessive as the current increases, unless cooling means are provided.

286. Treatment of plates. A further objection to the electrolytic rectifier is the necessity for occasionally "treating" the plates to form the necessary insulating and rectifying films.

287. General applications. As a result of the low efficiency, the rapid deterioration, and the rapid heating of the electrolytic rectifier, it is seldom used for ordinary loads. Its present field appears to be limited to X-ray equipments and experimental purposes where a cheap rectifying device is required for light intermittent service.

288. Artificially cooled electrodes. Recent improvements have been made in electrolytic rectifiers which permit operation at higher current densities. One of these consists in cooling the aluminum cathode by a stream of water. The effect is such that a current ten times as large can be permitted with the cooled cell as with the same cell uncooled. An excellent rectifying effect with a cooled cell may be obtained with frequencies as high as 4,000 to 10,000 cycles per second.*

MECHANICAL RECTIFIERS

289. The vibrating type of alternating-current rectifier is a simple, efficient and inexpensive piece of apparatus adapted particularly to the charging of three-cell vehicle batteries.

290. General characteristics of vibrating type of rectifier. It is essentially an electrically operated vibrating switch which reverses the connection of the alternating-current line to the battery in synchronism with the alternations of the current, this reversing action being accomplished at the moment when the current flow is zero. There is therefore very little sparking at the contacts and the current delivered is unidirectional and pulsating.

291. The principle on which the vibrating rectifier operates is as follows: a small transformer serves to reduce the alternating-current line voltage to a suitable value; two alternating-current magnets are connected across one-half of the low-voltage winding and are so arranged as to present at any instant poles of like polarity before those of a steel magnet which is excited from the battery. Hence during one-half cycle of the alternating current, one of the poles of the pivoted magnet will be attracted and the other repelled, and the opposite action will take place during the other half-cycle. The pivoted magnet is connected to one terminal of the battery and the other terminal of the latter is connected to the middle point of the low-tension winding of the transformer. Two platinum contacts carried on the pivoted magnet are thereby brought alternately in contact with two other contacts connected to the low-voltage terminals of the transformer, as shown in Fig. 76. It is of no importance which terminals of the battery are connected to the binding posts of the apparatus, since the winding of the pivoted magnet automatically determines the proper polarity of the binding posts.

292. Sparking. A properly designed vibrating rectifier should operate without sparking, otherwise the life of contacts will be short. To secure sparkless operation, contact should be broken at the instant the current falls to zero and should be made again at the moment the instantaneous value of the alternating voltage wave is equal to the e.m.f. of the storage battery. If contact is broken before the current reaches zero and made again some time after the alternating e.m.f. has reached the proper value, the maximum input to the battery will not be obtained; on the other hand, if the current reverses before contact is broken, part of the battery charge will be dissipated in the circuit.

When the wave-form of the alternating-current supply differs from a sine-wave it may be necessary to change the adjustment slightly to prevent

* See *Elek. Zeit.*, Aug. 21, 1913. *Phys. Zeit.*, June 15, 1913.

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SECTION 7

ALTERNATING-CURRENT GENERATORS AND MOTORS

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SYNCHRONOUS MACHINES

GENERAL

1. Definition. A synchronous generator (or motor) usually consists of a system of alternately north and south magnetic poles, comprising the field, which moves with respect to a system of suitably connected conductors in which the alternating e.m.f. is induced. These conductors together with their mounting are called the armature. See Fig. 1. The magnetic poles of the field are usually excited with direct-current supplied by a separate generator called an **exciter**. See Par. 9.

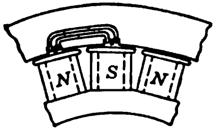


FIG. 1.—A portion of the armature and field of a synchronous machine.

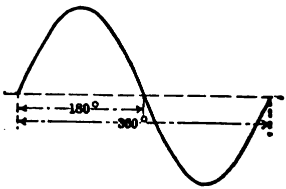
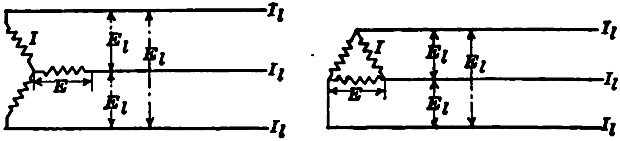


FIG. 2.—A graph of a cycle of e.m.f.

2. The "cycle." In the ordinary heteropolar alternator, the e.m.f. induced in each armature conductor reverses with the passage of each pole, *i.e.*, for a peripheral movement equal to one pole pitch (the peripheral distance between the centres of adjacent poles). The set of values comprised within a double reversal, or corresponding to a movement equal to twice the pole pitch, repeats itself indefinitely, and is called a cycle of values, or simply a cycle. See Fig. 2. The graph of these values plotted against time in rectangular coordinates, is referred to as the **e.m.f. wave** of the machine in question.

3. Frequency. The time required for the execution of a cycle is called the **period** of the alternating e.m.f., and the number of cycles per second is called the frequency. Frequency, f, is expressed by the relation: $f = p \times$ rev. per second, where $2p$ is the number of poles. Modern commercial frequencies in the United States are 60 and 25 cycles per sec.

4. Electrical and magnetic degrees. It is customary to refer to a cycle as 360 electrical degrees (see Fig. 2), or one electrical revolution, and to the circumferential distance from the centre of one pole to that of the next alternators the phases are internally connected, with only three terminals brought out. There are two principal methods of making these connections, Y and Δ (see Figs. 8 and 9). Let E and I represent respectively, volts and amperes per armature phase; and E_l and I_l the line volts and amperes. Then, in the Y armature, $E_l = E\sqrt{3}$, and $I_l = I$; and in the Δ armature, $E_l = E$, and $I_l = \sqrt{3}\,I$. Therefore the power in each case will be $3EI \cos\theta = \sqrt{3}\,E_lI_l \cos\theta$, where θ is the common phase difference between the voltage and current of each phase, balanced load assumed.



Figs. 8 and 9.—Internal and external e.m.fs. and currents in three-phase alternators with Y and Δ connections.

7. Note on phase classification. There is a slight inconsistency in the usual classification of alternators and systems. In the ordinary three-phase alternator (Fig. 5) there are, in each 360 magnetic degrees of circumference, six coil groups or belts of conductors. In these groups are being generated six different e.m.fs. differing in phase progressively by 60 deg. or one-sixth of a cycle. If the six terminals of the three phases be connected to three equal loads, the six currents in the six leads, when counted positive in the same direction along the line, will differ in phase progressively by 60 deg. If, however, the three phases be connected in Y or Δ, with three leads connected to the load, the three currents, counted positive in the same direction along the line, will differ in phase by 120 deg. or one-third of a cycle. To be consistent these two systems should be referred to as "six-phase" and "three-phase" respectively, although the alternator is the same. Moreover when a closed-coil armature is used for alternating e.m.f. generation, as in the case of a synchronous converter, it is called "three phase" when it has three 120-deg. taps and three phase-belts of 120-deg. span, and six phase when it has six 60-deg. taps and six phase-belts each of 60-deg. span. Thus, to be consistent, the ordinary three-phase alternator should be called a six-phase alternator, although mostly used to supply three-phase circuits.

8. Single-phase generators* are occasionally required for railways and also for certain electrochemical and electrothermal processes. Most single-phase generators are simply Y-connected three-phase generators with one of the three legs left idle. When a generator is operated single-phase, it is important that the pole shoes should be fitted with a heavy amortisseur or squirrel cage winding to damp out the effects of the pulsating armature reaction (Par. 44). Furthermore it is important that all parts of the magnetic circuit shall be well laminated in order that pulsations in the resultant m.m.f. may not occasion excessive iron losses.

Occasionally single-phase generators are supplied with distinctly single-phase windings as shown diagrammatically in Figs. 10 and 11. The windings in these two figures differ from one another in the extent to which the conductors are distributed over the surface of the stator. The complete distribution employed in Fig. 11 is wasteful. The proportions of Fig. 10 are more nearly correct. (See Par. 28, Par. 31, and Fig. 32.) A single-phase generator for a given kv-a. output and a given power factor, voltage and speed, is inherently more heavy and expensive than the equivalent polyphase generator by fully 65 per cent. Even then, if the speed is very high, as

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* Waters, W. L. "Modern Development in Single-phase Generators." *Trans.* American Institute of Electrical Engineers. Vol. XXVII, 1908, p. 1069 and from 1086 to 1097.

Hobart, H. M. "The Relative Costs and Operating Efficiencies of Polyphase and Single-phase Generators and Transmitting Systems." *Trans.* American Institute of Electrical Engineers, Vol. XXXI, 1912, p. 115.

is generally arranged between the two main bearings to permit of moving the stator longitudinally, in order to render the rotor accessible. In small machines, however, the bearings are fitted in the end shields. In this type and, in fact, in all types of two-bearing, belt-driven machines, the bearing at the pulley end should be of especially liberal proportions. In England, rope drive is much more usual than belt drive.

13. Engine type. (Direct-connected to reciprocating engines.) In this type sufficient momentum must be provided in the rotating element to ensure the required degree of uniformity in the angular velocity. Three arrangements to accomplish this end are: (a) a separate fly-wheel; (b) the fly-wheel as an integral part of an internal rotor, Fig. 12; (c) the fly-wheel as an integral part of an overhung rotor, Fig. 13.

In America the fly-wheel effect is expressed in terms of the WR^2 where the weight of the rotor in pounds is denoted by W, and the radius to the centre of gyration, in feet, is denoted by R. In countries employing the metric system, the fly-wheel effect is expressed in terms of the GD^2, where D is the diameter at the centre of gyration in meters, and G is the weight of the rotor in kilograms. The greater the weight of the required fly-wheel, the more liberal must be the design of the bearings.

14. Water-wheel type alternators have speeds ranging widely in accordance with the head of water under which the prime movers operate. The Keokuk 9,000-kv-a. generator (Par. 11) has a rotative speed of 58 rev. per min., and the 5,000-kv-a. (Niagara) generator (Fig. 13) has a rotative speed of 250 rev. per min.

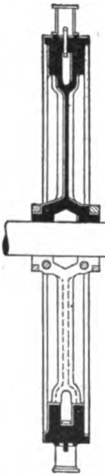

Fig. 12.—Fly-wheel rotor for alternator.

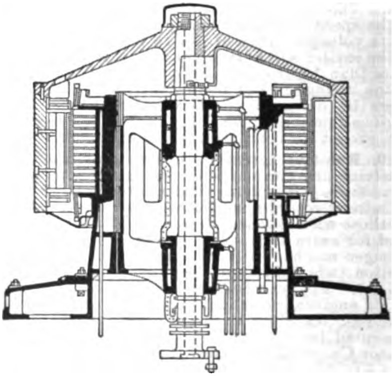

Fig. 13.—Umbrella type of revolving-field alternator.

Even for the same head, water-wheels are built for any speed within quite a wide range. On the whole, the water-wheel will be lower in price and more efficient when constructed for a moderately low speed. On the other hand, the weight and cost of the generator will decrease with increasing rated speed, up to fairly high speeds. Consequently the most economical compromise will usually be at some intermediate speed. At all but very low heads, therefore, the tendency is toward fairly high speeds, though of course the speeds are far lower than for steam turbine-driven generators. For 5,000- to 10,000-kv-a. water-wheel sets, speeds of some 300 to 400 rev. per min. are now often employed. An additional reason for not resorting to much higher speeds is the necessity for providing in the design sufficient mechanical strength to ensure that the machine will safely withstand speeds approaching double the normal speeds, in the event of accident to governors or gates; see Standardization Rules, Sec. 24. See also paper in Vol. XXXI of Trans.

A. I. E. E. by D. W. Mead entitled "The Runaway Speed of Water-wheels and its Effect on Connected Rotary Machinery." Water-wheel generators of both the horizontal and vertical types are built in sizes up to 15,000 kv-a. Fly-wheels are not usually supplied for water-wheel generating sets, owing to the uniform rotative effort of the water-wheels.

15. Steam turbine-driven types.* Extra high-speed generators are now almost invariably constructed with the cylindrical type of rotor carrying the field winding embedded in slots distributed over its surface. Owing to the great stresses associated with high peripheral speeds, the entire rotor (including the extensions constituting the shaft) is often made from a single piece of steel. In the largest machines, peripheral speeds of the order of 25,000 ft. per min. (127 meters per sec.) are employed. Bipolar 25-cycle designs are now under construction for rated loads of 25,000 and 30,000 kv-a. at a speed of 1,500 rev. per min. Bipolar 60-cycle designs for a speed of 3,600 rev. per min., have been built in sizes up to 5,000 kv-a.

It is characteristic of extra high-speed alternators of great capacity that since they are so exceedingly small for their output they can only be maintained at appropriately low temperatures when in operation, by circulating through them enormous quantities of air. For this purpose, and also in order to ensure reasonable absence of noise in their neighborhood, such generators are of the completely enclosed type with definite inlets and outlets for the circulating air. These subjects are discussed in Par. **129** to **139**.

ARMATURE WINDING

16. Considerations affecting the choice of armature winding for an alternator. (a) Efficient e.m.f. generation, *i.e.*, without considerable differential generation in series-connected conductors. This indicates coils whose pitch or span is about 180 deg. The pitch is on other accounts sometimes as low as 0.66 or even 0.50. (b) Wave shape. In most cases an approximate sine-wave is desired, which ordinarily means a distributed winding (several slots per pole per phase). It is not necessary to have a whole number of slots per pole per phase. In fact a fractional number is sometimes desirable, *e.g.*, a machine with 1½ slots per pole per phase will have as good a wave shape, other things being equal, as a machine with five slots per pole per phase. Wave shape also usually indicates a fractional-pitch winding (Par. **20**), *i.e.*, coils with a pitch less than 180 deg. (c) From the standpoint of heat dissipation, as well as of wave shape, the winding should be distributed rather than concentrated; this also reduces the leakage reactance slightly. On the other hand, much distribution means more insulation space and less slot space for copper, particularly in high-voltage machines. (d) From the standpoint of first cost it is important that the coils shall be wound and insulated before being placed in the machines, also that they shall be of one shape rather than of many shapes. This involves the necessity of open slots, although magnetic wedges are sometimes inserted after the winding is in place, in order to secure the advantages of closed or partly closed slots.

17. Classifications of armature windings: (a) coil-end classification (spiral or lap; one range, two range, three range or barrel); (b) according to the number of layers (one or two); (c) according to the pitch of the coils; (d) open slots (usually with form wound coils) or closed slots; (e) according to the number of slots per pole per phase; (f) according to the number of circuits in each phase; (g) according to the number of phases; (h) in three-phase windings, Y or Δ connection.

Diagrammatic illustrations of three-phase windings are shown in Fig. 14 which explains itself. All of these illustrations are for **single-layer wind-**

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* Kloss M. "Selection of Turbo-Alternators," *Journ.* Inst. Elec. Engrs., Vol. XLII, p. 156.

Stoney, G. and Law, A. H. "High-speed Electrical Machinery," *Journ.* I. E. E., Vol. XLI, p. 286.

Walker, Miles. "Design of Turbo Field Magnets for Alternating-current Generators," *Journ.* I. E. E., Vol. XLV, p. 319.

Smith, S. P. "Non-salient Pole Turbo-alternators," *Journ.* I. E. E., Vol. XLVII, p. 562.

Lamme, B. G. "High-speed Turbo-alternators," *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 1.

ings, such that they can be wound with one coil-side per slot. It will be observed also that, in effect, they are all **full-pitch windings**, *i.e.*, that the two groups of active conductors belonging to any given phase and lying under adjacent poles are always 180 deg. apart, as groups, although some individual coils of the spiral windings have a pitch less than 180 deg.

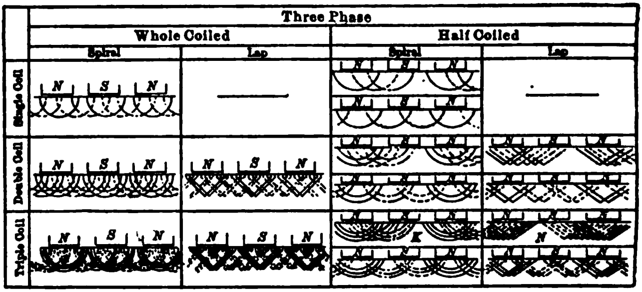

Fig. 14.—Three-phase windings.

18. A three-phase spiral winding with three slots per pole per phase is shown in Fig. 15, and a two-phase spiral winding with six slots per pole per phase in Fig. 16. For obvious reasons these are sometimes called **chain windings**. They are also **two-range windings**, *i.e.*, the coils extend outward in two ranges, or rows. Fig. 5 shows part of a **three-range winding**.

19. Two-layer lap winding. A more common type than any of the windings mentioned in Par. **18**, is the two-layer lap winding, shown in Fig. 17. This type has the advantage not only of a single shape of coil, but also that the coil pitch may be any whole number of slots, without disturbing the symmetry of the winding.

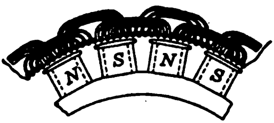

Fig. 15.—Three-phase, spiral, two-range winding.

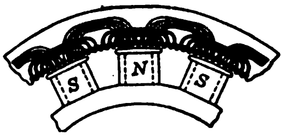

Fig. 16.—Quarter-phase, spiral, two-range winding.

20. Fractional-pitch winding. When the coil pitch is less than 180 deg., the winding is called a fractional-pitch winding. Fractional-pitch windings are much used not only because of their effect on the wave shape (Par. **25** et seq.), but also because of the saving in coil-end copper and in over-all length of machine. The gain is particularly noticeable on two-pole machines where fractional pitch is practically universal. It is also possible with this type of winding to have a fractional number of slots per pole, which tends to eliminate tooth harmonics from the e.m.f. wave. The end connections of the two-layer lap winding stand out in a single range, but because of its appearance and continuity it is often called a **barrel winding**. Figs. 17 and 18 show samples of three-phase, two-layer lap windings with full pitch and 50 per cent. pitch respectively. The between-coil connections and phase terminals, are shown for only one phase. All things considered, the two-layer lap winding is the most flexible and generally useful type. In very high-voltage machines, the necessity for insulation between the two layers is an objection, particularly with fractional pitch, when there is a relatively large potential difference between the two coil-sides in a slot.

21. Fractional pitch single-layer lap winding. It is also possible to have fractional-pitch coils with a one-layer lap winding, but here the number of combinations is quite limited, see Figs. 19 and 20. Inter-coil connections are shown for only one phase. Fractional-pitch one-layer polyphase windings have the serious fault that in a certain portion of the slots, the phases alternate with one another, causing a very unfavorable distribution of the m.m.f. of armature reaction. Thus with three phases *A*, *B*, and *C*, four slots per pole per phase, and 75 per cent. pitch, the distribution of the phases in successive slots is as follows: *ACAABABBCBCCACAABABB*, etc. When each slot contains conductors of only one phase, the m.m.f. distribution is very unfavorable, but with a two-layer winding with four slots per pole per phase, and the same coil pitch, we obtain the following arrangement:

$$\begin{Bmatrix} AAAABBBBCCCCAA \\ CCC\,AAAABBBBCC\,C \end{Bmatrix} \text{etc.}$$

This arrangement provides a nearly sinusoidal distribution of the m.m.f.

22. Multi-circuit windings. Another classification of windings is according to the number of similar circuits in each phase; *e.g.*, a two-circuit 220-volt alternator could be changed to a single circuit 440-volt machine by series-connecting the two parallel circuits.

In three-phase alternators there is still another distinction, namely, between Y and Δ connection of the three phases.

E.M.F. GENERATION

23. Electromagnetic induction. The law of electromagnetically induced e.m.f. may be stated in two ways: (a) whenever a conductor cuts a magnetic flux, an e.m.f. is induced which is proportional to the rate of cutting, *i.e.*, to the flux cut per sec.; (b) whenever the flux linked with a loop or coil of wire, changes for any reason, an e.m.f. is induced in the loop or coil, proportional to the rate of change of the flux and to the number of turns in the coil. For all ordinary cases, statements (a) and (b) are exactly equivalent. For the consideration of alternator electromotive forces, statement (a) will ordinarily be found the more convenient.

24. E.m.f. formulæ. Let l = gross length of armature core, inches. v = peripheral velocity in ft. per sec. $\mathfrak{B}_1$ = maximum gap density (maxwells per sq. in.) of equivalent sine-wave. e'' = root-mean-square volts per in. of active conductor. N = series-connected active conductors per phase (twice the number of turns per phase). E = volts per phase. k_b and k_p are the differential factors, Par. 28 and 29. Then

$$e'' = \frac{12}{\sqrt{2}} v\mathfrak{B}_1 10^{-8} = 8.5 v\mathfrak{B}_1 10^{-8} \qquad \text{(volts)} \qquad (1)$$

and

$$E = k_b k_p e'' N l = 8.5 k_b k_p v \mathfrak{B}_1 N l 10^{-8} \qquad \text{(volts)} \qquad (2)$$

Another very common variety of the e.m.f. formula is obtained as follows: let Φ = flux per pole in maxwells; then the average e.m.f. per active conductor is $2f\Phi 10^{-8}$, and neglecting differential action, the average e.m.f. per phase is $2f\Phi N 10^{-8}$. To obtain the root-mean-square volts and at the same time to take account of the differential action, involves the form factor (k_f = ratio of root-mean-square to average volts), and the differential factors, giving for the induced volts

$$E = 2k_f k_b k_p f \Phi N 10^{-8} \qquad (3)$$

The three k's are usually combined in a single term K which has an average value of 1.05 for full-pitch windings.

25. E.m.f. wave shape. Assuming constant speed, the e.m.f. generated by a single active armature conductor, or by a group of series-connected conductors making up a coil side and lying in a single slot, is proportional at each instant to the density of the magnetic flux through which it is cutting, and when plotted in rectangular coordinates will have the same shape as the "**field form**," *i.e.*, the curve showing the peripheral distribution of flux entering the armature from the field poles (see Par. 32 and 33). This will be referred to as the elementary or slot e.m.f. It is an alternating e.m.f.

but usually not sinusoidal, see Fig. 21. The no-load wave-shape of the machine is then obtained by adding together the e.m.fs. of the series-connected coil sides. This is very tedious as it involves the point-by-point addition of several dephased non-sinusoidal waves. An approximation of some kind is usually employed. The most satisfactory method of handling this problem is as follows: Analyse the field form or slot e.m.f. into its fundamental and harmonics; compound or add vectorially in their proper phase relation, the fundamentals of the several series-connected conductors or coil-sides, to obtain the fundamental of the resultant e.m.f.; and compound similarly the harmonics of each order to obtain the resultant harmonic of that order. To this end the armature conductors are grouped as follows.

26. Similars. Any number of conductors or coil sides, 180 magnetic degrees apart (generally called similars), connected in series, alternating right and left across the face of the armature, will yield an e.m.f. wave of the same shape as that of the field form or slot e.m.f., the result being simply the product of the e.m.f. of a single conductor or coil-side, by the number in series.

27. Phase-belt. In nearly all alternators the conductors of a single phase are not confined to one slot per pole, but are distributed in several slots. The group of conductors belonging to one phase and corresponding to one pole, will be referred to as a phase belt. When the number of slots per pole per phase is a whole number, all the phase belts of a given phase are similars, and the phase e.m.f. will have the same shape as that of a single belt. In a 2-layer winding the group of conductors for one pole and phase may be more conveniently separated into the top-of-slot belt and the bottom-of-slot belt, particularly in the case of fractional pitch windings where these two belts are displaced circumferentially. See Fig. 78 and 79, pages 499 and 500.

28. Belt differential factor. In general the resultant or vector sum of the e.m.fs. of the several coil-sides in a given belt will be less than their numerical sum, owing to their phase differences. The ratio of the vector sum to the numerical sum will be called the differential factor, which is always equal to or less than one. In the case of differential action within a single-phase belt, the differential factor will be called the **belt differential factor,** k_b. Remembering that a fundamental phase difference of β deg. means an nth harmonic phase difference of $n\beta$ deg., it is easy to see that a fundamental phase difference which affords a relatively large differential factor for the fundamental, may give a very small differential factor for one or more of the harmonics. Thus, in a three-phase alternator with two slots per phase per pole, or six slots per pole, the phase difference between two adjacent slots is 30 deg. for the fundamental, 5×30 deg. $= 150$ deg. for the fifth harmonic, etc. The belt differential factors will then be $k_{b1} = \cos 15$ deg. $= 0.966$, $k_{b5} = \cos 75$ deg. $= 0.259$, $k_{b7} = -0.259$, etc. Thus the 5th and 7th harmonics are greatly reduced without appreciably reducing the fundamental. Differential factors for the fundamental and for the various odd* harmonics up to the 27th, for 60-deg. and 90-deg. belts and for various numbers of slots per pole are given in Table I, Par. 31. Differential factors for a 120-deg. belt may be obtained by multiplying those of the 60-deg. belt (same N_{sp}) by the 66⅔ per cent. pitch differential factors, Fig. 22.

29. Pitch differential factor. When the coil pitch differs from the pole pitch, the e.m.fs. developed in the two sides of a single coil, or in the two series-connected belts of a phase-group of coils, will differ in phase by an angle β, which is the angle (in magnetic degrees) by which the coil pitch differs from the pole pitch. This introduces another differential factor $\left(\cos \frac{\beta}{2}\right)$ for the fundamental and $\cos \frac{m\beta}{2}$ for the mth harmonic, which will be called the pitch differential factor. Its values are plotted in Fig. 22.

30. Phase differential factor. The addition of the two e.m.fs. of two phases of an alternator, involves differential action of exactly the same kind as that between the two series-connected belts of a fractional-pitch winding (Par. 29). In a three-phase Y-connected machine, the angle is 60 deg., which is equivalent to a ⅔ pitch; and the phase differential factor for the fundamental and for all the odd harmonics not a multiple of three, is 0.866; while for the harmonics which are multiples of 3, it is zero (see Fig. 22).

* Even harmonics are not present in any appreciable degree in the e.m.f. waves of commercial alternators.

By a suitable combination of belt, pitch. and phase-differential action, any harmonics present in the field form may be practically ironed out of the terminal e.m.f. leaving only a sine-wave which is the resultant of the fundamentals of the e.m.fs. in all the series connected conductors.

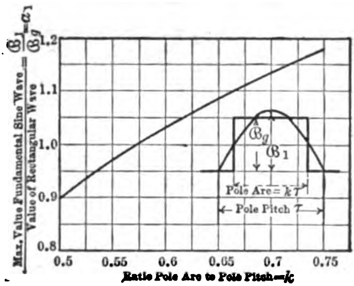

FIG. 23.

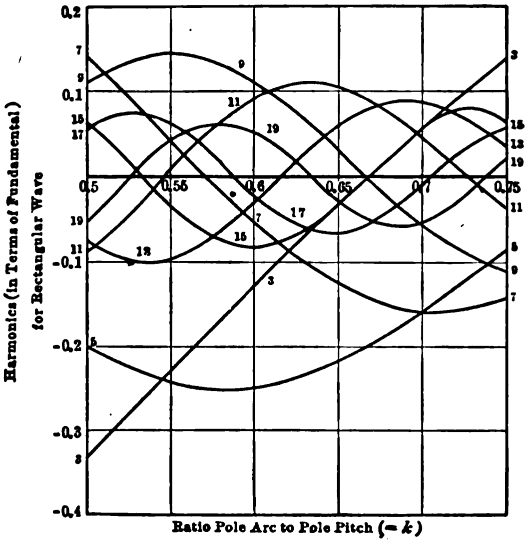

FIG. 24.—Harmonics of rectangular field forms (in terms of fundamental) plotted as a function of ratio of pole arc to pitch.

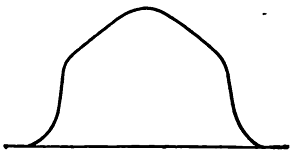

FIG. 25.—Observed field form.

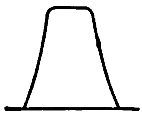

FIG. 26.—Observed field form.

centre of each pole could be filled with iron if desired. Neglecting the effect of slot openings and assuming that the current is distributed uniformly over each belt, the magnetic potential differences (ampere-turns) across the air gap, and therefore the field form, is shown in Fig. 29.

A simple manner in which to obtain the equivalent sine-wave of such a field form is as follows: Any such distributed field winding may be considered as made up of pairs of conductors, the two in each pair being 180 deg. apart. Consider the m.m.f. of a single pair. The field form of the pair if acting alone will be a rectangle, Fig. 30, of which the fundamental sine-wave has a maximum value, $A_1 = 4A \div \pi$. The 3rd harmonic has $\frac{1}{3}$ of this amplitude, the 5th, $\frac{1}{5}$, etc. Assuming that the resultant of the overlapping rectangular m.m.f. and flux distributions of the several pairs of conductors into which the winding has been artificially subdivided, is a curve whose harmonics are small and easily ironed out of the e.m.f. by the differential actions of the winding (*i.e.*, assuming a final sine-wave of e.m.f.); it is obviously unnecessary to consider anything but the *fundamental* of each rectangular field

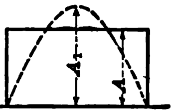

FIG. 30.—Field form of single 180-deg. loop, with its fundamental.

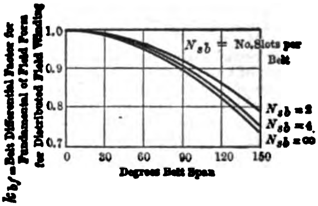

FIG. 31.—Belt differential factor for m.m.f. of distributed field windings.

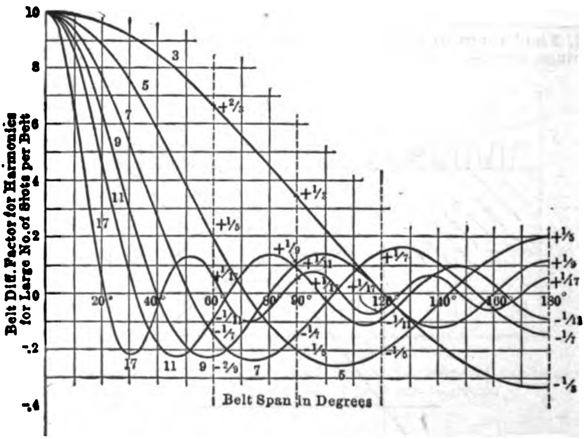

FIG. 32.—Curves of belt differential factors for harmonics vs. belt span.

form (Fig. 30), and to compound or add together the various fundamentals, which can be done geometrically, exactly as with the fundamentals of the e.m.fs. in the several conductors. It is thus possible to use the same differential factors as for the e.m.fs., except that the belt of conductors or of pairs of conductors is no longer confined to the definite widths of 60 deg., 90 deg., or 120 deg., although usually within these limits. The belt differential factor k_{bf} for the fundamental, is given in Fig. 31 for various numbers qualities of the iron may not seriously affect the saturation curve, unless very high densities are used, since the reluctance of the iron portion is small as compared with the air-gap reluctance.

The reluctance of the magnetic circuit is ordinarily divided into five parts, air-gap, armature teeth, armature core, pole core, and yoke. For a given no-load terminal voltage (E), the flux per pole (Φ) entering the armature, is determined by the equation $\Phi = (E \times 10^8)/(2k_f k_b k_p f N)$. See Par. **24.** To obtain the flux Φ_e in the pole core, the field leakage must be added, or Φ must be multiplied by the leakage coefficient ν.

36. Field leakage between salient poles. The leakage coefficient (ν) for salient poles is defined as the ratio of the maximum flux (Φ_e) in the pole core, to the flux (Φ) entering the armature from one pole. The difference between them is the leakage flux (Φ_l).

$$\Phi_e = \Phi + \Phi_l \text{ and } \nu = \Phi_e/\Phi = (\Phi + \Phi_l)/\Phi = 1 + (\Phi_l/\Phi)$$

This leakage flux can be divided into two parts, that (Φ_{lc}) which leaks be-

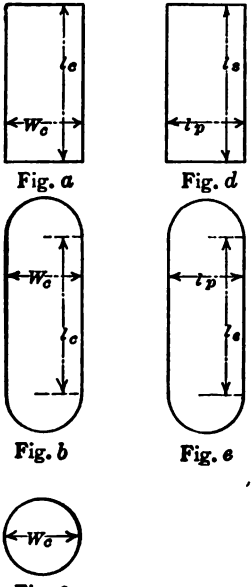

Fig. 34.—(*a, b, c, d* and *e*).—Diagrams for field leakage calculations.

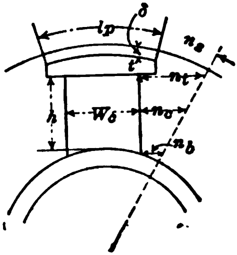

Fig. 35.—For field leakage calculations.

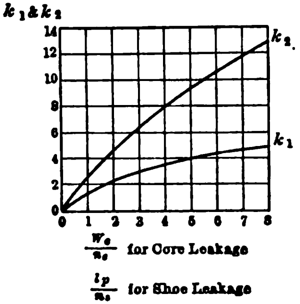

Fig. 36.—Curves of constants k_1 and k_2 employed in field leakage calculations.

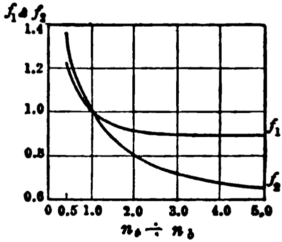

Fig. 37.—Curves of constants f_1 and f_2 employed in field leakage calculations.

length of path for this density. A considerable error in this item is evidently a very small part of the whole number of ampere-turns per pole.

For a non-salient pole machine the ampere-turns for the rotor can best be determined by finding the density midway between the poles, as for the armature core, and approximating to an equivalent length of path for this density. The rotor teeth may be treated exactly as the armature teeth.

A curve of terminal volts plotted against the necessary ampere-turns for the iron part of the magnetic circuit is called an **iron saturation curve.**

40. Ampere-turns for air-gap. If the armature were smooth-cored with no air-ducts, the cross-section of the air-gap would be the area of the pole face plus an allowance for fringing of the flux at the edges, and the actual density would be that determined by dividing the total flux per pole by this cross-section. This will be called the mean pole-face density. Since the flux is crowded into the teeth as it enters the armature, the density which must be used in computing the necessary ampere-turns is somewhat higher than the mean pole-face density.

The flux does not all enter the tips of the teeth, but fringes from the sides of the teeth, having the effect of increasing the width of the tooth tip (w_{tt}). This equivalent tooth-tip is given by the expression $w_{tt} + 2\delta c_f$ where c_f is the fringing constant and δ the length of the air-gap. Values of c_f as a function of w_{so}/δ (the width of slot opening divided by the air-gap length) are shown in Fig. 39. If τ_t is the tooth-pitch, $a_a = (w_{tt} + 2\delta c_f)/\tau_t$ is the fractional part of the tooth-pitch, which is effective as a flux path, or the fractional equivalent tooth-tip. Fig. 40 gives values of a for various values of $k_{so} = w_{so}/\delta$ and $q_{so} = w_{so}/\tau_t$.

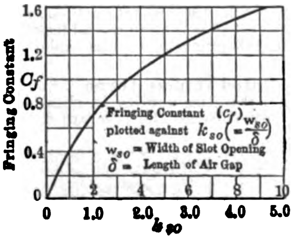

FIG. 39.—Curve for calculating air-gap reluctance.

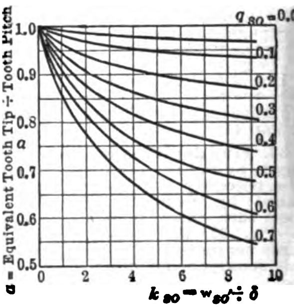

FIG. 40.—Slot contraction factor.

The peripheral-contraction factor K_1, or the ratio of effective peripheral surface to actual peripheral surface is equal to a_a for a salient-pole machine, since there is contraction only on the armature side of the air-gap. For a slot-wound field one must determine the contraction factor both for the armature (a_a) and for the field (a_f). In this case $K_1 = a_a a_f$.

The equivalent length of the armature core (l_e) is given by the expression $l_e = l + \delta - N_d(w_d - 2c_f\delta)$ where c_f is the fringing constant for the air-ducts. N_d = number of ducts and w_d = width of each duct. The longitudinal-contraction factor (K_d) is the fractional-equivalent armature length. It is $K_d = (l_e/l)$. The corrected gap density $\mathcal{B}_{ge}$, upon which we must base our calculation of ampere-turns for the air-gap, is $\mathcal{B}_{ge} = \mathcal{B}_g/(K_1K_d)$, where $\mathcal{B}_g$ is the mean density where the gap is shortest.

As explained in Par. 32 $\mathcal{B}_g = \mathcal{B}_1/a_1$, where $\mathcal{B}_1$ is the maximum value of the equivalent fundamental sine-wave of flux under the pole, and a_1 is a constant depending upon the ratio of pole arc to pole pitch. Therefore $\mathcal{B}_{ge} = \mathcal{B}_g/(K_1K_d) = \mathcal{B}_1/(a_1K_1K_d)$, and the necessary ampere-turns Ni_g for the gap are given by the equation $Ni_g = 0.313\delta\mathcal{B}_{ge}$. Adding the value of Ni_g to the number of ampere-turns per pole necessary to drive the flux through the iron parts of the magnetic circuit, we have the total number of ampere-turns per pole corresponding to the total flux Φ, and therefore corresponding to the no-load voltage with which we began. This gives, therefore, one point on the no-load saturation curve. By taking values of voltage between

44. Armature reaction. The magnetic p.d. across the gap due to the armature m.m.f. may be considered as made up of two parts: (a) A sinusoidally distributed p.d. stationary with respect to the field poles; and (b) pulsating kinks due to the distribution of the armature current in belts and to its localisation in slots. (b) is larger, the smaller the number of phases. Neglecting (b), the maximum or crest value of this equivalent sinusoidally distributed m.m.f. is

$$A_1 = 0.45\, k_b k_p \Delta \tau \qquad \text{(amp-turns)} \qquad (6)$$

where Δ = r.m.s. ampere conductors per in. of armature periphery, τ = the pole pitch in inches; k_b = the belt differential factor, see Table I; Par. **31**; and k_p = the pitch differential factor, see Fig. 22.

If the field m.m.f. were also sinusoidally distributed along the air-gap, it would be an easy matter to compound or add vectorially these two m.m.fs., in order to obtain their resultant. This is nearly enough the case for alternators with distributed field windings. In the case of salient-pole machines, the m.m.f. across the gap at no-load is practically constant at all points of the pole face, but in order to simplify their treatment, the equivalent sinusoidal m.m.f. distributions will be considered. This method results in considerable errors in some cases. The crest value of this equivalent sinusoidal distribution is

$$F_1 = a_1 F_g \qquad \text{(amp-turns)} \qquad (7)$$

where a_1 (Par. **32** and **33**, Fig. 30) is about 1.27 and F_g is the constant magnetic potential difference (in ampere-turns) between armature core and pole core. With narrow or chamfered pole faces, a_1 will be slightly less. $F_g = K_2 F$, where F is the total field ampere-turns per pole and K_2 a constant varying in different machines and with different fluxes. A rough average value of K_2 is 0.8, although in extreme cases it differs considerably from this value.

Eq. (6) holds for any number of phases; but for the case of the *single-phase* alternator, the alternating armature m.m.f. must be replaced by two half-value revolving m.m.fs., one forward and one backward with respect to the armature; or one stationary and the other at double frequency with respect to the field. Eq. 6 gives only that component which is stationary with respect to the field. The other component induces double frequency e.m.fs. and currents in the field coil, and reactive e.m.fs. in the armature. (In the balanced polyphase case the backward revolving components of the several phases cancel or neutralize each other.)

45. Leakage reactance is generally supposed to represent that part of the flux linked only with the armature conductors, but as a matter of fact the only such flux is some of that linked with the coil ends, since the whole effect of the armature m.m.f. in the vicinity of the air-gap is merely to distort the main flux. However, owing to the localisation of the current in slots surrounded by magnetic material which moves with the slot currents, and owing to the grouping of the slots in phase belts which move relatively to the field, there are local flux pulsations which are best treated as if separate from the main flux, although as a matter of fact they are only pulsating distortions of the latter. Armature leakage reactance of an alternator is about as difficult to define as to compute. For most practical purposes the following method will give satisfactory results.

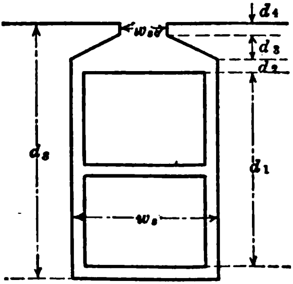

FIG. 42.—Slot section.

46. Slot leakage is the cross-slot flux, computed as if independent of the main flux. Referring to Fig. 42 the "inch permeance," or the flux linkage per amp-inch of slot, is

$$\varphi_s = 3.2 \left(\frac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{so}} + \frac{d_4}{w_{so}} \right) \qquad \text{(maxwells)} \qquad (8)$$

and the corresponding or slot reactance per phase is

$$x_s = 2\pi f\, k_p^2\, lN\, N_{cs}\, \varphi_s\, 10^{-8} \qquad \text{(ohms)} \qquad (9)$$

For very hurried computations φ_s is sometimes approximated without computation; it varies from 8 with shallow open slots to 15 with deep nearly closed slots.

49. Coil-end leakage. This computation is simplified by the fact tha φ_f, the flux per ampere-inch of outside phase-belt-bundle, is nearly a constan quantity for full-pitch windings. Its values for all pitches of working range are given in Fig. 44.

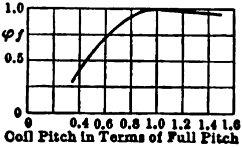

Fig. 44.—Curve of values of flux per ampere-inch for coil ends.

The coil-end reactance in ohms is then—

$$x_f = 2\pi f \varphi_f l_f \frac{N^2}{2p} 10^{-8} \quad \text{(ohms)} \quad (17)$$

where l_f = the length of a single coil end, or the free length corresponding to one active conductor, N the active conductors per phase, and $2p$ the number of poles.

The coil-end *reactance ratio* (Par. 46) is—

$$q_{xf} = 1.48\, k_f \varphi_f \frac{k_3}{k_b k_p} \frac{\Delta}{\mathfrak{B}_1} \quad (18)$$

where k_f $(= l_f/\tau)$ is about 1.5 times the per cent. coil-pitch expressed as a fraction (somewhat larger for very high-voltage machines), and $k_3 = \tau/l$.

50. Total leakage reactance.

$$x = x_s + x_f = 2\pi f N 10^{-8}\left(k_p^2 l N_{sp} \varphi_s + \frac{N}{2p} l_f \varphi_f\right) \quad \text{(ohms)} \quad (19)$$

$$q_x = q_{x_s} + q_{x_f} = \frac{\Delta}{\mathfrak{B}_1}\left(4.44 \frac{\varphi_s}{N_{sp}} \frac{k_p}{k_b} + \frac{1.48\, k_f}{k_b k_p} \varphi_f k_3\right) \quad (20)$$

51. Alternator vector diagram. Assume a sinusoidal peripheral distribution of m.m.f. on both armature and field and a uniform peripheral reluctance. (This assumption is warranted in non-salient pole machines, but gives rise to considerable errors in some salient pole machines.) The resultant m.m.f. and gap-flux distribution will then also be sinusoidal.

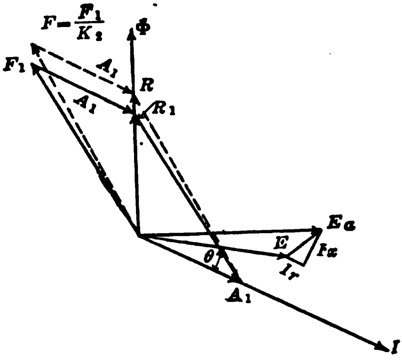

Fig. 45.—*General* alternator diagram for non-salient poles (full lines). Salient poles (broken lines).

Referring to Fig. 45, designate the flux by Φ, the corresponding reluctance a.t. across gap by R_1, the armature amp-turns by A_1 (see Par. 44), and total a.t. across the gap by F_1 all sinusoidally distributed. These are all space vectors on the assumption that the field rotates counter-clockwise with respect to the armature, R_1 being the resultant of F_1 and A_1. In salient-pole machines substitute F (the full field amp. turns × 1.27) for F_1 and the corresponding R for R_1. This partly balances the error due to the unsymmetrical peripheral reluctance.

Considering Φ as a time vector, the induced e.m.f. E_a will lag 90 deg. Subtracting Ir and Ix from E_a gives the terminal voltage E, where θ is the load phase angle. Hereinafter this diagram will be called the *general* alternator diagram.

52. Application of alternator diagram to the regulation problem. Given the winding data of armature and field, the armature resistance and leakage reactance, and the saturation curve, the excitation and regulation for any load and power-factor may be obtained as follows:

factor saturation curve will then be obtained by drawing lines from E_a equal and parallel to $\overline{cb}$, as shown. The fact that Ir is neglected is not significant, since it is in this case at right angles to E and does not affect the result appreciably. This curve may also be determined experimentally.

56. Load saturation curves at other power-factors. If the load saturation curve at other power-factors could be obtained, it is obvious that the regulation and excitation for any power-factor and terminal voltage could be obtained directly therefrom. A semi-empirical method of obtaining these curves, recommended in the latest edition of the Standardization Rules of the A. I. E. E. is given in Sec. 24.

57. E.m.f. method. This method practically assumes a field flux wholly dependent on the field m.m.f., as given by the saturation curve, and that all the drop is due to an internal impedance which is commonly called the **synchronous impedance,** z_s, of which the **synchronous reactance** is x_s. Fig. 49 shows saturation and short-circuit characteristics with the derived synchronous impedance curve, the ordinates of the latter being the ratios of corresponding ordinates of the other two.

58. The m.m.f. method. This method is best understood by reference to Fig. 50, where the general diagram is dotted in. Starting with E and I, add Ir to E to get E', which is assumed to be the total induced e.m.f., corresponding to E' as taken from the saturation curve. From R' subtract the m.m.f. A' taken from the short-circuit characteristic corresponding to the particular current in question. A' is the F of Figs. 47 and 51 and includes with the armature $m.m.f.$ A, an additional $m.m.f.$ $\overline{AA'}$ (Fig 50), which is practically equivalent to R of Fig. 47, and which is the approximate m.m.f. equivalent of Ix. Under short-circuit conditions, $E' = Ir$ and the diagram reduces to Fig. 51, whence it is obvious that the field ampere-turns at short-circuit practically corresponds with what we have called A'.

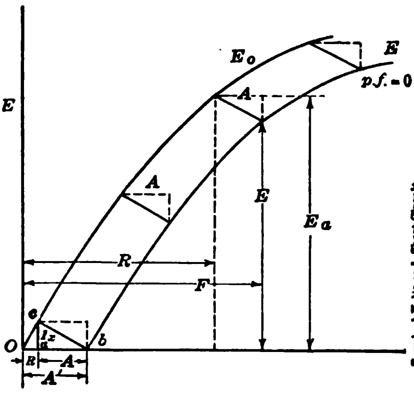

FIG. 48.—No-load saturation curve and zero-power-factor load saturation curve.

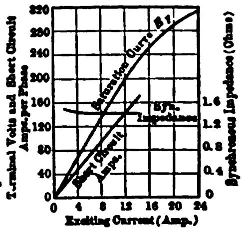

FIG. 49.—Alternator characteristic curves.

59. Excitation characteristics. Curves showing the relation of excitation (for constant terminal voltage) to the load current, at various power-factors, are shown in Fig. 52 for a 1,600 kv-a. slow-speed alternator with close regulation, and in Fig. 53 for a 6,250 kv-a. turbo-alternator with poor regulation. These were computed by the m.m.f. method.

60. Relation of regulation to per cent. armature strength and length of air gap. A study of Figs. 45 and 50 will show that for a given current and power-factor, the regulation depends upon the following ratios

$$Ir/E_a = q_r;\ Ix/E_a = q_x \text{(see Eq. 20)};\ \frac{A}{R} = q_A$$

Of these four ratios, q_r varies from less than 0.005, in large turbo-alternators, to 0.02 or more in small slow-speed machines; q_x from 0.04 to 0.15 or more; q_A from 1.00 to 0.35; and k_{sf} from 1.5 to 2.0. These last two are the dominant factors in regulation.

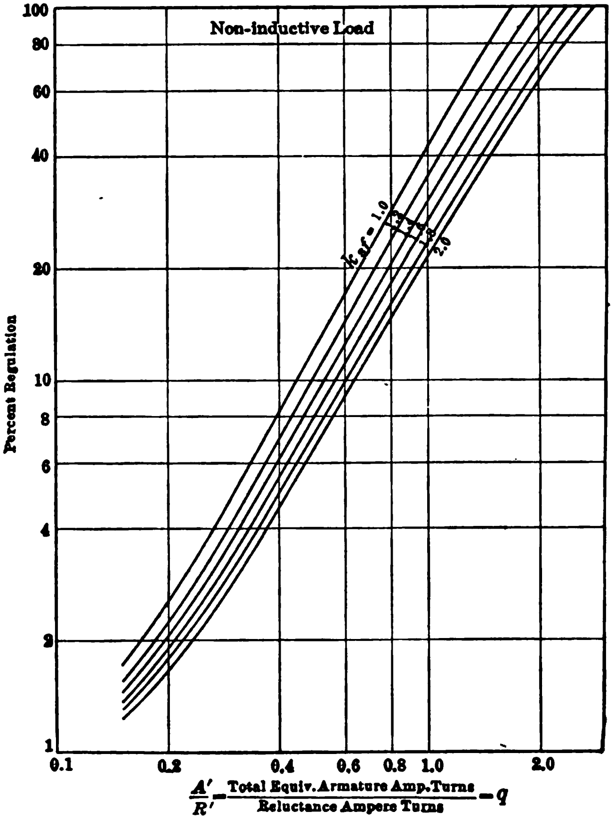

FIG. 54.—Per cent. regulation plotted in terms of per cent. armature reaction.

Since (approximately) $R = 0.313\mathcal{B}_1\delta/(K_1K_dK_2)$ (see Par. 33 and 40),

$$q_A = (A/R) = (1.43k_bk_pK_1K_dK_2\Delta_T)/(\mathcal{B}_1\delta) \qquad (21)$$

or taking average values for the K's,

$$q_A = 0.9(\Delta_T)/(\mathcal{B}_1\delta) \qquad (22)$$

Thus assuming $\mathfrak{B}_1$ and Δ to be fixed for any given case, the regulation at a given power-factor is largely dependent upon the ratio of pole pitch to air gap and upon the saturation factor.

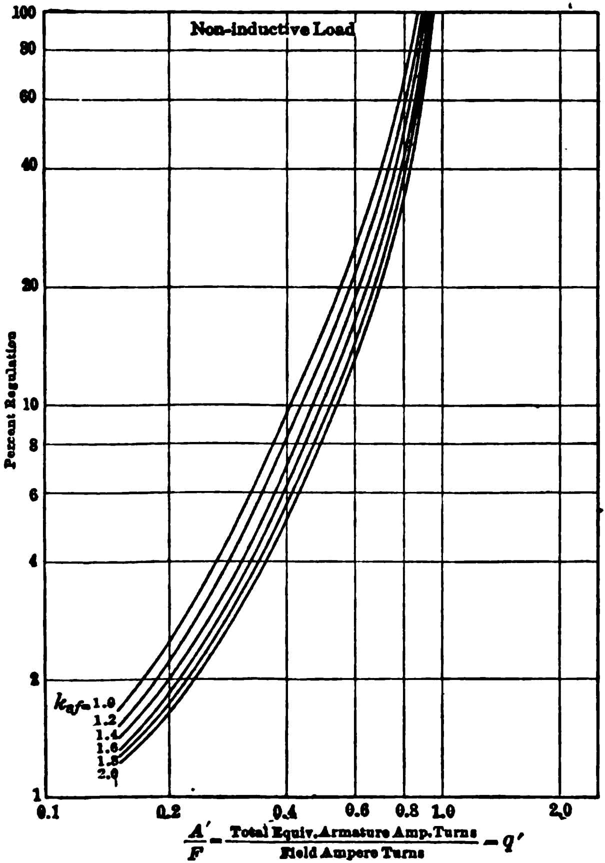

Fig. 55.—Per cent. regulation plotted as a function of $\frac{A'}{F}$.

From the Alternator Diagram (Fig. 45), with some approximations we get, for non-inductive load,

$$\text{Reg.} = \frac{1}{1 - q_r}\left[\sqrt{1 + q_x^2}\left(1 - \frac{1}{k_{sf}}\right) + \frac{\sqrt{1 + q^2}}{k_{sf}}\right] - 1 \text{ (roughly approx.)} \quad (23)$$

Substituting average values for large machines, $q_r = 0.005$, $q_s = 0.07$.

$$\text{Reg.} = 1.005\left(0.007 + \frac{\sqrt{1+q^2} - 1.0024}{k_{sf}}\right) \quad \text{(roughly appox.)} \qquad (24)$$

or in terms of $q' = A' + F$;

$$\text{Reg.} = 1.005\left(0.007 + \frac{1 + \sqrt{1-q'^2} - 1.0024}{k_{sf}}\right) \quad \text{(roughly approx.)} \qquad (25)$$

Figs. 54 and 55 are plotted from Eqs. 24 and 25. For small low-speed machines where q_r and q_s are larger than here assumed, the curves will lie a little higher at their lower ends.

Thus good regulation means large R' and long air gap, longer in proportion to Δ and τ, *i.e.*, very long for large high-speed machines such as turbo-alternators. In fact, to obtain a regulation of even 10 per cent. in large turbo-alternators would necessitate a tremendous air gap and more field copper than there is room for.

61. Value of close regulation. With automatic voltage regulators such as now employed, close regulation is no longer necessary even in small plants. Moreover large low-reactance machines are dangerous in case of sudden short-circuits (Par. 62 to 64). If, however, the ratio of armature ampere-turns to field ampere-turns is too high, the gap flux distortion in a salient-pole machine may be sufficient to seriously distort the e.m.f. wave. This does not apply with equal force to non-salient-pole machines, which include most of the large high-speed alternators, where large q_A is commercially necessary.

62. Short-circuits. If the external impedance of an alternator be gradually reduced to zero, with full-load excitation and normal speed maintained, the short-circuit current, in terms of full-load current, will be $F/A' = 1 + q'$ (see Figs. 50 and 51), and correspondingly less at no-load excitation. If an alternator with a regulation of 5 per cent. and a saturation factor of 1.6, is short-circuited with full-load excitation, the short-circuit current will be about 3 times full-load current. At no-load excitation the short-circuit current will be 2.7 times full-load current. For an alternator with 20 per cent. regulation and a saturation factor of 1.6, the short-circuit current will be 1.56 for full-load excitation and 1.18 with no-load excitation.

63. Sudden short-circuits. Since on short-circuit, most of the field m.m.f. is consumed in balancing the armature m.m.f., the net m.m.f. and the flux are greatly reduced. If the short-circuit is applied suddenly, the sudden decrease in flux induces a large e.m.f. and current in the exciting winding, which tries to keep the flux from changing, and as the electromagnetic inertia and the time constant of the combined circuits are large, an appreciable time elapses before the field is destroyed. Meanwhile the opposing m.m.fs. of armature and field rise until nearly all the field flux is shunted across between field and armature. To do this requires an m.m.f. as many times greater than that at full-load, as the full-load field flux is greater than the total full-load leakage flux (field and armature). Thus if $\nu = 1.12$ at full-load zero p.f., and $q_s = 0.10$ (salient pole slow-speed machine), the r.m.s. armature amperes will rise temporarily to nearly 5 times its full-load value, and owing to the fact that one of the phase currents will be boosted up above its zero axis, because of the position of that phase at the instant of short-circuit, the maximum instantaneous current in one phase may be nearly double the maximum value of the above r.m.s. current.

In non-salient pole turbo-alternators ν may be as low as 1.04, q_s as low as 0.04, the r.m.s. current nearly 12 times full load, and the instantaneous maximum more than 20 times normal. This means mechanical stresses on coil ends more than 400 times normal, which is more than they can readily be made to withstand.

64. Current-limiting reactances. As the total leakage $(\nu - 1 + q_s)$, should not be less than 0.15, external reactances must in some cases be supplied to protect against sudden short-circuits. See Par. 140.

65. Rating of alternators. As the armature current, irrespective of power-factor, determines the armature copper loss, it is customary to rate alternators in kv-a. rather than in kw. In fact at low power-factors, and therefore at smaller values of delivered power, but with a given current and

The power (P_2) transformed is a function of φ, the coupling angle; it is

$$P_2 = \frac{E_2^2}{z_e} \cos \theta - \frac{E_1 E_2}{z_e} \cos (\theta - \varphi) \qquad \text{(watts)} \qquad (26)$$

The significance of the negative sign is that the electrical power is negative, *i.e.*, received rather than delivered. In Fig. 57, $-P_2$ is plotted against φ; whence it appears that as the motor lags (not in speed but in phase) behind the supply e.m.f., the output increases to a maximum, then decreases, becomes negative and returns to zero. As soon as φ has opened out to a point such that P_2 is sufficient to carry the load, it will hang at that point as if the motor were driven by an elastic coupling. If the load increases, φ will increase accordingly, until the maximum point is passed, when the motor will break down. During a little more than a half of each slip cycle (see Fig. 57), the motor is acting as a generator, since $-P_2$ is positive, and is in series short-circuit with the line. So much of the kinetic energy of momentum is lost during this half of the slip cycle that a synchronous motor will practically never pull back into step after once breaking, even if the mechanical load be immediately removed.

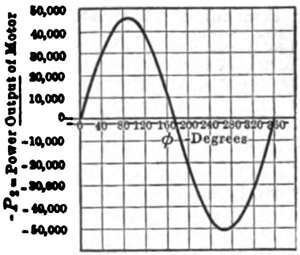

Fig. 57.—Synchronous motor output vs. coupling angle.

For visualizing these relationships and their causes the Blondel diagram is by far the simplest device.

70. Blondel diagram. Referring to Fig. 58, the isosceles triangle $\overline{OAC}$ is constructed on the base E_1 with base angles, $\theta = \tan^{-1}(x_e/r)$. It can easily be shown that with constant impressed voltage E_1, and constant load,

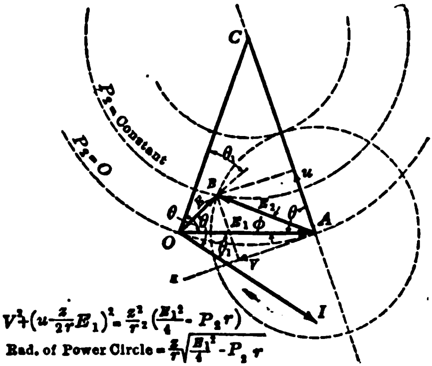

Fig. 58.—Blondel diagram for synchronous motor.

P_2, the locus of the point B, as the excitation and E_2 vary, is a circle with centre at C and with radius $\sqrt{(E_1/2)^2 - P_2 r} + \cos \theta$. If $P_2 = O$, the radius is $(E_1 + 2 \cos \theta) = \overline{CA}$, and the circle passes through O and A. As P_2 increases, the radius decreases until it becomes zero, which corresponds to the maximum possible output with the given motor at the given impressed e.m.f. But this theoretical limit is never reached practically, because of the very large value of E_2 required to reach up to the high-power circles of small radii. This will be better appreciated by reference to the diagram of Fig. 59, where the proportions are more normal and the point C is far off the page.

For varying load and constant excitation, B moves along a circle about A, clockwise for increasing and counter-clockwise for decreasing loads. The maximum load for any given excitation occurs when B falls on $\overline{AC}$; beyond that B swings around on to circles of smaller power, and the motor breaks down; *i.e.*, the decrease of $\cos \theta_2$ more than balances the increase in I.

71. Interpretation of Blondel diagram. In Fig. 58 the area inside of the zero-power circle corresponds to motor power, and that outside to generator power; the area to the left of $\overline{AC}$ corresponds to stable operation and that to the right to unstable operation; the area within the zero-power circle and between $\overline{AC}$ and $\overline{OC}$ corresponds to stable motor operation with a lagging current, and that to the left of $\overline{OC}$ to stable motor operation with leading current.

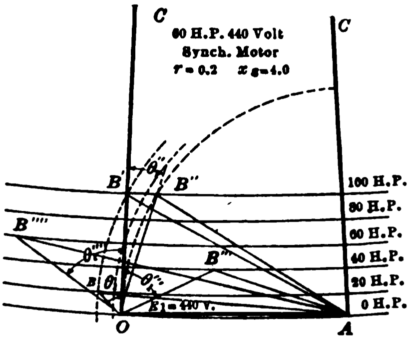

FIG. 59.—Portion of Blondel diagram drawn to scale.

The point B is not only the extremity of the E_2 vector, but may be used also as the outer end of the current vector, since E is proportional to I, and angle $\overline{COB} = \theta_1$. Thus when B falls on $\overline{OC}$, I is in phase with E_1 and I is a minimum for that particular load. With normal steady load conditions, the angle ϕ never approaches the angle θ, *i.e.*, the point B never

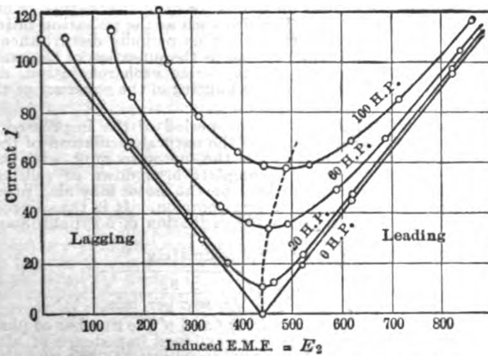

FIG. 60.—V-curves for 60-h.p. synchronous motor.

approaches the breakdown point on $\overline{AC}$ (see Fig. 59); but if either the load or the frequency of supply pulsates or changes suddenly, a hunting may be set up which will carry B over into the region of unstable operation.

72. Excitation and power-factor curves. The familiar "V" curves of current vs. excitation or induced e.m.f. may be easily obtained from the Blondel diagram. This has been done for a 60-h.p. motor, and the result is shown in Fig. 60. Power-factor curves similarly obtained, are shown in Fig. 61.

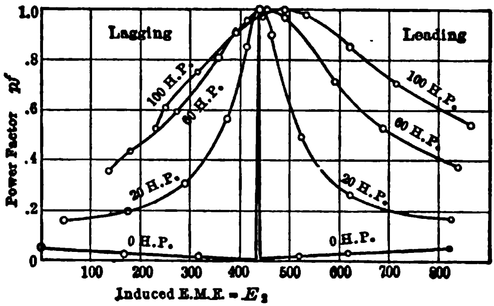

FIG. 61.—Power-factor curves for 60-h.p. synchronous motor.

73. Synchronizing power. By this is meant the stiffness of the coupling or the change in power absorbed per degree change of the coupling angle ϕ, it increases with the air gap and inversely as $q'(=A'/F)$. See Par. 60.

74. Hunting of synchronous motors. Owing to the elastic nature of the electromagnetic motor coupling, any impulse will tend to set up an oscillation about the position of equilibrium, which will continue until the energy by which it was initiated, is absorbed by the extra losses incident to the oscillation. Such oscillation is called hunting, and the absorption of the energy of oscillation is called damping.

75. Hunting may be instigated either by a temporary disturbance, such as a sudden change of load on the motor or of the frequency of supply, or by some periodic disturbance (Par. 76) such as the pulsation of impressed frequency set up by the prime mover. This periodic disturbance may be one of comparatively high frequency due to the pulsation of the crank effort of a reciprocating steam or gas engine during each revolution, or one of comparatively low frequency due to the hunting of the governor of the prime mover.

76. Frequency of hunting. If the period of the impressed disturbance be approximately equal to that of the natural oscillation of the motor, there will obviously be a tendency for the motor to hunt with increasing amplitude, which may result in a complete breakdown or pulling out of step. A periodic pulsation in the load on the motor may also produce the same result, although such is much less common. It is thus important to know what is the natural frequency of oscillation of a synchronous motor, and upon what factors it depends.

The natural hunting frequency is approximately

$$f_h = 0.422\, E_1 \sqrt{\frac{pp'}{Jz_e \text{ rev. per. min.}}} \qquad (27)$$

where J is the moment of inertia in *lb. ft.*^{2} and p' the number of phases.

The z_e used in Eq. 27 should be the combined impedence of alternator, line and motor. The smaller the motor as compared to line and alternator, the less will be the effect of line and alternator impedence upon the hunting period of the motor.

77. Dampers. Forced hunting may be considerably reduced and temporary oscillations more quickly damped out, by means of field dampers, consisting of: (a) a copper loop around each pole face; (b) a copper bridge between poles; or, better still, (c) a squirrel-cage set of copper conductors

83. Effect of differing impressed and induced wave shapes on power-factor. When the impressed and induced e.m.f. waves are of different shape, the unbalanced e.m.f. harmonics produce wattless harmonic currents, which though small compared to the full-load current may be considerable with respect to the no-load fundamental current. Thus the p.f. at no-load may be less than unity even with the fundamentals of the current and e.m.f. in phase.

SYNCHRONIZING

84. Necessary conditions. Impressed and induced e.m.fs. equal, opposite, and of same frequency.

85. Synchronizing with lamps. Connect lamps in series between the in-coming machine and the line. When the lamps are bright (or dark, according to whether the machines are connected in unison or in opposition in the synchronizing circuit), and the beats are very slow, showing opposition of phase and approximate synchronism, the line switch may be closed and the machine will quickly settle down to stable operating conditions. If a motor, the load may then be applied.

In the case of a three-phase machine, lamps should be connected in at least two phases, and if both sets are not dark at the same time, there is indication that the three phases are not connected in the proper order and that two of them should be interchanged. The chief objection to the use of lamps for synchronizing is that they do not tell just when the two e.m.fs. are in exact opposition, nor whether the in-coming machine is fast or slow, although with a little experience it is possible to become quite proficient in their use.

86. Synchroscope. Various electromagnetic instruments called synchronizers, synchronoscopes, synchroscopes, etc., have also been devised for indicating synchronism. In most of these, the principle of operation is that of the rotary field, synchronism being indicated by a pointer on a dial. When the in-coming machine is above or below synchronism, the pointer revolves in one direction or the other respectively, and at a rate proportional to the slip (or beat) frequency. At synchronism the pointer stands still, and in a position on the dial which indicates the relative phase of the two e.m.fs.

One form of synchronizer is constructed as follows: The armature consists of two coils at right angles connected in parallel, a non-inductive resistance in series with one and an inductive resistance in series with the other. The stationary field coil is connected to the supply bus and the armature to the in-coming machine. The split-phase revolving field produced by the armature currents, reacts on the alternating field to produce a rotation whose speed is equal to the difference between the frequencies of armature and field currents. When these are equal the armature coil remains stationary.

PARALLEL OPERATION OF ALTERNATORS

87. Mechanical analog. When two or more alternators are connected in parallel and driven at the same frequency, they are as if coupled together by an elastic coupling just as in the case of a synchronous motor connected to a generator. Thus they must run at exactly the same frequency as long as they are coupled.

88. Division of load. Consider two similar alternators driven by separate prime movers, of which the speed characteristics are shown in Fig. 62, as *a* and *b*. Then if the speed is that represented by the horizontal line $\overline{ss}$, the powers supplied by the two prime movers will be P_a and P_b respectively. The division of load will then be wholly dependent upon the speed characteristics of the prime movers, *i.e.*, upon the governors.

89. Division of reactive current. The only effect of changing the excitation on either machine is to change the division of reactive current: *e.g.*, starting with equal loads and currents, if the excitation of *a* be increased, it will take more of the lagging reactive current, and *b* will take less. Any inequality of excitation is equalized by a circulating reactive current which transfers the excitation from the overexcited machine to the underexcited one. The terminal voltage will be determined in any case by the total excitation of both machines and by the magnitude and p.f. of the load.

When the voltage of a power plant is controlled by a Tirrill regulator, acting on the exciter bus from which the fields of all the parallel connected units are supplied, the per cent. increase in excitation for a given increase of load will obviously be the same on all the alternators. But if one alternator has a close regulation and another poor regulation, and if in the first case they shared the active and reactive currents in proper proportion, with increased load the close regulation machine will be relatively overexcited and will take more than its share of the lagging reactive current.

90. Switchboard control of speed of prime movers. In prime movers with very close speed regulation (no-load to full-load), it is obviously necessary that the two speeds be very closely adjusted (Fig. 62), and this is often difficult by the cut-and-try method, which in some cases requires shutting down each time to adjust the governors. Large units are often provided with a means of governor adjustment during operation. This may be accomplished by means of a small motor connected through worm gearing to the governor adjustment and controlled from the switchboard.

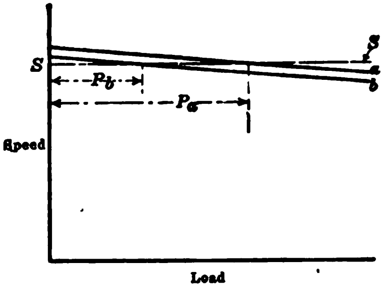

Fig. 62.—Diagram of division of load between two parallel-connected alternators.

91. Governor damping to prevent hunting. Sudden changes of load frequently cause the governor to hunt, *i.e.*, open up too wide, then close too far and so on. This may be easily prevented by a dash-pot connected to the governor.

ELEMENTARY OUTLINE OF THE DESIGN OF SYNCHRONOUS MACHINES

92. Specifications. Every electrical machine is built to meet certain specifications whether proposed by the purchaser, his engineer, or the manufacturer. In addition to the customary specifications there is always the question of first cost which must be reduced to a minimum. Many of these specifications, requirements, or standards are thoroughly treated in the Standardization Rules of the American Institute of Electrical Engineers; these are given in Sec. 24. For a synchronous alternator the specifications refer briefly to the following: frequency; number of phases; rev. per min.; terminal voltage; rated output in kv-a.; minimum power-factor; temperature rise (Sec. 24); efficiency (Sec. 24); inherent regulation; per cent. leakage reactance volts; insulation tests (Sec. 24); wave form. These are not all specified in each case, whereas in some cases much more elaborate specifications dealing with the details of mechanical and electrical design are supplied. With reliable manufacturers, very simple specifications are ordinarily sufficient, telling chiefly what the machine shall accomplish rather than how it shall be built. In the case of many modern alternators, regulation is not a controlling specification, it being in most cases important to have a high reactance rather than a low one (Par. 63 and 64). Efficiency as such is also not directly a controlling factor in design, but chiefly as it is necessary to keep down the heat developed in the machine. A fraction of 1 per cent. in efficiency is not as important to the user as a safe operating temperature.

93. List of symbols used.

$\mathfrak{B}_1$ = Max. value of equivalent fundamental sine-wave of air-gap flux density (lines per sq. in.).
$\mathfrak{B}_g$ = Actual max. flux density in air-gap at pole-face (lines per sq. in.).
$\mathfrak{B}_t$ = Maximum apparent tooth-density of flux (lines per sq. in.) in teeth.
D = Diameter at air-gap (inches).
d_s = Depth of slot (inches).
e'' = Volts induced per in. of active armature conductor.
f = Frequency (cycles per sec.).
h_c = Allowable copper watts per sq. in. of armature surface.
K = kv-a. output.
K_a = kv-a. developed in the armature.

k_b = Belt differential factor.
k_o = specific output.
k_p = pitch differential factor.
k_3 = ratio of pole pitch to gross armature core length.
l = gross armature core length.
m = cir. mils per amp.
p = no. of pairs of poles.
q_A = ratio armature to gap amp-turns at full load.
q_{il} = ratio of net iron length of armature to gross length.
q_p = ratio of coil pitch to full pitch.
q_{sw} = ratio of slot width to tooth pitch.
R = rev. per min.
T_c = Temp. difference in deg. cent. between armature conductor at centre and at end.
v = peripheral velocity, ft. per sec.
w'_c = wt. of armature copper (lb.) per kv-a. output.
Δ = peripheral loading; ampere conductors per in. of armature periphery.
ξ = output coefficient.
τ = pole pitch (in.).

94. Output equation. The volt-amperes per sq. in. of peripheral surface (Par. 28 et seq.) are $\Delta e'' = 8.50 k_b k_p \Delta v B_1 10^{-8}$, and the total power developed, in kv-a. is, $K_a = 8.50 \pi k_b k_p \Delta v B_1 D l 10^{-11}$. Allowing a maximum drop of 5 per cent. between induced and terminal volts, and taking B_1 corresponding to full-load, the kv-a. output is

$$K = 2.54 k_b k_p \Delta v B_1 D l 10^{-10} = k_o D l \quad \text{(kv-a.)} \quad (28)$$

or since $D = 720 v \div (\pi R)$

$$l = 1.72 \times 10^7 K R \div (k_b k_p \Delta B_1 v^2) \quad \text{(inches)} \quad (29)$$

$k_o = 2.54 k_b k_p \Delta v B_1 10^{-10}$ is the **specific output**, or the kv-a. per sq. in. of projected area of the air-gap cylinder. By substituting for v its value $\pi DR/720$, we obtain

$$K = 1.11 k_b k_p \Delta B_1 D^2 l R 10^{-12} = \xi D^2 l R \quad \text{(kv-a.)} \quad (30)$$

where $\xi = K/(D^2 l R) = 1.11 k_b k_p \Delta B_1 10^{-12}$ is called the **output coefficient.** Taking $k_b = 0.950$ and $k_p = 0.95$, this may be written, $\xi = (\Delta/1{,}000)(B_1/10^4)10^{-8}$. Sometimes k_o and sometimes ξ is more convenient as a starting-point for preliminary design, both being rough measures of the economy of material.

Major design constants. B_1, v and Δ are the major design constants, since their choice (R being specified) determines the general dimensions D and l of the machine. The larger these constants, the smaller in general will be the product Dl, and, within certain limits, the weight and cost of the machine. The considerations which govern the choice of these constants are so numerous that they cannot all be given their due weight in any direct method of attack. Some of the more important considerations and limitations are as follows: Par. 95 to 107.

Ratio of pole pitch to core length.

$$k_3 = \tau/l = 3.5 k_b k_p \Delta B_1 v^3 \div (10^7 f K R)$$

Number of poles.

$$2p = 120f/R \quad (31)$$

Pole pitch.

$$\tau = 6v/f \quad \text{(inches)} \quad (32)$$

95. Tooth-density limit. In order to avoid excessive eddy-current losses in the slot conductors and in the teeth, the flux density B_{tr} at the narrowest part of the teeth should not exceed (for open slots) the values of Par. 42, although for partly closed slots and stranded conductors 10 to 15 per cent. higher values are safe. B_g is related to B_{tr} as follows for the rotor or internal element, and parallel-sided slots:

$$\mathfrak{B}_g = \mathfrak{B}_{tr} q_{il}(1 - q_{sw} - 2d_s/D) \quad (33)$$

and for the stator or external element

$$\mathfrak{B}_g = \mathfrak{B}_{tr} q_{il}(1 - q_{sw}) \quad (34)$$

$\mathfrak{B}_g$ is usually slightly less than $\mathfrak{B}_1$, (the crest of the fundamental sine-wave of flux, see Fig. 23, and Par. 32). Also in extreme cases the tooth saturation flattens the flux distribution curve still more. For laminations 0.014 in. thick, q_{il} varies from 0.7, in an exceptionally well ducted core, to 0.8, in a poorly ducted core, and 0.9 in a core without ducts. Thus if $\mathfrak{B}_{tr}$ is assumed at its reasonable upper limit, and qu is known, the relation of $\mathfrak{B}_g$ to q_{sw} is fixed.

96. Heating limit. At 60 deg. cent. the copper loss under 1 sq. in. of armature surface is $h_c = \Delta/m$, the resistance of one circ. mil. inch of copper at 60° cent. being just 1 ohm. h_c is obviously limited: (a) by the heat dissipating power (H_c) per sq. in. per deg. cent. of temperature rise, (b) by the allowable temperature rise, T, (c) by the relative amount of core loss, and (d) by the relative amount of coil-end surface. Assuming average values of (b), (c) and (d), H_c will vary with the nature of the ventilation, the peripheral velocity, and the amount of heat thrown off by the rotor. For open, salient-pole machines, a very rough preliminary guide is

$$h_c = \Delta/m = 0.4(1 + 0.016v) \text{ (watts per sq. in.)} \quad (34a)$$

For high-speed turbo-alternators h_c has little relation to v, owing to the widely differing methods of ventilation, and varies from 0.8 to 1.6.

97. Temperature gradient in slot conductors. Assume that all the heat developed in the active conductor is conducted longitudinally to the coil ends. This is roughly true in high voltage stators. Then the temperature difference between centre and end of conductor will be $T_c = (l^2 \times 127^2)/m^2$, where l is the gross core length in inches. Or if T_c be limited, l will be limited, thus $l = (m\sqrt{T_c})/127$. Thus the larger the value of m, the longer may be the armature core without excessive temperature differences. The table in Par. **98** gives the temperature differences in deg. cent. for various values of l and m.

98. Temperature differences between centre and end of armature conductors

l, Armature length (in.)	Temp. difference T_c (deg. cent.)			
	600 circ. mils per amp.	800 circ. mils per amp.	1,000 circ. mils per amp.	1,200 circ. mils per amp.
0	0.0	0.0	0.0	0.0
10	4.48	2.52	1.61	1.12
20	8.98	5.05	3.23	2.25
30	40.3	22.65	14.5	10.1
40	71.7	40.3	25.8	17.9
50	112.0	63.0	40.4	28.1
60	162.0	91.0	58.1	40.4
70	220.0	124.0	79.1	55.0
80	286.0	161.0	103.0	71.5
90	364.0	205.0	131.0	91.0
100	448.0	252.0	161.0	112.0

99. Weight of copper vs. Δ. With $h_c(=\Delta/m)$ limited, m must increase with Δ. Then the total weight of active copper (also of total copper if k_3 be unchanged) will be proportional to Δ.

100. Depth of slot. On the same basis the slot depth will be proportional to Δ^2. Slot reactance does not limit Δ and slot depth, as is sometimes the case with induction motors (see Par. **251**).

101. Armature-reaction limit. If on the score of regulation, e.m.f. wave shape, or stability, it be desired to keep $q_A (= A \div R)$ within any given limit, it might become necessary to limit the ratio $\Delta/\mathfrak{B}$, see Eq. 22, Par. **60**.

102. Choice of $\mathfrak{B}$ and Δ. From the standpoint of the economy of material or of the maximum output coefficient, that value of q_{sw} is the best which results in the maximum product $\mathfrak{B}_1\Delta$. But since, for a given depth of slot, Δ increases as $\mathfrak{B}_1$ decreases, the maximum product will occur where the net width of slot (excluding insulation) is approximately equal to the minimum tooth width, *i.e.*, when $q_{sw} > 0.5$. A considerable change in q_{sw} from the exact value which makes $\mathfrak{B}_1\Delta$ a maximum, does not seriously reduce this product, so that considerable variations from the best value of q_{sw} will be found, as there are other considerations involved.

$\mathfrak{B}$. Assume q_{sw} chosen, *e.g.*, to keep down the ratio $\Delta/\mathfrak{B}$ (Par. **101**), or to make $\mathfrak{B}_1\Delta$ a maximum (Par. **102**). Assume also $\mathfrak{B}_{tr}$ as chosen (Par. **95**); then $\mathfrak{B}_g$ is given by Eq. 34.

Δ. Assuming h_s constant, the upper limit of Δ is likely to be set for turbo-alternators by the limited space for copper on the rotor, since this limits F, and A (and therefore Δ) must be smaller than F. A glance at Fig. 63 shows that the cost of copper is not likely to set the Δ limit. In fact, an increase of Δ, within certain limits, results in a more than balancing saving in iron. Moreover, the correspondingly larger m reduces T_c, the temperature difference between the centre and ends of the active conductors (see Par. 98). If close regulation is specified, it may be necessary to use a low Δ and high $\mathfrak{B}_1$, see Par. 60, particularly in high-speed turbo-alternators; but if, as is usually the case in this country at the present time, low regulation is not specified, Δ may be carried much higher than has heretofore been customary.

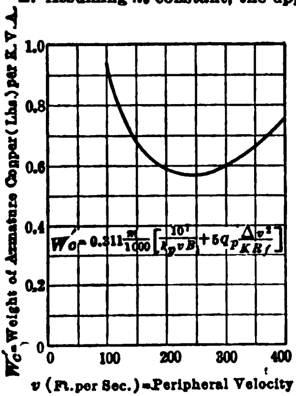

FIG. 63.—Armature copper per kv-a. vs. v, for a 10,000-kv-a. 25-cycle 2-pole turbo-alternator.

The following formulæ give a rough idea of the range of Δ for modern alternators: at 60 cycles $\Delta = (450 \text{ to } 700)(\text{kv-a.}/100)^{0.135}$; at 25 cycles $\Delta = (500 \text{ to } 800)(\text{kv-a.}/100)^{0.135}$. The higher values are for very well-ventilated and the lower for moderately ventilated machines (see Fig. 64).

103. Choice of peripheral velocity. Assuming that $\mathfrak{B}_1$ and Δ have been chosen, the choice of v determines the proportions of the machine. Coil-end

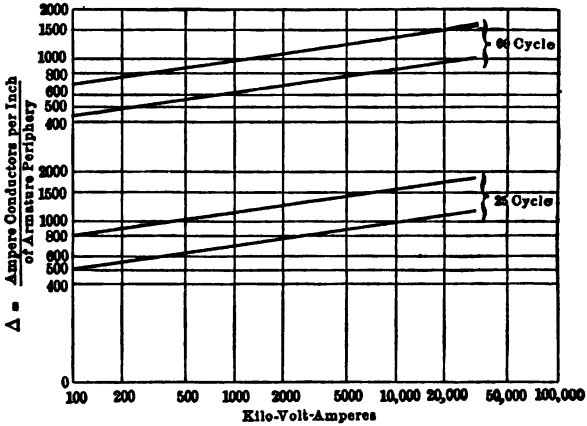

FIG. 64.—Peripheral loading of alternators.

reactance does not enter seriously into consideration, as in the case of the induction motor. The weight of active iron is nearly independent of v.

The weight of armature copper is a consideration but a relatively unimportant one in high speed machines; in lbs. per kv-a. it may be expressed approximately as follows:

On alternating-current machines of 1,000 volts and upward, the armature-slot insulating material may consist of micanite, micarta or Bakelised paper tubes, or of insulations built up of empire cloth, oiled linen, or other suitable materials. In Fig. 65 is given a curve showing suitable thicknesses of slot insulation from copper to iron in terms of the voltage.

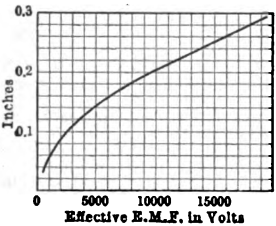

Fig. 65.—Slot insulation thicknesses for alternators.

109. For heat-resisting qualities and allowable working temperatures of different classes of insulations, see Sec. 24. Other references are as follows: A. P. Fleming and R. Johnson: "Chemical Action in the Windings of High-voltage Machines." *Journ.* I. E. E., Vol. XLVII, p. 530, 1911.

110. Instance and cause of an insulation failure. In 1905 Mr. J. S. Highfield published in *The Electrician* (Vol. LIV, p. 573) a description of an insulation failure in the windings of a 10,000-volt alternator. The failure was attributed to chemical actions stimulated by the ozone formed as a consequence of corona discharges. Highfield's article led to considerable correspondence in subsequent numbers of *The Electrician* and the views put forward are of great interest. "High-voltage Tests and Energy Losses in Insulating Materials," by Mr. E. H. Rayner appears on page 3, Vol. XLIX of *Journ.* I. E. E. (1912). Rayner concludes his paper with a large and valuable Bibliography of the subject.

111. Effects of temperature on disruptive strength. Lamme has dealt with these effects very thoroughly in his paper on "High-speed Turbo-alternators" appearing on page 1 of Vol. XXXII of *Trans.* A. I. E. E. (1913) Lamme and Steinmetz have continued the discussion of the subject in a paper entitled "Temperature and Electrical Insulation" which appears on page 79 of Vol. XXXII of *Trans.* A. I. E. E. (1913). As to the design of the insulation from the standpoint of the heat flow through it, the best information as yet available on the subject is contained in the following four papers: (a) Symons, H. D. and Walker M. "The Heat Paths in Electrical Machinery," *Journ.* I. E. E., 1912, Vol. XLVIII, page 674. (b) Williamson, R. B. "Notes on Internal Heating of Stator Coils," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 153. (c) Langmuir, Irving. "Laws of Heat Transmission in Electrical Machinery," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 301. (d) Randolph, C. P. "The Conduction of Heat; with Results of an Investigation of the Thermal Resistivity of Heat-insulating Materials," General Electric Review for Feb., 1913, page 120.

112. Field insulation. For the field windings of low-speed and moderate-speed synchronous machines the problems associated with the insulation are comparatively simple. Wherever reasonably practicable, the field winding will consist of a flat-ribbon conductor wound on its thin edge. It is important that the design shall comprise features ensuring absolute absence of any relative motion between the conductors, as the result of centrifugal forces and of vibration. The use of coils of flat strip with the edges left bare in the customary manner, is excellent from the standpoint of ability to rapidly dissipate heat to the surrounding air in virtue of the rapid motion of these coils through the air. Since the voltage is low and the temperature moderate, it is practicable to employ the simplest methods, so far as the insulation is concerned. But in the case of extra high-speed turbine generators the field windings must be embedded in slots in the surface of the cylindrical rotor, and the difficulties of providing a suitable design of insulation are very great. It is true that the voltage of the excitation is low, but the difficulty arises from the high temperature to which the insulation is subjected. The facilities for ventilation are necessarily exceedingly poor, and the space for the copper is so restricted that it is necessary to operate the field winding at high current densities. The result is that portions of the insulation in the slots of high-speed rotors are usually subjected to temperatures much above 100 deg. cent. and frequently temperatures approaching 150 deg. cent. are experienced at the very hottest spots of the rotor insulation in designs of the most difficult ratings. Consequently mica must be the chief ingredient of the insulation, notwithstanding that the voltages are very low. The construction must present the utmost rigidity since the slightest displacement of any insulating material will suffice to unbalance the rotor. The case is ably presented by Lamme in a section entitled Rotor Insulation on p. 29 of his paper on "High-speed Turbo-alternators," in Vol. XXXII (1913) of the *Trans.* A. I. E. E.

113. Insulation of alternator leads and connections. Acute problems are not often encountered in the insulation of the leads and connections, since, on the one hand, machines are rarely built for pressures in excess of 15,000 volts, thus eliminating the questions arising in connection with the insulating of extra high-pressure leads; and, on the other hand, the voltages in large machines are rarely lower than 2,000, so that there do not arise any questions associated with the handling of very large currents. This latter statement should be conditioned by calling attention to the instantaneous current flowing on the occasion of sudden short-circuits. Such a current (Par. 63) may for an instant amount to from ten to twenty times the full-load current of the machine and is associated with the development of enormous mechanical forces. Consequently the problems of leads and connections reduce chiefly to the provision of elaborate mechanical support for all leads, conductors and cables from the armature windings to the switchboard. The end connections of the stator windings must be elaborately supported; many fine machines were wrecked before this was realized. The end connections are sometimes lashed by stout bands of cord to heavy rings which are supported by stepped brackets constituting extensions of the frame of the machine. It would be futile to here attempt to describe all of the various methods to which resort has been had in solving this difficulty. These have been described and illustrated in various papers among which may be mentioned the following:

Walker, Miles. "Short-circuiting of Large Electric Generators," *Journ.* I. E. E., 1910, Vol. XLV, p. 295.

Field, A. B. "Operating Characteristics of Large Turbo-generators," *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1645.

Lamme, B. G. "High-speed Turbo-alternators," *Trans.* A. I. E. E., Vol. XXXII, p. 1.

114. Requisite protection against potential stresses caused by special conditions, grounded phase, switching, etc. If a Y-connected generator is operated with the common connection grounded without any resistance, then if a dead short-circuit to ground occurs on one of the three lines, although the circuit-breakers will at once disclose the faulty line, severe mechanical stresses will be imposed on the windings of the generator, due to the sudden short-circuit. If on the other hand, the neutral point is connected to ground through a resistance, the amount of current which can flow when a dead ground occurs on one of the lines will be limited by the amount of the resistance. Let us consider the case of a Y-connected generator with a pressure of 7,000 volts in each leg of the Y, and with a 9-ohm resistance to ground. If a dead ground occurs on one of the lines leading from the generator, then asuming that the resistance of the winding and line and ground aggregate 1 ohm, only $7,000/(9+1) = 700$ amp. can flow through the ground. But this will raise the potential of the neutral point from zero to $700 \times 9 = 6,300$ volts, and this combined with the pressure of the other two phases, on which no ground has occurred, will increase the pressure between the high-tension ends of these windings and the frame of the machine to about 12,000 volts. Thus while the use of a resistance between neutral and ground *decreases* the severity of the mechanical stresses to which the windings of the generator will be exposed on the occasion of sudden short-circuits on the line, it *increases* the severity of the potential stresses on the main insulation.

The extra stresses imposed upon the main insulation of the machine would be still greater were the machine to be operated with its neutral grounded through a resistance, and with its terminals tapped into auto-transformers by means of which the generator voltage is stepped up (say in the ratio of 1:2) to the line pressure. Consequently when auto-transformers are employed, the generator must not have its neutral connected to ground through a resistance, but must be dead-ground. If the stepping-up is accomplished by means of transformers with distinct primaries and secondaries instead of with auto-transformers, then the generator's neutral may be grounded through a resistance. **Operation with grounded neutral is to be pre-**

ferred for systems from which many expensive underground cables are supplied, since a ground on some one cable will clear that cable off the line by the opening of its local circuit-breakers and without interruption to the rest of the system. But for a system consisting of a single long line with an important distribution system at its distant end, and where, consequently, any interruption of the supply would be very serious, there is a widely held opinion that the generator should be operated with non-grounded neutral, since it is maintained that the development of a ground at some one point of the line is then less likely to shut down the system. It will, however, increase, by 73 per cent., the extreme potential stresses across the generator's main insulation, and this must be recognized in the proportioning of the generator's insulation.

Switching operations, arcing grounds, lightning-arrester discharges, and other disturbances are likely to occasion surges in a system. The generator windings must be protected against the resulting high-potential stresses. Sometimes such protection is afforded by suitable reactances interposed between the line and the generator, and sometimes the last few turns in the winding are especially insulated so that the steep potential wave front shall not occasion breakdown between adjacent turns.

LOSSES AND EFFICIENCY

115. Core losses. The data in the following table serves as an approximate guide to the determination of the *no-load* core loss in synchronous machines.

Density in stator core (below slots) lines per sq. in.	Core loss in stator core (including teeth) (watts per lb.)	
	25 Cycles	60 Cycles
40,000	1.1	2.7
50,000	1.4	3.7
60,000	1.7	4.9
70,000	2.0	....
80,000	2.4	....
90,000	2.8	....

There are further core losses called *stray* core losses which increase as the load increases. These are due to the flux distortion in core and teeth, caused by the armature m.m.f.

116. Effect of rated speed on losses. Returning to a consideration of the no-load core losses it is of interest to note that the inherent nature of low-speed and high-speed designs is such that while the no-load core loss may constitute a relatively small component of the total loss in low-speed synchronous machines, it is necessarily a large component in high-speed synchronous machines. The reverse is the case with the armature copper loss, which is relatively high in low-speed machines, and relatively low in high-speed machines. In a group of 3,000-kv-a. 25-cycle close-regulation designs for various speeds, particulars of which are given by Hobart and Ellis in "High-speed Dynamo Electric Machinery" (John Wiley and Sons, N. Y., 1908), the rated speeds and these two losses in per cent. of output are as follows:

Rated speed	No. of poles	*A* No-load core loss (%)	*B* Armature copper loss at full-load (%)	Ratio of *A* to *B*
83	36	1.93	.93	2.07
125	24	2.02	.73	2.77
250	12	2.17	.57	3.82
375	8	2.24	.50	4.45
500	6	2.27	.50	4.39
750	4	2.30	.47	4.92

121. Calculated values of bearing friction for several turbo-alternators

No. of poles	Rated output (kv-a).	Speed (rev. per min.)	Bearing friction in horse-power		
			Turbine bearing	Middle bearing	Bearing at collector end
4	9,400	1,800	7	62	24
4	6,300	1,800	11	60	14
4	6,300	1,800	6	41	13
4	3,100	1,800	4	25	5
4	2,500	1,800	6	21	6
2	2,500	1,500	3	20	4

122. Summary of losses. We have now reviewed the component losses in synchronous machines. These are: (a) no-load core loss; (b) extra core loss increasing with load; (c) full-load copper loss in armature winding; (d) eddy loss at full-load in armature winding; (e) field copper loss at full-load; (f) windage and bearing friction loss.

Losses (a), (c), (e) and (f) may be considered accurately determinable either by test or calculation. Losses (b) and (d) are not commercially determinable; *i.e.*, their determination would require an elaborate and expensive investigation in each case. A reasonable value may be assigned to the sum of losses (b) and (d) (Par. **127**), in cases where they cannot be determined from tests. It may in general be stated that all the losses except loss (b) and loss (d) are readily susceptible to either exact or sufficiently approximate determination, and hence they may be designated as **determinable losses.** It is in commercial transactions futile to attempt to conclusively determine losses (b) and (d). Consequently it is desirable to group these two losses together, and to designate them as: **indeterminable losses or stray losses.** It should usually be practicable in a commercial transaction, involving efficiency guarantees, for the parties to the transaction to agree upon a reasonable value to assign in any case to the indeterminable losses in the event that it is not expedient to make the test set forth in Sec. 24.

123. The efficiency. The true efficiency of a machine is the ratio of the output to the input. The efficiency should be based upon the rated output, pressure, power-factor and speed. The losses on which the efficiency is based, should be corrected to 75 deg., the temperature of reference for efficiency determinations (see Sec. 24). The determination of the true efficiency of a machine involves either an accurate determination of all the component losses, or else an accurate measurement of the output and of the simultaneous input. In other than small machines, both of these methods of determination are impracticable unless resort is made to expensive scientific measurements.

Consequently in practice, use should be made of two approximate efficiencies. These may be designated as follows: (a) the efficiency exclusive of stray losses; (b) the conventional efficiency.

124. The efficiency exclusive of stray losses. This is the ratio of the output of the machine to the sum of the output and the determinable losses as obtained by the separate measurement or calculation of each determinable loss. This efficiency is necessarily greater than the true efficiency, but approaches it in machines in which the indeterminable losses are negligible.

125. The conventional efficiency differs from the efficiency exclusive of stray losses, to the extent to which appropriate values for the indeterminable losses are included in estimating the input. In all matters relating to guarantees, the allowances to be made for the indeterminable losses are specified in each case. The conventional efficiency is, by definition, less than the efficiency exclusive of stray losses, except in cases where the convention is to take the stray losses equal to zero (see Standardisation Rules, Sec. 24). With the application of a reasonable amount of care in assigning appropriate values to the indeterminable losses, the difference between the conventional efficiency and the true efficiency should usually be quite unimportant and often negligible.

to render the stator frame sufficiently stiff to ensure absence of sagging. Any sagging would unbalance the air gap, which must be of uniform depth over the entire circumference.

The field winding should usually consist of flat copper, wound on its thin edge. The heat then readily flows to the outer surface, and is carried away by the surrounding air.

132. Intense forced cooling and ventilation. Extra high-speed steam turbine-driven generators of large capacity present the most extreme instances of the necessity for forced cooling and ventilation. The quantity of air which must be forced through such machines per kv-a. of rated output in order to limit the temperature rise at full-load to permissible values, is of the order of from 2.5 cu. ft. per min. for a 25,000-kv-a. machine to 4.5 cu. ft. per min. for a 5,000-kv-a. machine, depending on the efficiency of the machine. The precise values vary with the arrangement of the ventilating passages, and the speed. The customary method of circulating the air consists in providing the rotor with fans which force air through appropriate passages. Fig. 66* relates to the ventilating method employed in the design

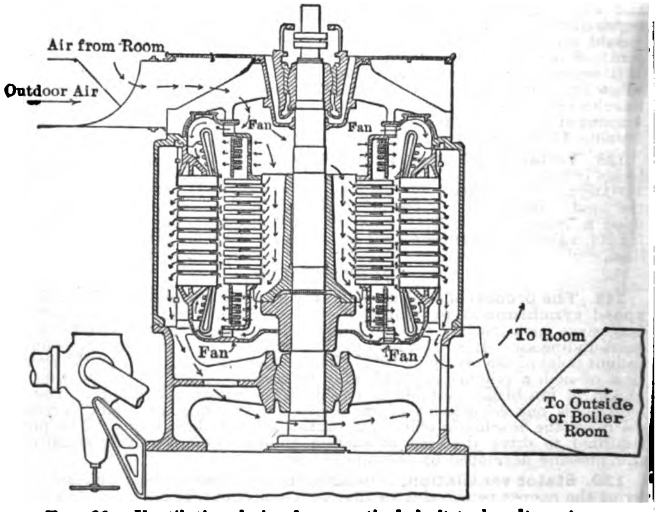

FIG. 66.—Ventilation design for a vertical-shaft turbo-alternator.

of a steam turbine-driven alternator of the vertical type. Mr. B. G. Lamme has dealt very fully with this subject in a paper entitled "High-Speed Turbo-alternators," at p. 1 of Vol. XXXII (1913) of the *Trans.* A. I. E. E. Lamme subdivides methods of cooling turbo-alternators by the forced circulation of air into three classes: (a) radial methods, (b) circumferential methods, and (c) axial methods.

133. In the radial system of ventilation all the air passes out radially through ventilating ducts in the stator core. In the design of these high-speed generators the rotor diameter is limited by the peripheral speed. Consequently the design is of relatively great length parallel to the shaft. There is very little space on the rotor even for the windings, owing to the limited radial dimensions, and it is often necessary to dispense with the circulation of

* From an article by E. Knowlton, "Ventilation of Steam Turbine-driven Alternators," *General Electric Review*, Oct., 1912, page 656.

air through the interior of the rotor. Even in the most favorable cases, such circulation of air through the rotor is limited to but a small part of the air required for the cooling of the stator. The greater part of the supply required for the stator is, in the radial system, first passed along the air gap; the radial depth of the air gap is often made very great expressly out of consideration for providing sufficient section for the flow of the required amount of air.

134. A typical arrangement of the radial system as applied by the General Electric Co. in its horizontal steam-turbine alternators is shown in Fig. 67. The system is described as follows: the air enters the generator at *AA*; passes through the air gap, windings and air ducts in the stator core to the annular spaces *BBB*; flows around circumferentially to the openings *CCC* in the bottom of the armature frame and thence to the outlet duct. In some machines part of the air passes through the field core. The movement of air is produced by fans on the ends of the rotor. In some instances the armature frame is modified so that the air is expelled from the top into the dynamo room. Proper passages must be provided below the generator for the ingoing and outgoing air. As shown in the sketch, air is taken in at both ends of the generator and discharged through an opening in the centre of the frame, and the passages must be so arranged as to prevent the outgoing heated air from mixing with the incoming cool air; a simple method of accomplishing this is also shown. In certain cases other arrangements may better suit local conditions. For approximation the area of the ingoing or outgoing duct will range from 5 sq. ft. for a 1,000-kv-a. to 15 sq. ft. for a 5,000-kv-a. generator. The outgoing air should be carried outside the building, care being taken that it cannot immediately re-enter the intake. The ducts should be as short and have as few bends as possible and these should be made with a large radius. Both ducts should have

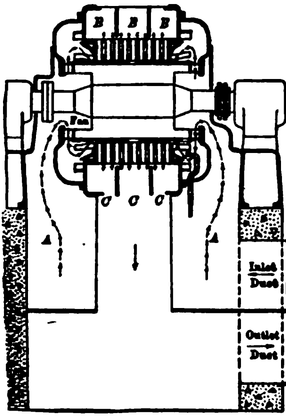

Fig. 67.—Radial system of ventilating a horizontal-shaft high-speed generator.

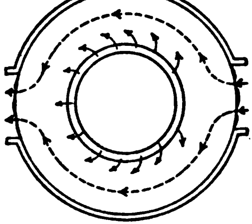

Fig. 68.—Circumferential system of ventilating turbo-alternators.

adjustable dampers so that part of the air may be taken from or expelled into the engine room. This will allow adjustments to suit weather conditions. The armature and field leads are brought out from the bottom of the generator frame, directly under the collector; this brings them to the air chamber under the armature. From here to the switchboard the leads may be carried in one of the air ducts or a separate duct, as is most convenient.

135. The circumferential system of ventilation is explained by reference to Fig. 68 (Lamme). The air enters at one side of the machine and is forced along the air ducts in the stator core back of the armature windings until it reaches the other side of the machine, whence it is discharged. Such circumferential circulation is usually supplemented by the supply of a further amount of air to the air gap to cool the rotor, as shown by the 13 little arrows curved toward the centre of the diagram. This air, after leaving the air gap passes into the stator ventilating ducts and reinforces the main streams of air. Lamme also illustrates in his paper (Ref. in Par. 132) a modification of the circumferential system in which the air enters the stator ducts at points of their outer circumference, flows down alternate vertical ventilating ducts in the stator core, then a short distance through longitudinal ducts, and returns through the intermediate vertical ventilating ducts back to the outer circumference of the stator.

136. The axial system of ventilation (often termed the longitudinal system) is illustrated in Fig. 69 (Lamme). The system has the advantage that the edges of each lamination are bathed by the circulated air. The conduction of heat is many times greater in the plane of the laminations than transversely thereto, the ratio varying from 20 to 100 according to the nature of the insulation between laminations, the thickness of the laminations, insulation, and their compression. Obviously the longitudinal method has a decided advantage in this respect at least. On the other hand it is difficult to arrange that a sufficient extent of surface shall be exposed to the air. As shown in Fig. 69, there is provided in the axial system a large number of longitudinal passages. These passages may lead to a large central outlet duct as in the case illustrated, or they may extend uninterruptedly right through the core from one end to the other.

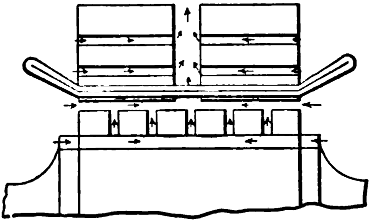

FIG. 69.—The axial system of ventilating turbo-alternators.

137. Air cleaning and cooling. It has been quite usual to take the ventilating air from the hot engine room, circulate it through the machine, and then return it to the hot engine room. Not only does this result in a high operating temperature (or else a lower output for a given temperature), but it also has the consequence that the air which is sent into the machine has taken up oily vapors whose presence aggravates the difficulties associated with the gradual clogging up of the ventilating passages in the machine with dust and dirt which is also carried into the machine in the circulating air. An expensive periodical cleaning of the machine must be undertaken.

In several important modern stations it is arranged that the air shall be taken from outside the station or from a cool basement (when one of sufficient capacity can be provided) cleaned by passage through cloth screens, and then led to the machine through suitable ducts. The cloth employed is of a closely woven variety similar to that known as Canton flannel, and there is required a surface of some two-tenths of a square foot per cu. ft. of air per min. Since a 10,000-kv-a. machine requires some 34,000 cu. ft. of air per min., it follows that for a machine of this capacity: $34,000 \times 0.20 = 6,800$ sq. ft. of screening surface must be provided. The cloth is supported upon wooden frames and the installation is generally regarded as constituting an undesirable risk from the insurance standpoint. Of the various kinds of cloth to which the term "fire-proof" is applied, it is rare to find any approach to genuinely fire-proof properties.

These air-filtering screens occupy a great deal of space and their effectiveness is gradually reduced as the meshes become clogged up with dust.

138. Air washing. Decidedly the best method of cleaning the air consists in passing it through sprays of water to wash it, instead of straining it through cloth screens. Mr. E. Knowlton deals at length with this method in the course of an article entitled "Ventilation of Steam-turbine Engine Rooms;" General Electric Review; September, 1913, page 627. See also a paper by J. Christie, entitled "Air Filtration, Cooling and Ventilation of Electrical Machinery;" Electrical Review; June 27, 1913, page 1088. Mr. Christie states that filter cloths wear out quickly and are expensive to renew. He states that $400 to $500 per annum for cloth and labor is by no means an outside figure for the efficient maintenance of this equipment.

139. The cooling of air incident to water filtering. The humidification of air in its passage through the water filter occasions a lowering of its temperature, the amount of which varies with the condition of the air. If it is utterly dry on entering the humidifier, the air will have experienced a considerable decrease in temperature by the time it has emerged from the humidifier and entered the machine which is to be cooled. As a consequence of these considerations, it is obvious that the average conditions regarding humidity and temperature in any locality, affect the amount of advantage to be derived by air filtering in addition to that of removing the dirt and the dust. The average reduction in the temperature of the air for the months of July and August in different parts of the United States is stated (Knowlton) to vary from 2.5 deg. cent. at points on the coast to 11 deg. cent. at points in the Middle South West. On certain days during these months the maximum reduction effected may considerably exceed these average values.

MECHANICAL CONSTRUCTION

140. Abnormal conditions requiring large factors of safety. In providing adequate strength in the design of synchronous machines it is usually utterly insufficient to take the conditions in the machine when running at uniform speed at its normal load as the basis which, with usual factors of safety, will lead to a satisfactory design. On the contrary, it is the conditions occurring during sudden short circuits (see Par. 63 and 64), and when the machine is carrying sharply fluctuating loads, which determine the strength required in the various parts. These are impossible of exact calculation; consequently, in the design of all those parts upon which the mechanical strength of the whole machine depends, large margins of the nature of safety factors must be added to the values which would usually be employed in machine design.

141. Critical speed of shafts. Irrespective of questions of cost, conditions arise with some capacities and speeds where it is impossible to find room for a shaft of large diameter, and it must have a critical speed below the operating speed. The peripheral speed at the bearing would otherwise exceed desirable values; furthermore, there is but limited room for accommodating the windings in the radial depth available between the surface of the rotor (which is itself of small diameter) and the surface of the shaft.

142. Effect of critical speed on rotor design. If the critical speed is to be well above the normal running speed, it is impracticable to employ laminated rotor bodies for capacities much above 1,000 kv-a. at a speed of 3,600 rev. per min. or above 5,000 kv-a. at 1,800 rev. per min. or above 7,500 kv-a. at 1,500 rev. per min. But for designs in which the critical speed is below the normal speed, it is practicable to employ rotor constructions with laminated cores up to ratings of over 2,000 kv-a. at a speed of 3,600 rev. per min. of some 10,000 kv-a. at a speed of 1,800 rev. per min., and of some 15,000 kv-a. at a speed of 1,500 rev. per min. In the construction of 1,500 rev. per min., 25-cycle, or 3,600 rev. per min., 60-cycle rotors solid cores are especially appropriate, since greater mechanical strength can be obtained in constructions in which the slots for the windings are milled out of a solid steel core. The rotor windings may be retained in the slots by solid steel or brass wedges, since the magnetism is of constant direction in each part and since the air gap is so deep in these extra high-speed generators that there is no loss in the rotor surface from pulsating influences from the alternating m.m.fs. due to the conductors in the stator slots. In some designs the shaft ends consist of enlarged extensions bolted to the rotor core.

143. Bearing lubrication. In small and medium sized machines of moderate speed, the lubrication of the bearings is accomplished in the usual manner by oil rings located in suitable recesses in the bearing and with their lower portions immersed in oil below the bearing lining. In large extra high-speed machines, the oil is forced into the bearings and after passing from them and being allowed opportunity to cool, it is again forced into the bearings. Sometimes in such machines and frequently in large water-wheel generators, copper tubes are embedded in the bearing just under the surface of the lining metal. Water is circulated through these tubes and plays a large part in maintaining the temperature of the bearing at a safe value. The following description relates to the water-cooled bearings of some horizontal turbo-generators built by the General Electric Company.

The general construction, including the arrangement of the cooling pipe and the grooving, is shown in Fig. 70. The bearing is provided with a coil

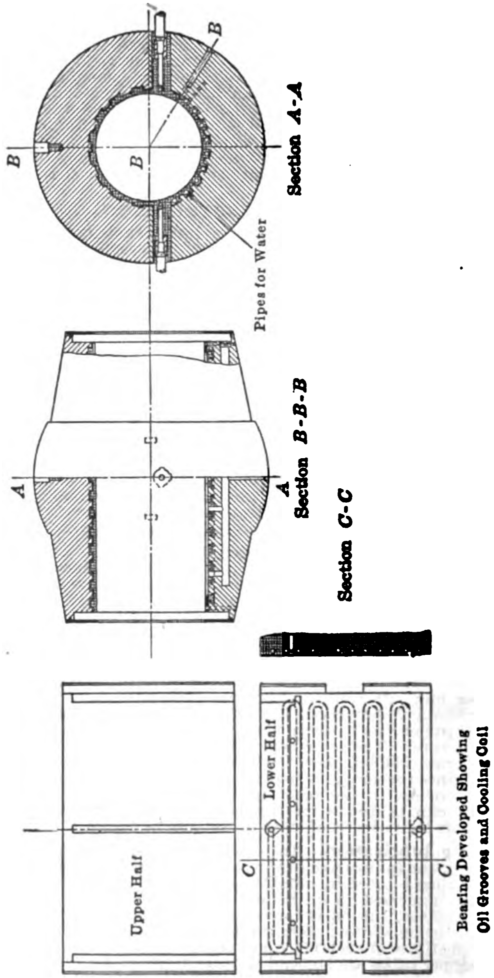

Fig. 70.—Water-cooled bearing.

of thin copper tubing cast into the babbitt lining close to the surface and having at the ends of the tubing, steel blocks securely brazed to the tubing and held in place by the babbitt. Water is led into the bearing by pipes

Ellis' "High-Speed Dynamo-electric Machinery," John Wiley & Sons, New York, 1908.

THE TESTING OF ALTERNATING-CURRENT GENERATORS

148. The heating test of large alternators under normal full-load conditions is troublesome and expensive, even when the necessary amount of power is available, and many suggestions, such as those of Mordey and of Behrend,* have been made with a view to reduce the amount of energy wasted during the tests. These methods necessitate alterations in the connections of either the armature coils or the magnet coils. If serious mechanical stresses are to be avoided, these methods can only be employed with machines having very large numbers of poles, and even then the magnetic conditions are not accurately the same as those which exist at normal full-load. The following method, known as the "intermittent short-circuit and open-circuit method," or, briefly, the "intermittent method," involves no change whatever in the connections of the machine, and requires the expenditure of only sufficient energy to cover the losses of the machine, and yet every part of the alternator reaches the same temperature as it would after an actual full-load heating test. The method involves a previous knowledge of the separate losses of the machine, but these are, in any case, determined in the ordinary course of a systematic test.

149. Intermittent method of making a heating test. Suppose a certain machine has at full-load: a friction loss of 10 kw.; an armature copper loss of 20 kw.; and an iron loss of 100 kw. In the course of an hour's run at full-load the loss of energy will be: $10 \times 60 = 600$ kw-min. as friction; $20 \times 60 = 1{,}200$ kw-min. as copper loss in armature; $100 \times 60 = 6{,}000$ kw-min. as iron loss.

Let the machine run for 5 min. with the armature short-circuited, and at such an armature current that the armature copper loss is 60 kw., *i.e.*, at a current equal to $\sqrt{3}$ times the normal current. Next let the machine run for a further 10 min. with open armature circuit, but overexcited, so as to give an iron loss of 150 kw. This adjustment is made according to indications of the wattmeter on the driving motor, allowance being made for other losses, such as losses in the motor itself and friction of the alternator and the driving mechanism. If this cycle of operations is repeated regularly throughout the time of the test, it is obvious that $10 \times 60 = 600$ kw-min. will be lost in friction per hr.; $60 \times 20 = 1{,}200$ kw-min. will be lost in armature copper per hr.; $150 \times 40 = 6{,}000$ kw-min. will be lost in the iron per hr., or, exactly the same loss in each case as would have occurred under normal full-load in the same time. There is still the **loss in the magnet windings** to be considered. During the short-circuit test this is less, and during the open-circuit test it is greater than the normal, so that on the average it does not differ very greatly from the normal. If, however, great exactness in this respect is required it is obtained as shown in Par. 150.

150. Further refinements of the intermittent method of making a heating test. In the above example one-third of the time of each period of the test was devoted to the short-circuit test, and two-thirds to the open-circuit test. These proportions may, however, be changed at will, and by varying the short-circuit current and the overexcitation correspondingly, the total energy expended in the armature copper and iron per hr. may be kept at the right value, while the average exciting energy will have some value other than before. Except in very extreme cases, *e.g.*, in the case of alternators which require only a very small change in excitation between no-load and full-load, and which at the same time have a very low value for the ratio

$$\frac{\text{short-circuit current at full excitation}}{\text{normal full-load current}};$$

it is always possible so to adjust the two time intervals, that while keeping the copper loss and the iron loss per hr. at the correct value, the exciting loss per hr. has practically the same value as at normal full-load. Exactness is, however, unnecessary, as, in any case, a simple calcula-

* These methods are described by Mordey, *Journ*. I. E. E., Vol. XXII, 1893. Behrend, *Elec. World and Engineer*, Vol. XLII, Oct. 31 and Nov. 14, 1903.

citation is zero the friction losses in watts are given by the formula $P = [K \times 0.148(S_1^2 - S_2^2)] + (2T)$. If the field is excited, the machine will come to rest in less time, and a larger loss P_1 will be obtained. This consists of the friction and core losses. By taking several curves with varying excitation, the core loss at different voltages may be determined, and a curve for core loss and voltage obtained. A typical set of retardation curves for a three-phase 350-kv-a., 2,100-volt, 50-cycle, 176-rev. per min. alternator is given in Fig. 72.

INDUCTION MACHINES

GENERAL THEORY OF THE POLYPHASE INDUCTION MOTOR

155. Principle of operation. The polyphase induction motor consists of a primary structure and a secondary structure. The former is usually stationary, supporting coils symmetrically on its inner periphery. These

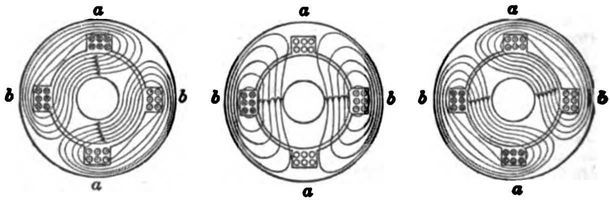

Fig. 73. Fig. 74. Fig. 75.

Figs. 73, 74, 75.—Diagrams of coils and magnetic flux in elementary two-phase two-pole induction motor.

coils are displaced in space (*e.g.*, two coils at right angles, or three at 60 deg.), and in them flow currents of the same frequency, but differing symmetrically in phase, *e.g.*, two at 90 deg., or three at 60 deg.). The secondary (usually rotatable) structure carries properly displaced short-circuited coils. The polyphase currents in the primary structure produce a revolving field.* As this cuts across the secondary conductors, currents are induced therein which, according to Lenz's law, are in such direction as to oppose the cause. That is to say, these secondary currents react on the revolving magnetic flux in such a way as to drag the secondary conductors and structure along with the rotating flux.

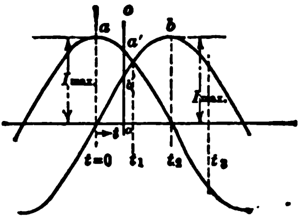

Fig. 76.—Current-time curves for two-phase indicator-motor windings.

156. Revolving field. Fig. 73 shows a two-phase, two-pole, laminated-iron stator with each coil imbedded in a pair of slots. The flux shown corresponds to the instant t_1 in Fig. 76. Figs. 74 and 75 show the flux corresponding to instants t_2 and t_3 in Fig. 76. The rotation or progression of the flux is obvious. If in place of the two-pole field of Fig. 73, we substitute a multipolar field, as many cycles of current variation will be required for one revolution of the magnetic field, as there are pairs of poles.

157. Synchronous speed and slip. The speed of the revolving field is called the synchronous speed, and the percentage by which the rotor or secondary falls below this speed is called the slip. If $2p$ represents the number of poles, and f the frequency, the synchronous speed in rev. per min. is $R_s = 60f/p$.

* See any elementary text-book on this subject.

162. Classification of stator windings. Stator windings correspond exactly with the armature windings of synchronous machines (Par. 16 to 22), and, as in that case, the two-layer lap winding is much the commonest type. Figs. 78 and 79 relate to a three-phase, four-pole, two-layer lap winding, with five-sixths pitch (ten slots in 12) and four slots per pole per phase. The bottom and top slot belts labelled *a* comprise the back-connected (*through* the paper) conductors of the *a* phase, those labelled *a'* the outward-connected (*from* the paper) conductors of the same phase; similarly with the *b* and *c* phases. Several coil ends of the *c* phase are shown diagrammatically. Fig. 79 shows a diagrammatic developed end view of the phase belts.

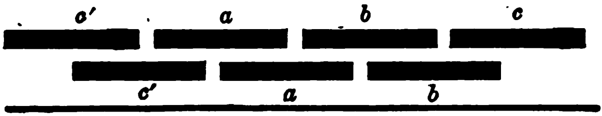

FIG. 79.—Sectional diagrammatic development of the phase belts of the winding of Fig. 78.

A developed diagram of connections of the windings of Fig. 78 is shown in Fig. 80, where the dotted lines indicate the bottom-slot coil sides or the lower layer.

163. Secondary or rotor windings. These may consist of any symmetrical arrangement of short-circuited conductors in which series-connected conductors do not generate opposing e.m.fs. There are three principal types.

(a) **Phase wound,** like the primary, except that the phases are short-circuited or brought out through collector rings for insertion of starting resistance. The number of phases need not be the same as for the primary, and is usually 3.

(b) **Independently short-circuited loops or coils.** The two active sides of each loop are approximately 180 magnetic deg. apart.

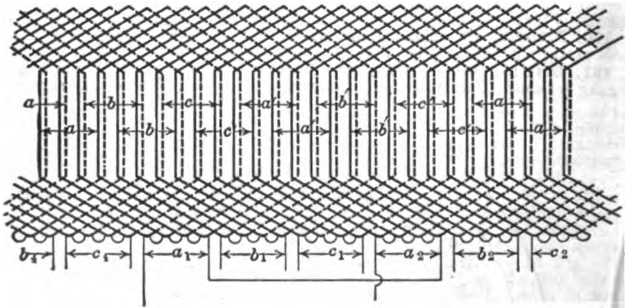

FIG. 80.—Developed winding diagram corresponding to Fig. 78.

(c) **Squirrel cage,** consisting of conducting bars in slots, all connected at the ends by conducting rings, called the end rings.

In (b) and (c) there are as many phases as there are slots per pole.

164. Peripheral distribution of current, m.m.f. and gap flux. The cylindrical shell comprising the currents on the two sides of the air gap, and the magnetic flux crossing the gap may be considered as the active region of any generator or motor, and the analysis of the phenomena in this region will yield most of the vital characteristics of the machine. Neglecting the localization of current in the slots and taking the average amperes per in. of periphery in each phase belt, the heavy full-line curves of Fig. 81 show the primary current distribution of a three-phase full-pitch winding at the rotates at the same velocity. The changes of the flux curve, in shape and magnitude, are graphically analysed for full-pitch windings on pages 380–390 of the 2nd edition of Hobart's "Electric Motors." See also pages 120–125 of Hobart's "Design of Polyphase Generators and Motors," especially the diagram on page 123.

165. Flux and current distribution for two-phase motors. In a two-phase motor the belts are broader, the steps in the current and flux distribution curves larger and the change of shape from instant to instant greater. The breaking up of the belts by using a five-sixths pitch in the three-phase, or a three-quarters pitch in the quarter-phase motor, reduces these variations and smooths out the curves.

166. Secondary current and m.m.f. relations. Since the secondary *e.m.f.* is induced by cutting the gap flux, the resulting secondary current will bear a definite space-phase relation to the gap flux (Fig. 84), and its *m.m.f.* will be sinusoidally distributed around the gap. Also, since the primary (or stator) counter *e.m.f.* is nearly equal to the impressed *e.m.f.* and is induced by the rotation of the gap flux at synchronous speed, the flux will be nearly constant in magnitude, for constant impressed *e.m.f.* Thus the resultant of the primary and secondary *m.m.fs.* will be nearly constant and such as to produce the constant flux.

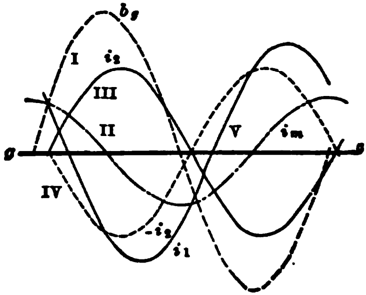

FIG. 84.—Peripheral distribution of flux and currents in polyphase induction motor.

167. Similarity of the induction motor to the transformer. Thus the induction motor is similar to a transformer. In fact, at standstill, it is a short-circuited polyphase transformer with distributed windings, and an air gap between primary and secondary. Like the transformer, the induction motor may be regarded as having three fluxes. These are the main flux, linked with both primary and secondary; and the primary and secondary leakage fluxes, linked only with the primary and secondary respectively (Par. 193 to 198). Owing to the air gap in the main magnetic circuit, the quadrature **magnetizing current** of the induction motor is several times as large as in a closed magnetic circuit transformer, even though the air gap is usually reduced to the lowest safe mechanical clearance. Because of this same air gap and the separation it makes necessary between the primary and secondary windings, the **leakage reactance** is also several times as large as in the average transformer.

Thus the **power-factor** of the induction motor is inherently low as compared with the closed magnetic circuit transformer. Representative power-factors for motors of various frequencies, speeds, and outputs, are given in Figs. 119 and 121.

168. Revolving flux and current distribution. Assume that the gap flux and currents are distributed sinusoidally around the gap periphery at any instant, and that the rotor conductors are independently short-circuited. Referring to Fig. 84, *gg* is the developed air-gap line; above this line is the primary or stator, and below it is the secondary or rotor. Flux directed upward in the figure is thus directed outward from secondary to primary; this direction will be called positive and will be indicated in the curve by ordinates measured upward from the gap line. Current directed outward from the paper will be called positive and will be so indicated in the curves. The flux and the rotor are assumed to be revolving counter-clockwise (right to left), the rotor less rapidly than the flux; therefore the rotor revolves clockwise with respect to the flux (left to right in the figure). Curve *I* represents by its ordinates the space variation of flux density, b_g, crossing the gap. This sinusoidal flux distribution will be assumed as the starting positions or space phases for a given condition of load. These distributions are shown in semipictorial fashion in Fig. 85, where the vectors B_g, I_2 and I_1 point to the positions at which the maximum positive values of these quantities occur, at the instant shown.

The time variation of all these quantities with respect to any particular point or conductor on the primary side of the gap, will be sinusoidal at primary frequency, and at secondary or slip frequency with respect to any point or conductor on the secondary structure. It is only from this point of view and with this understanding that it is possible to represent consistently primary and secondary variables on the same vector diagram.

Thus the vectors of Fig. 85 may be used to represent not only the space phases, but also the time phases of the several variables, when viewed from either stationary or rotating structure, it being obvious that there is no fixed phase difference between the primary current in a particular *primary* conductor, and the secondary current of very different frequency in a particular *secondary* conductor. By extending the vector diagram of Fig. 85 we obtain the complete space and time vector diagram of the induction motor in Fig. 86.

174. Analysis of vector diagram. E'_1 is that part of the impressed e.m.f. to neutralise the counter e.m.f. induced by the mutual flux Φ, the direction of the vector Φ being that of the plane of the coil when it links the maximum flux, just as the direction of B_g is that of the plane of the coil when it is cutting the densest gap flux and generating the maximum e.m.f. I_m is the magnetising current and I_{e+h} the core loss energy current, their

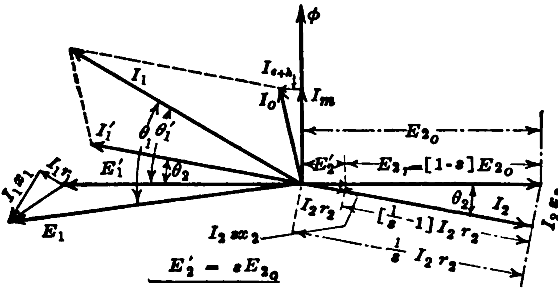

FIG. 86.—Vector diagram for induction motor.

sum being I_0, commonly called the exciting current. Assuming all secondary quantities reduced to primary turns, $E_{20} = E'_1$ is the e.m.f. that would be induced in the secondary at standstill. The actual secondary induced e.m.f. is E'_2, which equals sE_{20}, where s is the slip. $E_{2r} = (1-s)E_{20}$, is the e.m.f. that would be induced in the secondary if revolving in the flux Φ at its actual speed, and will be called the speed e.m.f. x_2 is the secondary leakage reactance at primary frequency, and sx_2 the same at slip frequency. The secondary resistance is r_2. The secondary current is therefore:

$$I_2 = \frac{E'_2}{\sqrt{r_2^2 + s^2x_2^2}} = \frac{E_{20}}{\sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} \quad \text{(amp.)} \qquad (37)$$

(The two e.m.f. triangles corresponding to these equations are shown in Fig. 86.) I'_1 is the part of the primary current to neutralize I_2, and I_1 the total primary current. I_1r_1 and I_1x_1 are the e.m.fs. consumed by primary resistance and leakage reactance respectively. E_1 is the impressed e.m.f.

175. The corresponding equivalent circuit scheme is given in Fig. 87, which is exactly that of a transformer with a non-inductive load resistance $(r_2/s)(1-s)$.

although none too accurate for poor motors. By a poor motor is not meant necessarily a poor design, but a poor result which may be due to difficult specifications, *e.g.*, relatively low speed or relatively high frequency.

180. Approximate working formulæ for torque, output and starting current. For most purposes the following are sufficiently accurate. It will be observed that the constants of the exciting circuit do not enter; this is due to the approximation, which is equivalent to neglecting the exciting current as far as it affects the quantities considered.

Torque

$$T = \frac{7.05}{R_s} \frac{p' E_1^2 \frac{r_2}{s}}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \qquad (42)$$

Slip corresponding to maximum torque

$$s_{T_{max}} = \frac{r_2}{\sqrt{r_1^2 + (x_1 + x_2)^2}} \quad \text{(lb. ft.)} \qquad (43)$$

Maximum or stalling torque

$$T_{max} = \frac{7.05}{R_s} \frac{p' E_1^2}{2\left[r_1 + \sqrt{r_1^2 + (x_1 + x_2)^2}\right]} \quad \text{(lb. ft.)} \qquad (44)$$

Starting torque

$$T_s = \frac{7.05}{R_s} \frac{p' r_2 E_1^2}{(r_1 + r_2)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \qquad (45)$$

Starting current

$$I_s = \frac{E_1}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad \text{(amps.)} \qquad (46)$$

$$T_s = \frac{7.05}{R_s} p' I_s^2 r_2 \qquad (47)$$

r_2 corresponding to maximum starting torque

$$r_2 = \sqrt{r_1^2 + (x_1 + x_2)^2} \quad \text{(ohms)} \qquad (48)$$

Output

$$P_2 = p' E_1^2 \frac{\frac{r_2}{s}(1 - s)}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(watts)} \qquad (49)$$

Maximum output, i.e., stalling load

$$P_{2max} = \frac{p' E_1^2}{2\left[(r_1 + r_2) + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}\right]} \quad \text{(watts)} \qquad (50)$$

Slip corresponding to maximum output

$$s_{P_{2max}} = \frac{r_2}{r_2 + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \qquad (51)$$

These approximations are fairly accurate except where the exciting current is large. As the primary current and power-factor are both largely affected by the approximation involved in the formulæ given above, their formulæ are not given. They can be most easily obtained from the circle diagram.

181. The method of percentages. For the purpose of discussing the operating characteristics of an induction machine, as well as in connection with problems involved in its design, the following method of valuing its constants will be found very convenient. Referring to Figs. 86 and 88, and remembering that $E_{2s} = E_1'$, let $I_1 r_1 / E_1' = q_{r1}$; $I_1 x_1 / E_1' = q_{x1}$; $I_2 r_2 / E_1' = q_{r2}$; $I_2 x_2 / E_1' = q_{x2}$; $q_x = q_{x1} + q_{x2}$. Let $I_2 \cos \theta_2 = I_T$ be called the torque current, since it is the component of I_2 which is effective in producing torque. $I_m / I_T = q_m$; $I_{e+h} / I_T = q_e$; $I_0 / I_T = q_0$; $q = q_x + q_m$ = total quadrapower-factor. T_{max}/T_f is plotted against q_x in Fig. 90, for $k_T = 1.9$. From which, if 2 is the lower limit for T_{max}/T_f, q_x must not be more than 0.26.

185. Per cent. stalling torque. Hobart gives the per cent. stalling torque in terms of σ (Par. 207) and q_m as follows ("Polyphase Generators and Motors," page 190): $qT_{max} = 0.4\ q_m/\sigma$. This is equivalent to $k_T = 2.3$, (since $\sigma = 0.93\ q_m q_x$), which is considerably larger than 1.9 used in Fig. 90.

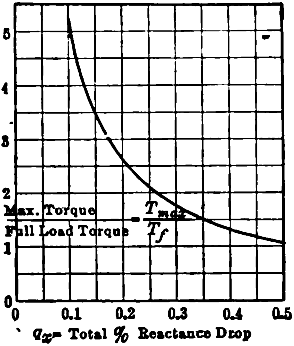

FIG. 90.—Ratio of maximum torque to full-load torque, plotted as a function of the total percentage reactance drop.

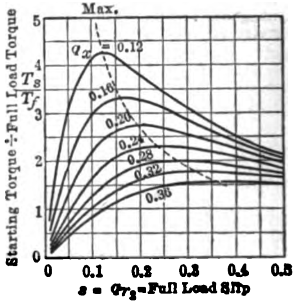

FIG. 91.—Ratio of starting torque to full-load torque.

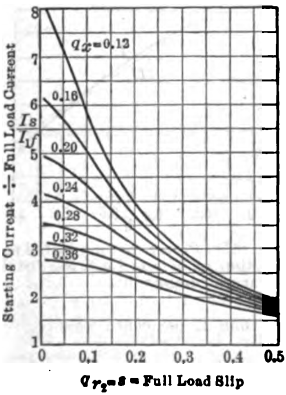

FIG. 92.—Ratio of starting current to full-load current, plotted as a function of the full-load slip.

186. Starting torque. Beginning with Eq. 45, it can be shown that the per cent. starting torque is

$$qT_s = T_s \div T_f = \frac{1.20 q_{r2}}{(q_{r1} + q_{r2})^2 + q_x^2} \quad \text{(approximately)} \qquad (54)$$

Assuming $q_{r1} = 0.02$, the ratio T_s/T_f is plotted against q_{r2} in Fig. 91, for several values of q_x within the range of commercial motors; from which the quantitative limitations in the starting torque of the induction motor are obvious. The maximum value of the ratio T_s/T_f is obviously the same as T_{max}/T_f and occurs when q_{r2} is about equal to q_x.

187. Secondary starting resistance. Except in machines of very low reactance, a large starting torque is only possible by employing a comparatively large secondary resistance. In a squirrel-cage motor this means large secondary copper loss and large slip. The desirable resistance of a squirrel-cage secondary is usually a compromise between the low-resistance needed for speed regulation and efficiency, and the high resistance desired for starting torque, the relative weight given to these two considerations being determined by the specifications. In a wound-rotor machine, resistance can be inserted in the secondary for starting and cut out after the machine has attained speed.

191. Summary. Figs. 89 and 93 show clearly the relations of all the vital operating characteristics (except heating) of induction motors of whatever size, frequency, or voltage, to a very few constants; and although the results are only approximate, they will give a fair quantitatave grasp of induction motor characteristics. The largest errors will occur in small or low-speed motors with large exciting currents.

The most important of these characteristics are almost wholly determined by q_m, q_x, and q_{r2}. The other q's may be approximated with sufficient accuracy, since they play only a small part, and a considerable error in their approximation does not seriously affect the results. Of q_m, q_x, and q_{r2} the last may be given almost any desired value without much affecting the other constants; whereas q_m, and q_x are intimately related to one another, to the major design constants, and to the details of design. Their computation is given below.

MAGNETIZING CURRENT*

192. Air gap and gap ampere-turns. The air gap is usually reduced to a comfortable mechanical clearance, and may be taken approximately as $\delta = 0.015\sqrt[4]{\text{kw.}}$ (inches). The gap ampere-turns are computed in the same manner as for the alternator (see Par. **40**, Figs. 39 and 40). Designate by a_1 and a_2, respectively, the primary and secondary slot-contraction factors; by $K_1 = a_1a_2$, the combined slot-contraction factor; by K_d the corresponding air-duct contraction factor; and by K_2 the ratio of gap ampere-turns to total ampere-turns. K_2 varies from 0.9 in slow-speed high-frequency machines to 0.7 in high-speed, low-frequency machines. These are, however, outside limits, and 0.8 may ordinarily be assumed as a fair average for a rough approximation. Then the total ampere-turns for the longest complete magnetic circuit is $Ni_l = (0.626\mathfrak{B}\delta)/K_1K_2K_d$.

Let Δ = peripheral loading corresponding to torque current I_T (Fig. 88); $\mathfrak{B}$ = maximum or crest value of equivalent sine-wave of gap-flux distribution; v = peripheral velocity (ft. per sec.) of revolving field; for k_b and k_p see Par. **28–31** (synchronous machines).

Then, assuming that the magnetizing current is equivalent to a sinusoidal distribution of current density, of root-mean-square value Δ_m, $\Delta_m = 0.116\mathfrak{B}\delta f/(k_bk_pK_1K_2K_dv)$ and the per cent. or fractional magnetizing current is

$$q_m = \Delta_m/\Delta = 0.116\mathfrak{B}\delta f/(k_bk_pK_1K_2K_d\Delta v) \tag{58}$$

For a three-phase motor $k_b = 0.955$. For five-sixths pitch $k_p = 0.96$. For open-slot stator and nearly closed-slot rotor, $K_1 = 0.65$ (approx.). For a well-ducted motor $K_d = 0.9$. For a 60-cycle motor, $K_2 = 0.8$ (approx.). Then, roughly, $q_m = (0.27\mathfrak{B}\delta f)/(\Delta v)$.

LEAKAGE REACTANCE*

193. The four elements of the leakage flux are computed as if separate from the main flux, whereas they are for the most part only distortional as to the main flux. Consider the phase-belt as the unit, Figs. 94 and 95.

194. Slot leakage.* This is the cross-slot flux (Fig. 94). The inch permeance or flux linkage (lines) per amp-in. of primary phase-belt is (see Fig. 42)

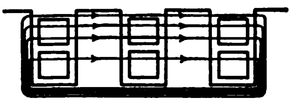

FIG. 94.—Illustrating cross-slot leakage flux.

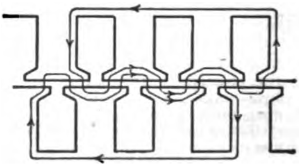

FIG. 95.—Illustrating tooth-tip leakage.

$$\varphi_{sb1} = \frac{3.2}{N_{spp}}\left(\frac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{so}} + \frac{d_4}{w_{so}}\right) \tag{59}$$

* Transactions American Institute Electrical Engineers, Vol. XXIV, 1905, p. 338. Also Vol. XXVI, p. 1245.

indicates a circumferential current backward through the paper). If the ring is set radially inward nearer the shaft, φ_f may be increased as much as 50 per cent. (see the upper curve). Or, if the end ring is placed nearer the core, φ_f may be considerably increased (25 or 30 per cent.).

197. Belt-leakage.* For three-phase motors and full-pitch windings the flux linkage per amp-in. of belt is

$$\varphi_{B_3} = k_B K_1 K_2 K_{d\tau} \div 314\delta = K_{B\tau} \div 314\delta \quad (61)$$

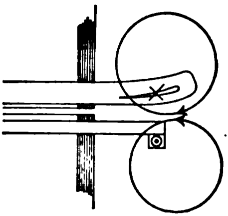

Fig. 99.—Coil-end leakage paths.

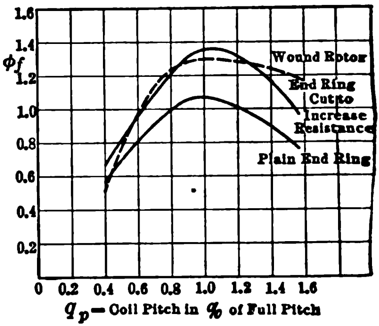

Fig. 100.—Coil-end flux linkage lines per ampere-inch of phase-belt bundle (primary and secondary) as a function of the coil pitch.

where k_B is given in Fig. 102 and $K_B = k_B K_1 K_2 K_d$. For a two-phase motor with full-pitch winding

$$\varphi_{B_2} = K_{B\tau} + 105\delta \quad (61a)$$

For a squirrel-cage motor, take values about one-half of these values.

A coil pitch of five-sixths in a three-phase, or of three quarters in a two-phase motor, reduces the belt width, permeance of the mean paths, conductors per belt, and mean phase-difference, each to one-half. The belt reactance is thereby reduced to about one-sixteenth of its full-pitch value.

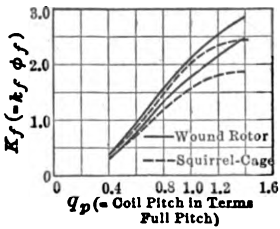

Fig. 101.—Coil-end leakage constant.

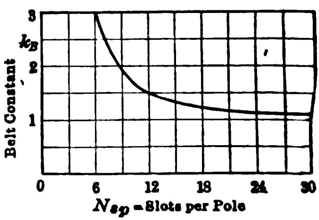

Fig. 102.—Belt leakage constant.

198. Summary. Adding together the several φ's with their proper pitch factors the total reactance for a three-phase motor is

$$x_3 = 2\pi f 2 p l N^2_{cpp} 10^{-8}(k_{ps}\varphi_{sb} + k_{pt}\varphi_{tb} + k_3 K_f + K_{B\tau} \div 314\delta) \quad (62)$$

where N_{cpp} = conductors per pole per phase.

* See *Transactions* International Electrical Congress, St. Louis, 1904; ———, Vol. I, page 706.

resistance varied (variable s), the locus of the current is a circle. The exciting current must be added to obtain the total current.

The corresponding diagram is shown in Fig. 104. If this diagram be rotated counter-clockwise until E_1 is slightly below the horizontal on the left, it will correspond with the left-hand side of the regular vector diagram, Fig. 86. The diameter of the circle in Fig. 104 is $E_1/(x_1+x_2)$. B_s is the short-circuit or standstill point; $\tan \varphi_s = \frac{r_1+r_2}{x_1+x_2}$, and $B_sG_s + G_sH_s = r_2 + r_1$.

The approximation involved in this diagram is such that serious errors are not introduced in the case of a good motor, *i.e.*, a motor with low exciting current and low reactance; but the errors become serious in poor motors.

200. Note concerning interpretation of approximate circle diagram. In what follows E_1 and I_1 are the volts and amperes of a single phase. If E_1 be the line voltage multiplied by $\sqrt{3}$, and I_1 the line current, p' should be omitted from all expressions for power and torque.

201. The impressed power is, $P_1 = p' E_1 I_1 \cos \theta_1 = p' E_1 \times \overline{BK}$; but since $p'E_1$ is constant, $\overline{BK}$ is proportional to and a direct measure of the power delivered to the motor; *i.e.*, a scale of watts or kilowatts can be chosen according to which $\overline{BK}$ indicates directly the impressed power, P_1.

202. Losses, output, torque and slip. According to the same scale $\overline{HK}$ indicates the core loss, $p'E_1I_{e+h} = P_{e+h}$. If I_0 is measured when the motor is running light, the corresponding power will include the friction loss, in addition to core loss, and since the friction loss is practically constant,

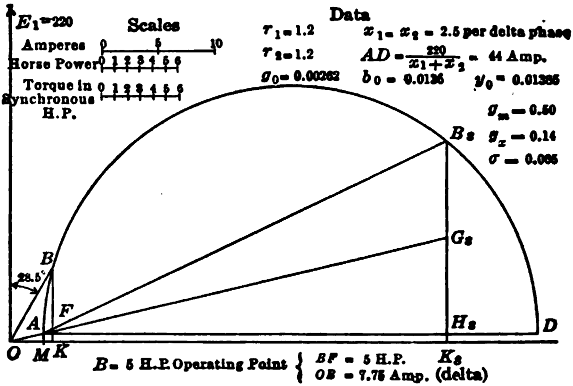

FIG. 105.—Approx. circle diagram for a 5-h.p. three phase, 6-pole, 220-volt, delta-connected induction motor.

it could be charged to the exciting circuit (Fig. 103), by increasing g_e in the proper degree. It will be so taken here, *i.e.*, that $\overline{HK}$ represents core and friction loss. Similarly $\overline{HG}$ represents the primary copper loss, $\overline{GF}$ the secondary copper loss, $\overline{FB}$ the output (P_2), $\overline{GB}$ the power transmitted across the air gap (*i.e.*, the torque in synchronous watts) and $\overline{GF} \div \overline{GB}$ the slip.

203. Efficiency (Par. 210–216). The efficiency is $P_2/P_1 = BF/BK$.

204. Power-factor (Par. 216). The power-factor, $\cos \theta_1$, may be readily determined from the diagram by drawing a unit circle about O and measuring the vertical intercept of the I_1 vector on this unit circle.

Thus for any point B on the circle, all the important variables of the induction motor may be readily determined from the circle diagram.

205. Experimental determination of circle diagram. The experimental data necessary is, ising current to the short-circuit current, but this is inaccurate for motors with high secondary resistances. It is dependent upon the machine proportions and independent of the load.

For all practical purposes it is

$$\sigma = 0.93 q_m q_s = \frac{3.95 S\delta}{\tau^2} + \frac{3.95 A}{N_{sp}^2} + \frac{1.32 K_f \delta}{l} + 0.0052 \qquad (66)$$

For values of S, A and K_f see Par. **195** to **198** and Figs. 96 to 101. S varies from 6 to 18 with an average of 10 to 12; A from 0.2 for open slots

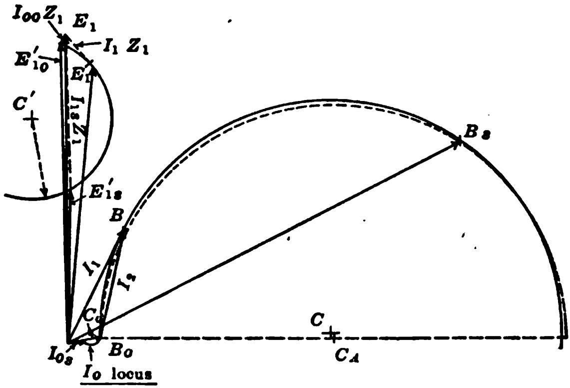

Fig. 107.—Approximate and accurate circle diagram of an induction motor.

on one side of gap to 0.42 for nearly closed slots on both sides, and K_f from 1.5 in good squirrel-cage motors to 2.2 in slip ring motors, see Fig. 101.

Kierstead has proposed a somewhat simpler though less rational formula; it is

$$\sigma = C\left(\frac{0.079}{l} + \frac{0.19}{\tau} + \frac{3}{N^2_{sp}}\right) \qquad (67)$$

where C varies with the air gap according to the accompanying table

δ	0.024	0.032	0.039	0.047	0.055	0.063	0.071	0.079	0.087	0.095
C.........	0.71	0.88	0.99	1.09	1.17	1.25	1.31	1.39	1.45	1.52

Of these equations, Eq. 66 gives results quite as accurate as the average test results can check, and for all types of machines. Eq. 67 gives fair results for the majority of standard machines, although inaccurate for extreme cases.

The leakage factor or circle ratio is much used by European designers. Reference may be made to Hobart's "Electric Motors" and "Design of Polyphase Generators and Motors" where the designing of induction motors is explained with the assistance of the circle diagram in a simpler though less accurate manner than is described in Par. **243** to **259** below.

208. Maximum power-factor. In terms of σ, it is given by various authors, thus

$$\text{Maximum power-factor} = \frac{1}{1+2\sigma} \qquad (68)$$

$$\text{Maximum power-factor} = \frac{1-\sigma}{1+\sigma} \qquad (69)$$

Density in stator core (lines per sq. in.)	Core loss in stator core (watts per lb.) for various frequencies		
	$f=15$	$f=25$	$f=50$
39,000	0.50	1.00	2.27
52,000	0.77	1.36	3.36
65,000	1.00	1.81	4.54
78,000	1.18	2.36	
90,000	1.45	2.81	

STANDARD POLYPHASE INDUCTION MOTORS

215. Representative power-factors and efficiencies of standard squirrel-cage motors. The losses and efficiency of a typical 5 h.p.,

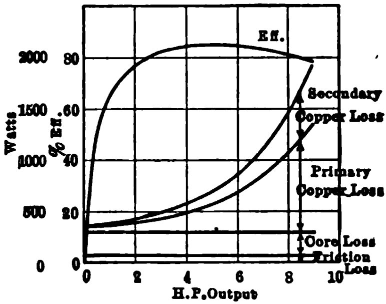

FIG. 108.—Losses and efficiency of a 5-h.p., 60-cycle squirrel-cage induction motor.

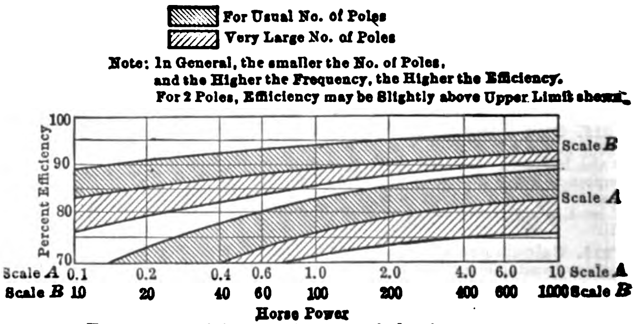

FIG. 109.—Efficiencies of average induction motors.

60-cycle, squirrel-cage induction motor are shown plotted against the output in Fig. 108. The efficiencies of average induction machines are plotted in Fig. 109. While in any concrete case the designer has the power-factor and the efficiency within his control to a certain extent, he cannot depart widely from representative values which are inherent to the rating. The table in Par. 216 is abstracted from more elaborate tables on pp. 116 and

Data of complete weight (exclusive of shaft and bearings) of five 33-cycle squirrel-cage induction motors for a synchronous speed of 124 r.p.m.

Rated output	Weight
1,000 horse-power	15 metric tons
2,000 horse-power	25 metric tons
3,000 horse-power	34 metric tons
4,000 horse-power	42 metric tons
5,000 horse-power	50 metric tons

218. Weights per horse-power. A $\frac{1}{16}$-h.p. 1,200-r.p.m. polyphase induction motor weighs a matter of 19 lb. while a 10,000-h.p. 120-r.p.m. polyphase induction motor would weigh some 176,000 lb. It is interesting to note that while the large motor has 150,000 times the output of the smaller, it only weighs about 9,000 times as much. Moreover its speed is about one-tenth as great as that of the smaller motor.

219. Starting apparatus for standard polyphase induction motors. Ninety per cent. of all the induction motors built in America are of the squirrel-cage type. Whereas the squirrel-cage motor when of small size is switched directly on the line at starting, it is necessary in starting larger squirrel-cage motors to employ induction starters or else the star-delta method. Slip-ring induction motors are started by means of a rheostat connected into the rotor circuits, and gradually cut out as the motor acquires speed. With the growth of electricity-distributing net-works, it has become expedient to relax the earlier onerous requirements imposed in the matter of permissible starting currents. On some systems fairly large squirrel-cage motors are permitted to be started by switching directly upon the line without induction starters. Designs in which the "deep-slot" effect (Par. 190) is correctly employed may be started directly from the line with a more moderate rush of current, and hence are the more appropriate as regards the lesser line disturbance at starting.

220. Induction-motor starting currents. The currents taken by good three-phase squirrel-cage induction motors at the moment of starting, have values approximately in accordance with the following table, which corresponds to $q_s = 0.13$ and $s = q_{r_2} = 0.04$, see Figs. 91 and 92 and accompanying text.

A	*B*	*C*	*D*
Pressure at motor in per cent. of line pressure	Line starting current in per cent. of full-load current	Motor starting current in per cent. of full-load current	Starting torque of motor in per cent. of its full-load running torque
40	112	280	32
60	250	420	72
80	450	560	128
100	700	700	200

221. Calculated starting characteristics. The following table, taken from page 451 of the 2nd Edition of Hobart's "Electric Motors" (Whittaker & Co., London, 1910) gives the calculated starting characteristics of a 6-pole 25-cycle 200-h.p. 500-rev. per min., squirrel-cage, three-phase, induction motor.

The motor to which these last results correspond, was designed for very high efficiency and without any regard to starting torque ($q_s = 0.12$ and $s = 0.02$). Consequently, we find that when started on the six-tenth taps of the induction starter, the starting torque is only 55 per cent. of full-load running torque and the line current is practically three times full-load current, a worse result than that of the average motor corresponding to the earlier table. By employing the "deep-slot" principle in the design of 60-cycle squirrel-cage induction motors, the application of the full-line pressure at starting will be accompanied by a much smaller flow of current from the line than that shown in the table for the average motor. While the torque may

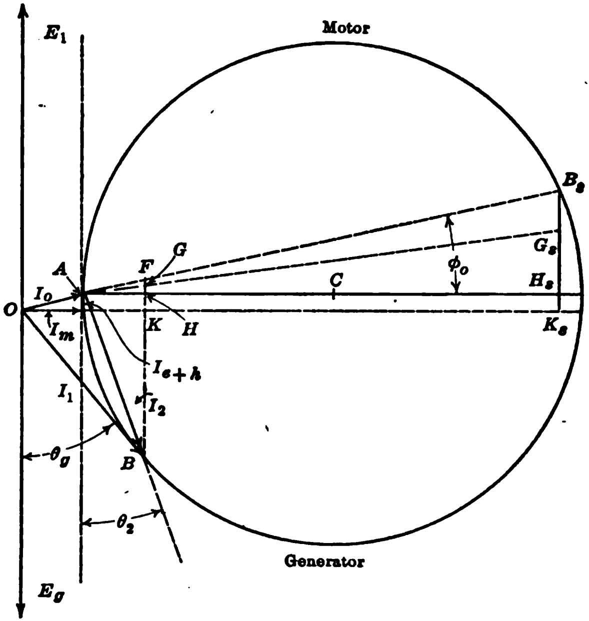

Fig. 110.—Circle diagram of induction generator.

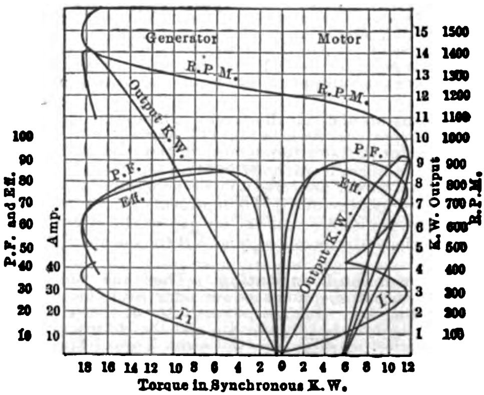

Fig. 111.—Generator and motor characteristics of induction machine.

234. Effect of angular variation of prime movers. Since the division of load in the case of parallel-connected induction generators is dependent upon the relative speeds rather than upon the relative angular positions of the rotors, the relative angular displacements within one revolution of a reciprocating steam or gas engine do not produce objectionable power surges between the various generators, as frequently occurs in the case of synchronous machines. Even gas engines are quite satisfactory in this connection.

235. Effect of e.m.f. wave shape on parallel operation. The induction generator is largely passive as to wave shape, the latter being impressed from without, and in the presence of e.m.f. harmonics, behaves like an inductive reactance which tends to damp the harmonic currents.

236. "Switching in." It is not necessary to synchronise when throwing in an induction generator, since the latter has no e.m.f. until excited from the line and when so excited is always in phase. It is only necessary to get the induction machine up to speed and throw it in. As the machine cannot pick up its load until the field is established, the first rush of current is wholly exciting current and practically independent of the slip. This initial current rush is quite analogous to that experienced when switching in transformers, and is explained on the same basis. Since with large units this exciting current rush is undesirably large, reactance coils are inserted while switching in, and then cut out as soon as the steady state is reached.

237. Hunting. The connection between the speed of a synchronous machine and its circuit frequency is exactly analogous to a mechanical elastic coupling, and that between an induction machine and its impressed frequency, to a friction coupling in which the friction grip is proportional to the slip. The latter tends to damp out any oscillations of the system, while the former has a natural period of its own which may tend to amplify some periodic disturbances of the system. The induction machine is thus decidedly superior on the score of hunting.

238. Short-circuits. The short-circuit current of a synchronous alternator consists of two parts: first, the transient part limited only by the combined equivalent leakage reactance of armature and field circuits; and second, the steady part determined by the much larger synchronous reactance of the armature. The former is the serious element, from three to five times the latter. It is this transient effect that twists the armature coil ends as if they were made of rope. With the induction generator the case is quite different. There is no steady portion, since the source of exciting current disappears when the short-circuit occurs, just exactly as in the case of a direct-current shunt-wound generator. The transient effect is present, but in only small degree since, with the same flux as in the synchronous machine, the reluctance of the magnetic circuit (and hence the energy of the field) is only a fractional part (sometimes less than 10 per cent.) as great.

239. Low-resistance squirrel-cage rotor. Since the induction generator requires no starting torque, the rotor is always of the squirrel-cage type and of as low resistance as is consistent with the cost of the copper and the available space. This means a very low secondary-copper loss, and a slip of less than 0.5 per cent. in large machines.

240. First cost and ventilation. Owing to the exceedingly simple rotor construction, the induction generator would be cheaper to build than a synchronous machine of the same capacity, were it not that the short air gap makes ventilation very difficult, and the more so in those ratings which are otherwise the best suited to this type of machine. This, together with the tooth-frequency losses incident to the short air gap, makes the induction generator of doubtful superiority except in special cases. The switchboard is also simpler, and the switching operations are of reduced complexity.

241. Best field of application for induction generators. The specifications from which the best induction machines can be produced are high speed, large output, and low frequency, which means steam-turbine or high-head water-wheel drive in large power stations. Unfortunately these are the specifications which lead to great difficulties in ventilation, owing to the short air-gap. A large city-railway system with the load considerably made up of synchronous converters with underground-cable distribution satisfies the conditions as to excitation.

q_{il} = net iron length ÷ gross core length
q_m = ratio of exciting current to torque current
q_p = ratio of coil pitch to pole pitch
q_r = resistance drop ÷ induced volts
q_{so} = slot opening divided by tooth pitch
q_{sw} = slot width ÷ tooth pitch
q_x = leakage reactance volts ÷ induced volts
q_{xB} = belt-leakage reactance volts ÷ induced volts
q_{xf} = coil-end reactance volts ÷ induced volts
q_{xs} = slot reactance volts ÷ induced volts
q_{xt} = tooth-tip leakage reactance volts ÷ induced volts
R = rev. per min.
S = slot factor
s = slip
$t.w.c.$ = total works cost (dollars)
V_{cm} = total volume primary copper (circular-mil in.)
v = peripheral velocity at synchronism (ft. per sec.)
w_s = width of slot (in.)
Δ = torque-current amp. conductors per in. of periphery
Δ_1 = primary amp. conductors per in. of periphery
Δ_m = magnetizing current amp. conductors per in. of periphery
δ = radial depth of air-gap (in.)
ξ = output coefficient, h.p.
ξ_k = output coefficient, kw.
σ = leakage factor (sometimes also termed the circle ratio).
τ = pole pitch (in.)
τ_t = tooth-pitch (in.)
φ_f = flux per amp. in. of phase belt bundle of coil-ends, Fig. 100

Subscript 1 refers to primary.
Subscript 2 refers to secondary.

245. The output equation. The volt-amperes induced per sq. in. of peripheral surface are, $\Delta e'' = 8.5 k_b k_p v B \Delta 10^{-8}$, see Par. 23.
and the kw. total developed are

$$K = 8.5 \times \pi k_b k_p \Delta v B D l 10^{-11} \qquad \text{(kw.)} \qquad (71)$$

This is the power P'_1 transmitted across the air gap and not the output, which is less by the secondary copper loss and the friction and windage loss. Assuming the latter to be about 1 per cent. and remembering that $q_{r2} = s$, we get as the horse-power output

$$\text{h.p.} = 3.55\,(1-s)\,k_b k_p \Delta \mathcal{B} v D l 10^{-10} = k_o D l \qquad (72)$$

where

$$k_o = 3.55\,(1-s) k_b k_p \Delta \mathcal{B} v 10^{-10} \qquad (73)$$

is the **specific output** in horse-power per sq. in. of projected area of the airgap cylinder. Assuming a three-phase motor ($k_b = 0.95$), of moderate capacity, with squirrel-cage rotor ($s = 0.03$), and five-sixths pitch of coils ($k_p = 0.96$),

$$k_o = 3.2 \Delta \mathcal{B} v 10^{-10} \qquad (74)$$

By substituting for v in equation 72, its value $(\pi DR/720)$, we get

$$\text{h.p.} = 1.55\,(1-s) k_b k_p \Delta \mathcal{B} D^2 l R 10^{-12} = \xi D^2 l R \qquad (75)$$

where ξ is called **output coefficient.** With the same assumptions as above,

$$\xi = 1.38 \Delta \mathcal{B} 10^{-12} \qquad (76)$$

If horse-power be replaced by kilowatts in Eq. 75,

$$\xi_k = 1.03 \Delta \mathcal{B} 10^{-12} \qquad (77)$$

Sometimes the output equation is more convenient in the form of Eq. 72, and sometimes in that of Eq. 75. Referring to Eqs. 72 and 75, and assuming R specified, $\mathcal{B}$, Δ, and v determine Dl, and $D = (720v)/(\pi R)$; or $\mathcal{B}$ and Δ determine D^2l, and $k_l = \tau/l = (\pi D)/(2pl)$, determines the ratio of D to l. As the cost of the machine increases approximately with Dl and with D^2l, $\Delta\mathcal{B}$ should be as large as possible.

246. Representative values of output coefficient. ("Design of Polyphase Generators and Motors," Hobart.)

$k_3 = \frac{1}{2}q_p$ (see Fig. 114) which is too small on the score of ventilation. However, as the minimum is a fairly flat one k_3 and v may be considerably increased without seriously increasing the copper volume, to the great gain of q_m and the ventilation. There is a pretty decided limit, however, since the coil-end copper increases as v^2 and the coil-end leakage as v^3. Assuming h.p. = 10, $R = 1{,}200$, $f = 60$, $\mathfrak{B} = 25{,}000$, $\Delta = 400$, $m = 600$; the weights of copper are as given in Fig. 114; D, l, q_{xf} and k_3 ($= \tau/l$) are also shown.

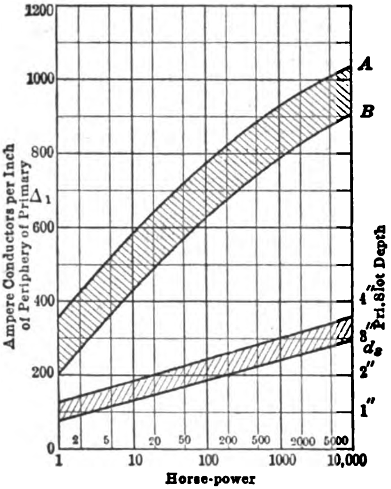

FIG. 113.—Values of peripheral loading and primary slot depth.

254. Total cost of manufacture or works cost. A very useful criterion of k_3 (and therefore of v), from the cost standpoint, may be obtained by the use of the following empirical formula for the total works cost (t.w.c.) taken from Hobart's "Electric Motors," 2d Edition, page 594.

$$\text{t.c.w.} = K_e D(l + 0.7q_{p}\tau) \quad \text{(dollars)} \qquad (79)$$

where K_e is a factor which varies but slightly with the size and proportions of the motor. By substituting, differentiating, and solving, the value of k_3 for a minimum *twc* is $k_3 = 0.71/q_p$. Again the minimum is a fairly flat one and considerable leeway is available. If larger values of v and k_3 are taken, larger B and Δ may also be employed.

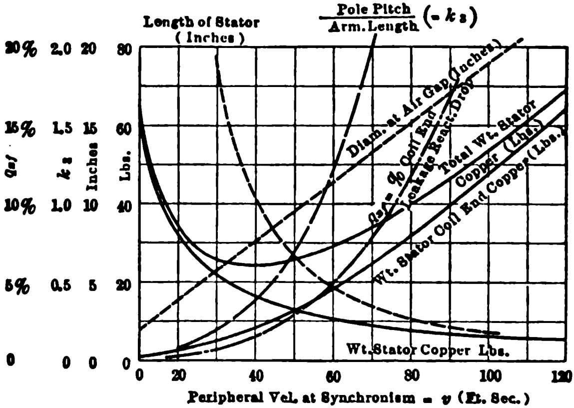

FIG. 114.—Influence of peripheral velocity on vital induction-motor characteristics.

256. Coil-end-leakage limit of peripheral velocity. The other limit to v is the coil-end leakage, which is proportional to v^3 (see Par. 196, Eq. 62a, and remember that k_3 is proportional to v^3). q_{xf} has been computed for the 10-h.p. motor of Fig. 114, and is plotted in Fig. 117. If Δ were taken larger, both the total copper and the q_{xf} curves of Fig. 114 would be higher. A change in $\mathfrak{B}$ would not affect either appreciably. By using a fractional-pitch winding, both of these curves would be lowered somewhat, but there is a limit to this, owing to the necessity for more active conductors to generate the same e.m.f., or larger values of $\mathfrak{B}$ and q_m. A larger value for R would lower both, and a larger h.p. would lower q_{xf}; but these are specifications. The curves of Fig. 117 show without necessary comment why v may not be carried above a pretty definite upper limit for any given specifications.

257. Fractional-pitch windings. The use of any considerable pitch reduction or chording (beyond the five-sixths used for the curves of Figs. 118 to 121) means an increased exciting current (q_m) and a decreased reactance (q_x), other things being equal. If the motor in question were properly designed for full pitch, the pitch reduction should be accompanied by a decrease of $\mathfrak{B}$, an increase of Δ and of v. This will not usually increase either the power-factor or the specific output (k_e or ξ), but rather the reverse. It will, however, increase the diameter and decrease the length of the core, thus increasing the natural heat-dissipating power of the machine. It will also reduce the overall length, which in some cases means a considerable saving in cost. The most obvious place for the fractional-pitch winding is the two-pole motor, where a pitch as low as 0.5 is sometimes used.

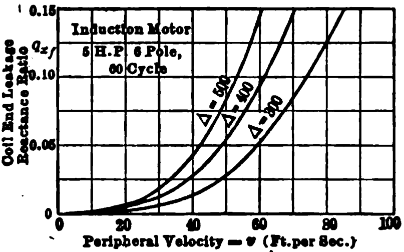

FIG. 117.—Coil-end leakage as function of peripheral velocity and of peripheral loading for a 5-h.p. motor.

258. Data. Figs. 118 to 121 give values of $\mathfrak{B}$, v and Δ_1, and the corresponding values of q_x, q_m, q, k_e, ξ, k_3, and power-factor, for squirrel-cage motors with open-stator slots and nearly closed-rotor slots, and a coil pitch of five-sixths except where otherwise designated. The curves have been computed on the following basis: Δ_1 is approximated largely on the basis of heating; the values of $\mathfrak{B}$ are a compromise between first cost and stalling torque on the one hand and power-factor on the other, with more weight given to the former; k_3 (upon which v depends) is a compromise between cost and ventilation. From these assumed values the other quantities have been computed. Both $\mathfrak{B}$ and k_3 are larger than are frequently met with in practice, and doubtless too large to meet some specifications.

If closed slots had been used on the stators, larger values of $\mathfrak{B}$ could have been employed to advantage, not only because of the lower reluctance of air-gap but also because of the higher allowable tooth density. This increased $\mathfrak{B}$ does not ordinarily result in an increase of power-factor, sometimes the reverse is true; but it does mean a smaller machine and less active material. This may or may not mean a cheaper machine, according as the extra cost of labor in winding is or is not made up by the saving in material. In general it would be cheaper in Europe and more expensive in this country.

Two-pole motors are rarely met with and the data for this type is given to show possibilities and the value of low coil pitch for two poles. The disadvantage is chiefly connected with the poorer natural ventilation of a long-core machine with short air-gap.

259. Caution. Such information as given in Figs. 118 to 121, and elsewhere in tables or curves, should be taken only as a rough guide, and as indicating the relations between the several quantities involved, rather than their absolute values. These latter may be altered over a moderate range to suit special specifications, and will vary considerably in machines

265. Exciting current. This is nearly twice as large as for the three-phase case, approximately half of it being the reflection in the primary of the no-load secondary current which supplies an *m.m.f.* in space and time quadrature with the primary *m.m.f.* and thus produces a revolving field.

266. Output and rating relative to polyphase machine. The safe single-phase rating of a three-phase motor at rated voltage is about 60 per cent. of the three-phase rating at the same voltage, but a better balance of losses is obtained at a slightly increased line voltage, when the safe output may be increased to about two-thirds that of the polyphase case.

267. Secondary current and copper loss. Unlike the three-phase motor, the rotor current of the single-phase motor is not zero at synchronism, but has a definite value. This may be looked upon as a part of the exciting current, and is present in lesser degree at higher slips. The secondary copper loss is also not zero at synchronism and is no longer proportional to the slip. It is obviously larger at all loads than when running three-phase.

268. Methods of starting. The most common method of starting single-phase induction motors is known as the split-phase method. The motor is supplied with an auxiliary winding in space quadrature with the

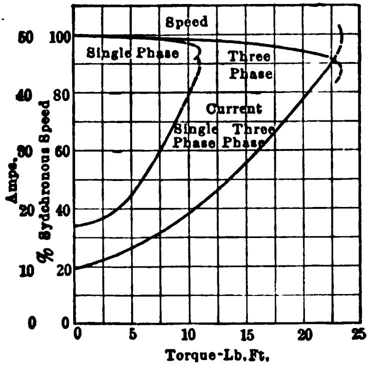

FIG. 124.—Characteristic curves of a three-phase induction motor operated (1) from a three-phase circuit and (2) from single-phase circuit.

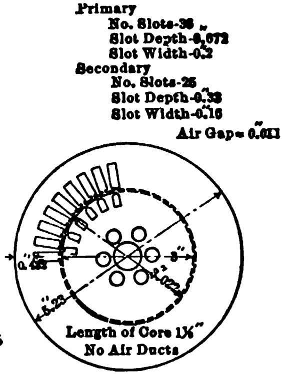

FIG. 125.—Dimensions and data of a one-eighth horse-power single-phase motor.

main windings (sometimes this consists of the third phase of a three-phase Y winding). The supply current is divided before it reaches the motor, one part going through a reactance to the main winding, and the other through a non-inductive resistance to the auxiliary or starting winding. If the resistance and reactance are properly chosen, the phase difference thus produced between the e.m.fs. E_m and E_s is sufficient to produce an elliptical revolving field.

Sometimes in the case of small motors which can be thrown directly on the line, L is omitted and the extra resistance is obtained within the starting winding itself by using a small size of wire. In this case the cutting out of the starting winding is accomplished automatically by a centrifugal device. The dimensions and data of such a motor are given in Par. 270 and in Fig. 125. Its test data are given in Fig. 126.

269. Design of single-phase induction motor. From the above it is obvious that to design a single-phase motor means simply to design a good polyphase motor for about one and one-half times the desired single-phase output.

obtained with increasing resistance steps. In Fig. 128 the current-torque curve for the above speed-torque curves, is shown, the torque per amp. being independent of the speed for this type of control. Since with this method speed variation is obtained by wasting energy in rheostats, it is not suited to continuous running at speeds much below synchronous speed.

273. Disadvantages of secondary-resistance control. For any one value of the resistance the speed changes greatly with variations of the load and rises to practically its synchronous value at no-load, whatever be the resistance. The higher the resistance, the more the speed will vary for a small change in load. An amount of power proportional to the speed reduction is lost in the resistance, that is, if the speed is decreased to 30 per cent. below normal, 30 per cent. of the energy taken from the line is lost.

274. Advantages of secondary-resistance control are simplicity of connections and relatively small increase in cost of motor, over that of a constant-speed induction motor. This method is exactly equivalent to the armature-series-

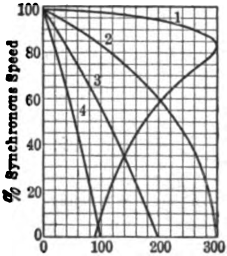

FIG. 127.—Torque speed curves of an induction motor with speed controlled by varying the resistances in series with the secondary circuits.

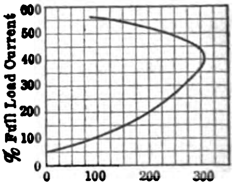

FIG. 128.—Torque-current curve for induction motor with secondary speed control.

resistance control of the speed of a direct-current shunt motor under constant voltage.

Uses—cranes, elevators and rolling mills.

275. Frequency changing as a means of securing various speeds. There are various ways of applying this principle and all are characterised by high first cost. *E.g.*, use several alternators of different frequencies, an objection being the trouble in throwing over from one to the other; or use alternator driven at variable speed, when each motor must have its own alternator.

276. Speed change by variation of number of poles (multispeed motors). It is obviously possible by regrouping the coils on the stator of an induction motor so as to alter the number of poles, to also alter the synchronous speed of the motor. With pole-changing a squirrel-cage rotor is generally used, as with a wound rotor the rotor conductors must also be regrouped. But in certain services such as in rolling mills, secondary resistance control demands a wound rotor. With an ordinary two-layer drum winding the pitch of the coils changes as the number of poles is changed: for instance a two-thirds pitch for four poles means a one and one-third pitch for 8 poles. On this account it is in practice unsatisfactory to carry the range of speed variation by pole changing beyond the 2 to 1 ratio. The above suggested pitch is on the whole the most satisfactory for a two to one change. It is quite possible to get into serious difficulties by the use of certain other pitches. This method of pole changing results in poor constants at one or both of the speeds, and the controller is usually expensive. Instead of regrouping the coils, the stator may be provided with separate windings of different pole numbers. This method is also expensive.

277. Direct-concatenation and differential concatenation control.* If the secondary of a wound rotor is connected to the primary of another in-

* Danielson, Ernst. "A Novel Combination of Polyphase Motors for Traction Purposes," *Trans.* A. I. E. E., Vol. XIX, page 527.

rating. If, however, a 16 h.p. 16-pole motor be concatenated with a 4-h.p. 4-pole motor, their combined synchronous speed at 60 cycles will be 360 rev. per min. Neglecting losses, four-fifths of the electrical power delivered to the 16-pole motor will be converted to mechanical power and one-fifth transmitted to the 4-pole motor and there converted into mechanical power. In this case, the breakdown output of the set will be a little less than four-fifths that of the large motor, which is not a sufficient reduction to influence the rating of the set, which on a heating basis will be only a little less than that of the larger motor, or a little less than four-fifths that of the two motors combined. The same is true of the differential concatenation with a speed of 600 rev. per min. This set thus has three speeds—360, 450, 600 (rev. per min.), all with approximately the same power, and a speed of 1,800 rev. per min. with the small motor alone, but at only 4 h.p. In differential cascade the small machine acts as an induction generator and frequency changer. This arrangement will not start itself except by connecting the small motor to the line until the speed is nearly that desired, then throwing over to the differential cascade connection. The cascade operation is thus much more economical and efficient for moderate speed changes, while the pole changing method is more satisfactory for a two- to one-speed ratio.

281. The spinner motor. Different speeds are secured with the spinner motor by a combination of electrical and mechanical features. The motor consists of a "stator" or fixed primary, a "rotor," and between them a "spinner" rotating independently of the rotor, and having a short-circuited winding which is the secondary for the stator, and a slip-ring winding which is the primary to the rotor. The primary on the stator and that on the spinner are wound for different numbers of poles, the stator being usually wound for the larger number of poles, owing to the larger diameter.

282. Securing various speeds with spinner motor. By clutching together the spinner and rotor, and exciting only the stator winding, one speed is obtained; by exciting only the spinner and locking it to the stator, a second speed of the rotor is obtained; by allowing the spinner to run free and exciting both winding so that the *m.m.f.* of each travels in the same direction, gives a third speed, the sum of the two elementary speeds, and by exciting them so that the *m.m.f.* travels around them in opposite directions gives a fourth speed, the difference between the two elementary speeds.

283. Bibliography of spinner motor. The development of the spinner motor is due Mr. Henry A. Mavor, who has described it in the following papers: "Electric Propulsion of Ships" read before the Institute of Engineers and Shipbuilders in Scotland, on Feb. 18, 1908; and "Marine Propulsion by Electric Motors," read at the Institute of Civil Engineers, on Dec. 7, 1909 (see p. 134 of Vol. CLXXIX of *Proc.* I. C. E.). The development of this type of motor has recently been taken up by the Oerliken Co., and a line of spinner motors developed by them is described on page 1247 of the Electrical World for May 30, 1914, in an article by A. Hoeffleur and M. P. Misslin entitled "Adjustable-speed Polyphase Induction Motors." The article contains complete data of the efficiency and other properties of these motors at various speeds.

284. Multiple motor. This is also the invention of Mr. Henry A. Mavor. A 500-h.p. motor of this type has been employed on the electrically equipped cargo boat Tynemount (Sec. 18). The rotor is of the squirrel-cage type. The stator has two independent mutually non-inductive windings of different pole numbers. For full-speed and power these two windings are fed with electricity of frequencies proportional to their pole numbers and hence cooperate to drive the rotor at a given speed. For low speed and power, the winding of greater pole-number is fed from the supply of lower frequency and drives the motor at the corresponding low speed. The motor is described in British Patent, No. 12917, of 1909.

285. The "Hunt" internally concatenated motor.* This machine operates upon the "cascade" principle, having two superimposed magnetic systems in the stator, one field being generated by the stator winding, and the second by the rotor winding which reacts upon the stator producing the second magnetic field and giving the cascade effect. Consider the case of a

* Hunt. *Journ.* I. E. E.; Vol. LII, 1913, p. 406.

winding is connected in the one or the other direction with respect to the main winding according to the direction of rotation desired. The scheme is indicated diagrammatically in Fig. 161. To reverse the direction of rotation, *a* would be connected to *c*, and *b* would be connected to *d*. It is to be observed that in Fig. 161, the axis of the main brushes coincides with the axis of the main stator winding but has the same angle to the resultant of the main and reversing stator windings, which, in Fig. 159, it had with the main stator winding. Were no reversing winding provided, then in order to reverse the direction of rotation it would be necessary to shift the brushes over to the corresponding angle on the other side from the position for normal direction of rotation.

307. Repulsion-induction motors may be fitted for adjustable-speed operation (Par. **299**) by employing a transformer with its primary excited from the line circuit and its secondary interpolated in the circuit of the energy brushes. Such motors are arranged for a speed range of about 2 : 1, approximately one-half of this range being below and one-half above synchronous speed. Finally, *RI* motors are also arranged to give variable speed by shifting the brushes. A speed variation of 2 : 1 is provided in this way.

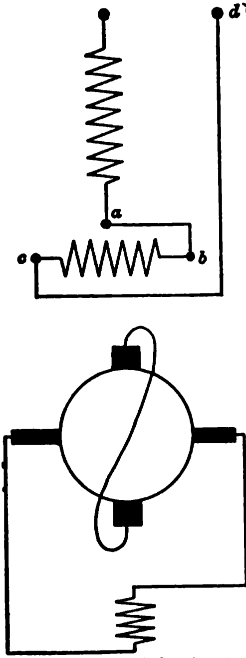

FIG. 161.—Diagram of circuits of reversible RI motor (General Electric Co.).

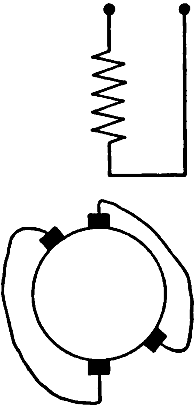

FIG. 162.—Diagram of Déri brush-shifting motor.

308. The Déri single-phase motor with speed control by brush shifting. Fig. 162 is a diagrammatic representation of the Déri single-phase motor. In this motor the speed is varied by varying the position of the brushes. Two of the brushes (those lying in the axis of the stator winding) are of fixed position. The other two are mounted on a movable yoke. For any given brush position the speed decreases with increasing load. Thus the motor has a series characteristic. The motor has good starting torque, the maximum value occurring when the movable brushes are at an angle of some 150 deg. to 160 deg. from the fixed brushes.

The motor is widely employed abroad for driving textile machinery. The simple mechanical arrangements required to effect the shifting of the brushes are less expensive than equivalent control devices which permit of ccomplishing the speed variations without brush movement. Schnetzler has described the Déri motor in a paper published in the E. T. Z. for Nov. 14 and 21, 1907 at pp. 1097 and 1128. There is also a description of the Déri motor occupying pages 669 to 685 of the 2nd Edition of Hobart's "Electric Motors."

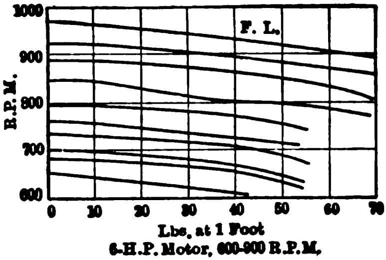

FIG. 163.—Speed-torque characteristics of a 6-h.p. Punga-Creedy single-phase motor for printing-press work. [Speed range is from 600 to 900 rev. per min.] [Messrs. F. Parkinson & Co. of Leeds, England.]

309. The Punga-Creedy single-phase commutator motor. Adjustable-speed, single-phase, commutator motors built under the Punga-Creedy patents have been placed on the British market by Messrs. F. Parkinson & Co., of Leeds. The motor is started by being thrown directly on the line and yields a starting torque of twice full-load torque, consuming twice full-load current. Figs. 163, 164 and 165 show (1) the speed-torque, (2) efficiency, and (3) power-factor curves for a 6-h.p. Punga-Creedy motor for printing-press work. Allusion has already been made in Par. 299 to the principles employed in motors of this class. The chief patents employed in the Punga-Creedy system are Punga's British Patent No. 10585 of 1906 and Creedy's British Patent No. 5136 of 1906. Punga and Creedy tested motors embodying these principles at early dates. The results of a number of these tests have been published in the *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 75, in a paper by Creedy titled "A sketch of the theory of adjustable-speed, single-phase commutator motors."

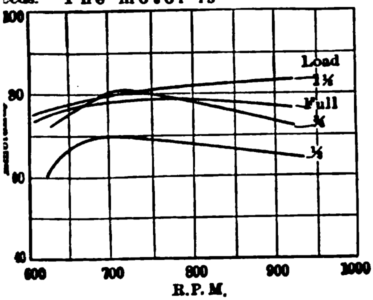

FIG. 164.—Efficiency curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 r.p.m. [Messrs. F. Parkinson & Co. of Leeds, England.]

310. Polyphase shunt commutator motors. The most usual arrangement of a polyphase shunt commutator motor is that known as the Winter-Eichberg type. It is shown diagrammatically in Fig. 166 and is seen to consist of a motor with a three-phase stator and a commutator rotor. The speed will depend upon the pressure applied to the commutator brushes. By using a

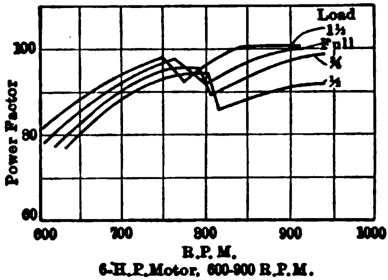

FIG. 165.—Power-factor curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 rev. per min. [Messrs. F. Parkinson & Co. of Leeds, England.]

an important characteristic of the system. It is rarely practicable o desirable to provide for more than 30 per cent. regulation on 60-cycle sys tems or 50 per cent. regulation on 25-cycle systems, since it is difficult t design the auxiliary motor *B* for good commutation except at low frequencies and the frequency supplied to its commutator is proportional to the slip o the rotor of *A*. Greater capacities and greater speed ranges can be supplie by these sets the lower the frequency of the system from which they ar operated. A disadvantage of the Krämer system relates to the fact tha since such sets are usually required for slow-speed work, the auxiliary machin

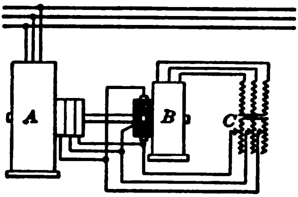

Fig. 170.—The Krämer system of speed control.

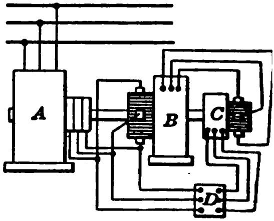

Fig. 171.—American variation of Krämer system.

B must be large and expensive, since the regulating motor must be designed to deliver its maximum output at the minimum speed of the main motor Furthermore, this arrangement necessitates a special design for the regulat ing motor for each installation where the synchronous speeds of the severa main motors differ, even though the total slip energy is the same in eacl case.

315. The Scherbius system of speed control. The arrangement in dicated in Fig. 172 is known as the Scherbius system. As in the Krämer system, the main motor *A*, is a simple induction motor with slip-rings. Th speed control is effected by an auxiliar set on an independent shaft. Thi auxiliary set comprises a commutato motor *B*, driving an induction generato

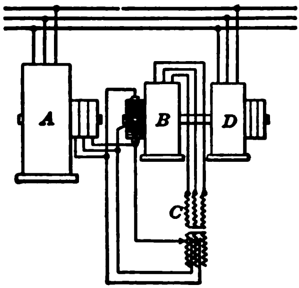

Fig. 172.—The Scherbius system of speed control.

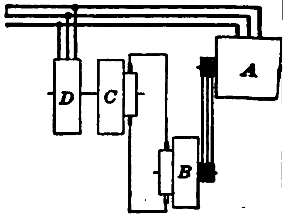

Fig. 173.—Synchronous converte method of speed control.

D. The auxiliary machine, instead of delivering mechanical power to th main motor's shaft as in the Krämer system, returns electrical energy to th supply system. The amount of power transformed by the auxiliary set controlled by the adjustment of the position of the taps in the transform *C* (or rheostat if an exciter is used as described in Par. 314 and Fig. 17 The greater the amount of energy absorbed by *B*, the lower will be the spe of the main motor *A*, just as in the case of the Krämer system.

It may, in general, be said of the Scherbius system that the first cost less than for the Krämer system and that the operation is equally successf nous condensers may simultaneously operate as motors and it is customary to proportion them to thus operate to the extent of a consumption of 70 per cent. of their rated kv-a. They can, when thus operating, be so excited that they also draw from the line, as leading wattless kv-a., 70 per cent. of their rated capacity in kv-a. thus effecting power-factor improvement at the same time that they are serving as motors to deliver mechanical energy. Synchronous condensers are fitted with amortisseur windings to improve their starting qualities and to serve in preventing surging and hunting.

321. Non-synchronous phase modifiers (or phase controllers). Several varieties of apparatus customarily called phase advancers, have been developed for use in connection with individual induction motors for the purpose of improving their power-factor. Such apparatus is supplied with very low frequency electricity from the secondary windings of the induction motors. The frequency is that corresponding to the "slip" of the induction motor. Such phase advancers have an inherent characteristic which may conveniently serve to distinguish them from synchronous condensers (Par. **319** and **320**). This characteristic is that they are *not synchronous machines.*

Leblanc was probably earliest in drawing attention to methods of securing phase control by the use of non-synchronous auxiliaries. His proposals may be explained by reference to the accompanying diagrams. In Fig. 174, *AC* and *BD* represent two series-excited machines which, by suitable mechanical means, are driven at some appropriate speed. The field *C* of *AC* and the armature *B* of *BD* are connected in series with phase *N* of the quarter-phase rotor *MN*. Similarly, the field *D* of *BD* and the armature *A* of *AC* are connected in series with the other phase, *M*. Thus the current

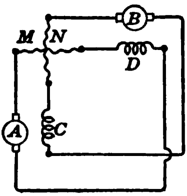

FIG. 174.—Leblanc phase advancer with two armatures and fields.

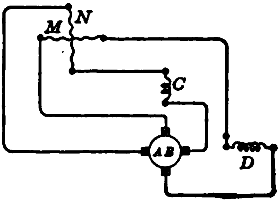

FIG. 175.—Leblanc phase advancer with a single armature.

for exciting the field surrounding each armature is displaced 90 deg. from the current in the phase with which the armature is in series. The armature pressure is consequently 90 deg. displaced from the pressure of the rotor winding with which it is in series. The resultant pressure and current in each rotor circuit, can, by these means, be displaced by any desired amount from the phase relations which would subsist were the rotor windings merely short-circuited on themselves in the customary way. Obviously, the greater the speed at which *A* and *B* are driven and the greater the m.m.f. provided by *C* and *D*, the more may the resultant pressures (and, consequently, also the currents) be advanced in phase from the conditions subsisting with a normally short-circuited rotor without a phase advancer.

In practice, however, it is more convenient to employ a single armature as indicated in Fig. 175, and to supply its commutator (assuming a bipolar design of phase advancer) with four brushes. The armature *AB* (Fig. 175) may be either directly mounted on the motor shaft or it may be driven at a suitable speed by an auxiliary motor. The currents supplied to the brushes will be of the low frequency corresponding to the slip of the rotor *MN* of the induction motor whose power-factor it is desired to improve. Fig. 17[illegible] differs from Fig. 175 simply in that a field structure is indicated surrounding the armature *AB*, and also in the subdivision of the field windings *C* and *D* among the four poles. It must be noted that although, geometrically speaking there are four poles, magnetically considered, it is a bi-polar design. Similarly, as shown in Fig. 177, a three-phase bi-polar advanc[illegible]

Dr. Kapp puts the cost of the vibrators as ranging from about $1.25 per h.p. in favorable cases, up to $4.00 per h.p. in relatively unfavorable cases, such, for instance, of considerable slip or low-pressure secondary windings or both.

330. General considerations in the design of phase advancers. In order to keep down the size and cost of the commutators and the losses at the brushes, it is desirable to wind the secondary of the main motor for fairly high pressure, and it is also desirable that the slip shall be small. It is claimed by Kapp that the smaller the slip, the more favorable is the case for employing a vibrating rather than a rotating phase advancer. The weight and cost per h.p. decrease with decreasing slip and increasing secondary pressure of the main motor. All of these types of phase advancer have the valuable feature of greatly increasing the instantaneous overload capacity of the motors with which they are employed. For a given load the primary current is considerably decreased, and the secondary current increased. This would lead to about the same total copper loss for a given load, were it not for the circumstance that it is usually quite practicable to increase the cross-section of the secondary copper. It is fair to state that the decrease in the losses in the main motor for a given load approximately off-set the losses in the advancer, leaving the efficiency substantially unimpaired at rated load. The efficiency will usually be materially improved at small loads. The power-factor and overload capacity may be both greatly increased.

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MOTOR GENERATORS

332. General flexibility of combinations. For transforming alternating electricity from one pressure or phase system to another of the same frequency, stationary transformers usually offer advantages over rotating apparatus. Even for such transformations, however, motor-generator sets permit of adjusting the ratio of transformation at will and over a wide range. This advantage of greater flexibility in the motor generator rarely suffices to justify its use in transformations where it is not desired to alter the frequency. For effecting all other transformations of electricity, motor generators usually represent the most satisfactory means, if questions of cost and efficiency are left out of account.

333. Motor generators for frequency changing. Transformations from alternating electricity of one frequency to alternating electricity of another frequency are usually effected by means of synchronous motor-generator sets. Such frequency changer sets are discussed in division headed Par. **346 to 369.**

334. Synchronous converters and motor converters. The lower cost and higher efficiency of transformations from alternating to direct current by means of synchronous converters (Sec. 9) or motor converters (Sec. 9) justify their use for certain classes of work notwithstanding certain less desirable features.

reference has already been made, describes interesting arrangements for synchronizing frequency-changer sets when operating in parallel.

352. Refinements of construction necessary to permit of parallel operation. From the above discussion it will be evident that in order to obtain an appropriate division of the load between two frequency changer sets operated in parallel, great exactness in construction and adjustments is necessary. It is desirable to be able to effect a final mechanical adjustment of the stators with relation to one another. This is often arranged by providing a cradle construction. The stator of one machine is bolted to a cradle fastened to the base. By "slacking off" the bolts, a small angular adjustment of the stator may be effected, and the bolts afterward tightened.

353. Efficiency of a motor-generator frequency changer. By using a motor-generator set as a frequency changer, each of the two machines has to be proportioned for the entire load to be delivered to the changed-frequency circuit, and the set is consequently large and expensive. Furthermore, if each machine has an efficiency of, say, 95 per cent., the combined efficiency is only 91 per cent. since $0.95 \times 0.95 = 0.91$.

354. Induction-type frequency changer. We shall now consider means by which better results, in these respects, may sometimes be obtained. These means rest fundamentally upon the circumstance that, in an ordinary polyphase induction motor, the frequency of the current in the rotor winding depends upon the speed of the rotor. Let us consider a 60-cycle three-phase induction motor with a three-phase rotor and three slip-rings. If the stator windings are connected to a 60-cycle circuit, then, if the rotor is restrained from moving, the frequency in the rotor windings will also be 60-cycles per sec. If, on the contrary, the rotor's speed is the same as that of the revolving magnetic field in the stator, and in the same direction, then the frequency in the rotor winding will be zero. Thus if the 60-cycle induction motor has four poles, the magnetic field will travel around the stator at a speed of: $(60 \times 60) + (4/2) = 1{,}800$ rev. per min.

If the rotor's speed is also 1,800-rev. per min. and in the same direction, then the frequency in the rotor windings will be zero. If, however, the rotor's speed is only 1,200 rev. per min. the frequency will be $[(1{,}800 - 1{,}200)/1{,}800] \times 60 = 20$ cycles per sec. If the rotor's speed is only 300 rev. per min., the frequency will be $[(1{,}800 - 300)/1{,}800] \times 60 = 50$ cycles per sec. If the rotor is restrained from running, the frequency will be $[(1{,}800 - 0)/1{,}800] \times 60 = 60$ cycles per sec. If the rotor is driven at a speed of 300 rev. per min. in a direction opposite to that of the magnetic field in the stator, the frequency will be $[(1{,}800 + 300)/1{,}800] \times 60 = 70$ cycles per sec.

In our case we wish a frequency of 25 cycles per sec. Consequently, if we denote by R the speed at which we shall drive the rotor we may have either $[(R - 1{,}800)/1{,}800] \times 60 = 25$ or $[(1{,}800 - R)/1{,}800] \times 60 = 25$ and $R = 2{,}550$ or $R = 1{,}050$.

355. Direct-current motor drive for induction-type frequency changer. Let us select the former case and drive the rotor at a speed of 2,550 rev. per min., by another motor. We can only do this if we have a source of supply of continuous electricity and employ a 2,550 rev. per min., continuous-electricity motor. We could not employ a 60-cycle induction motor to drive the rotor since this would run at only 1,800 rev. per min., if wound with 4 poles and at 3,600 rev. per min., if wound with 2 poles, and we require it to run at 2,550 rev. per min.

356. Alternating-current motor drive for induction-type frequency changers. If there is no source of continuous electricity supply, thus limiting us to the use of a 60-cycle motor to drive the rotor of the frequency changer, then we shall have to abandon the plan of employing a 4-pole frequency changer and we shall be obliged to employ one with more poles which, consequently, will be heavier and more expensive. We can determine upon a suitable combination by consulting the table in Par. **357**.

357. Selection of proper speed and number of poles in induction-type frequency changers. In the table given in Par. **358**, the smallest number of poles which, in column *IV*, corresponds to the synchronous speed of a 60-cycle motor, is 14, corresponding to a rotor speed of 300-rev. per min. Our frequency changing outfit thus consists of a 14-pole induction motor with its rotor driven by a 300-rev. per min., 60-cycle synchronous motor which will, consequently, have $2 \times [(60 \times 60)/300] = 24$ poles. But, for so we may employ a 4-pole frequency changer and drive its rotor at 300 rev. per min. in opposition to the 1,500 rev. per min. of the stator field. If the output delivered from the frequency changer is 1,000 kw., then $(300/1,800) \times 1,000 = 167$ kw. is provided by the driving motor and $(1,500/1,800) \times 1,000 = 833$ kw. is provided by the frequency changer itself in its transformer capacity, and at high efficiency.

Obviously the less the required alteration in frequency, the greater is the appropriateness of the induction-type of frequency changer as compared with the motor-generator type.

361. Relative merits of various kinds of motors for driving the rotor of an induction-type frequency changer. Whether or no it may be practicable to employ an induction motor to drive the rotor, depends to a considerable extent upon the importance or otherwise of supplying absolutely constant frequency at all loads. When it is permissible that the frequency may decrease 1 or 2 per cent. or more from no-load to full-load, an induction motor may provide the most satisfactory solution, since it eliminates the necessity for having a supply of continuous electricity for excitation.

In some instances instead of employing a squirrel-cage induction motor and then having a slip necessarily proportional to the load, it becomes appropriate to drive the frequency changer's rotor by a slip-ring induction motor and regulate its slip, and consequently the frequency supplied, by regulating the resistance in its rotor circuits. This becomes the more expedient, the smaller the proportion of the total energy which is supplied by the driving motor. For instance, in the example in Par. **360**, only $(300/1,800) \times 100 = 16.7$ per cent. of the total output, is provided by the driving motor. and a considerable rheostatic loss in its rotor circuits would not seriously affect the efficiency of the complete outfit. It should again be emphasised that induction-type frequency changers are not used in commercial practice. Synchronous motor-generator sets are practically always employed.

362. Frequency changers for connecting two systems, each of which has its own generating machinery of fixed frequency. We now come to the problem encountered when frequency changers are employed between two systems each of which has a definite frequency imposed upon it by its own generating plant. Synchronous motor-generator sets have nearly always been employed for this class of work. Thus, in order to link up two systems with frequencies of 60 and 25 cycles per sec., respectively, two synchronous machines of 24 and 10 poles respectively are coupled together. It is necessary for the frequencies of the two systems to be exactly identical in order to successfully operate such plant. Furthermore, there are the various complicated relations necessarily observed in synchronising such apparatus, as already discussed in Par. **349**.

Indeed, there is the further consideration that when **sets for parallel operation** are so proportioned and adjusted that they share the load in appropriate proportions when delivering power from, let us say, a 25-cycle system to a 60-cycle system, the division of the load will be altered when it is desired to reverse the sets and deliver power from the 60-cycle set to the 25-cycle system. Notwithstanding the niceties imposed by the relative-frequency conditions, synchronous motor-generator sets constitute the usual means employed.

When synchronous sets are employed to link two large systems, the slightest alteration in the relative frequencies of the two systems occasions enormous fluctuations in the load carried by the frequency changers. This difficulty is less the greater the size of the frequency changers as compared with the size of the systems connected. Unless the frequency changers are of large size as compared with the size of the systems which they connect, they will be pulled out of step if there is any slight change in the ratio of the frequencies of the two systems. Consequently, when the frequency changers cannot be of relatively great size, it would be preferable to employ sets in which an induction machine constitutes the motor member.

363. Induction-motor drive for non-reversible frequency changers. Where the object is to deliver energy always in the same direction, the employment of an induction machine with a slip-ring rotor as motor element, and the control of its precise speed by the adjustment of a rheostat in its rotor circuits provides freedom from the necessity for maintaining at exactly the same value the ratio of the frequencies of the inter-connected systems.

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SECTION 8

DIRECT-CURRENT GENERATORS AND MOTORS

GENERAL PRINCIPLES

1. Lines of magnetic flux. A magnetic field may be represented by continuous lines, called lines of flux, whose direction at any point in the field is that of the force acting on a north pole placed at the given point; they therefore emerge from a north pole and enter a south pole (Sec. 2).

2. Electromagnetic induction. When the total magnetic flux threading a coil undergoes a change, an electromotive force (e.m.f.) is generated or induced in the coil. This e.m.f. is proportional to the time rate of change of flux. One volt is generated in a coil of one turn when the rate of change of flux threading the coil is 10^8 lines per sec.

3. Magnitude of induced e.m.f. In Fig. 1, N and S are respectively the north and south poles of a magnet and ϕ represents the direction of the magnetic flux passing from the north to the south pole. When coil A is moved from position 1 where the flux threading the coil is ϕ, to position 2 where the flux threading the coil is zero, in t sec., the average e.m.f. generated in the coil is $E = (\phi/t)\ 10^{-8}$ volts.

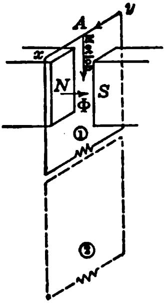

Fig. 1.—Direction of generated e.m.f.

4. The direction of the generated e.m.f. may be found by **Fleming's right-hand rule,** which states that if the thumb, forefinger, and middle finger of the right hand be placed at right angles to one another so as to represent three coordinates in space, with the thumb pointed in the direction of motion of the conductor relative to the field, and the forefinger in the direction of the lines of flux, then the middle finger will point in the direction of the induced e.m.f. (Sec. 2). The direction of the e.m.f., found by Fleming's rule, is shown by the arrow in Fig. 1, and it may be seen (Sec. 2), that the magnetic effect of the current produced tends to prevent the flux threading the coil from decreasing or, as stated by Lenz's law (Sec. 2), the generated e.m.f. always tends to send an electric current in such a direction as to oppose the change of flux which produces it.

5. Force on a conductor in a magnetic field. A conductor L cm. long, carrying a current of I amp. perpendicular to a magnetic field of $\mathcal{B}$ lines per sq. cm., is acted on by a force of $\mathcal{B}LI/10$ dynes in a direction found by **Fleming's left-hand rule,** which states that if the thumb, the forefinger and the middle finger of the left hand be placed at right angles to one another so as to represent three coordinates in space, with the thumb pointed in the direction of the force on the conductor and the forefinger in the direction of the lines of flux, then the middle finger will point in the direction of the current.

6. Identity of generator and motor structure. Diagram A, Fig. 2, shows a generator under load; the direction of rotation is determined by the prime mover, while the direction of the current in the conductors may be found by the right-hand rule (Par. 4). A force is exerted on the conductors, inasmuch as they are carrying current in a magnetic field; the direction of this force is found by the left-hand rule (Par. 5) and is opposed to e.m.f. is being generated in it, that is, it should be midway between the poles or in the neutral position.

9. Field excitation. The m.m.f. necessary to establish the flux in the magnetic circuit is obtained by means of field coils which are wound upon the poles of the machine. The exciting current for the field coils may be supplied in various ways. When a generator supplies its own exciting current it is said to be **self-excited;** when the exciting current is supplied from some external source, such as an exciter, the machine is said to be **separately excited.** The different connections used are shown diagrammatically in Fig. 4.

Diagram *A* shows a separately excited machine. Diagram *B* shows a **shunt machine,** in which the field coils form a shunt across the armature terminals and have many turns of small wire carrying a current which is proportional to the terminal voltage of the machine. This field current seldom exceeds 5 per cent. of the armature current under full-load conditions. Diagram *C* shows a **series machine,** in which the field coils are in series with the armature and have fewer turns than the coils of a shunt winding, but employ a larger size of wire because they carry the whole or a fixed proportion of the total current. Diagram *D* shows a **compound machine** in which there is connected to the terminals a shunt winding which carries an exciting current proportional to the terminal voltage; and also a series winding which carries a current proportional to the armature current. This method of connection is known as the "**long shunt.**" Diagram *E* shows a compound machine connected in another manner. The connection in this case is known as the "**short shunt**"; that is, the shunt coil is connected to the terminals of the armature. Small machines using permanent magnets for field poles are called **magnetos.**

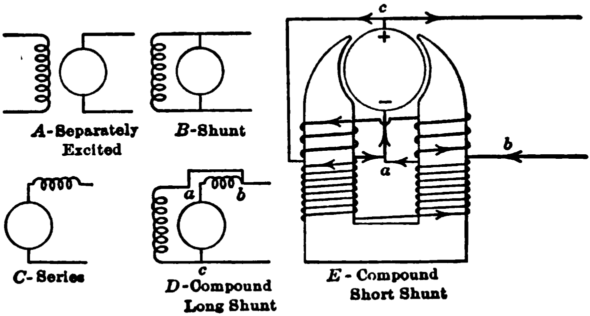

Fig. 4.—Methods of excitation.

CLASSIFICATION OF TYPES

10. Classification according to the number of poles, as follows:

(a) **Bipolar machines** (Fig. 4) have only two poles.

(b) **Multipolar machines** (Fig. 46) have more than two poles; the number of poles is always a multiple of two.

(c) **Homopolar machines** (Fig. 89) have two poles, but the conductors always cut lines of unidirectional flux. The resulting e.m.f. is continuous in one direction and therefore no commutator is required.

11. Classification according to the method of drive, as follows:

(a) **Belted-type motors and generators** are self-contained. This type of machine includes bearings, shaft extended for a pulley and a sliding base with belt-tightening device. An outboard bearing is usually provided with machines of larger capacity than 200 kw. at 600 rev. per min.

(b) **The engine-type generator** has its armature mounted on a continuation of the crank shaft of the engine, and **slow-speed units** are generally supplied without base, bearings, or shaft, these being furnished by the engine builder.

(c) **The direct-connected turbo-generator** has its armature shaft coupled directly to that of a steam turbine. In this type the construction of the generator is special on account of the high speed.

(d) **The geared turbo-generator** has its armature shaft connected to the shaft of a steam turbine through a reduction gear, so that a generator of moderate speed and simple construction may be used.

(e) **The water-wheel type generator** has its armature shaft coupled directly to that of a water wheel. Such a generator may be of either the horizontal or the vertical type and is generally supplied complete with base, bearings, shaft and coupling.

(f) **The back-geared type motor** embraces a speed-reduction gear as an element of the machine. The slow-speed shaft is supported in bearings attached to the frame.

12. Classification according to special features of construction, as follows:

(a) **Interpole machines** (Fig. 24) have small auxiliary poles which carry series windings and improve commutation.

(b) **Compensated machines** (Fig. 27) have series windings on the pole faces to neutralize armature reaction. Such machines may also have interpoles.

(c) **Miscellaneous.** Under this class may be included **mill motors,** used in rolling mills; **flame-proof motors** for mine service; **variable-speed generators,** for train lighting; etc. (Par. **183** to **215**).

ARMATURE WINDINGS

13. The Gramme ring winding is almost obsolete; examples of it are shown in Figs. 3, 5, and 6 merely to present clearly the meaning of the terms used in describing the various types of winding.

14. A re-entrant winding closes or re-enters on itself. **A singly re-entrant winding** closes on itself only after including all of the conductors; see Figs. 3 and 6. **A doubly re-entrant winding** closes on itself after including half of the conductors; see Fig. 5.

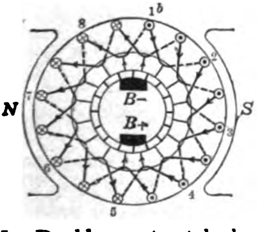

Fig. 5.—Doubly re-entrant duplex winding.

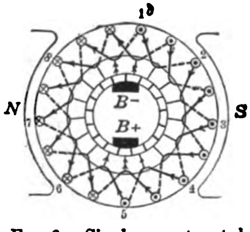

Fig. 6.—Singly re-entrant duplex winding.

15. A simplex winding has only two paths through the armature from each brush; see Fig. 3. **A duplex winding** has twice as many, or four paths, through the armature from each brush. In this winding each brush should cover at least two commutator segments; see Figs. 5 and 6. Although it is possible to use **multiplex** and **multiply re-entrant** windings, they are seldom found in modern machines. Even duplex windings are rarely used except for machines of very large current capacity.

16. The drum winding has coils shaped as shown in Fig. 7. At any instant, two sides of each coil are under adjacent poles. Since the number of conductors in each coil must be a multiple of two, the total number of conductors must be even. A winding made with coils of this shape must lie in two layers and is called a **double-layer winding.**

17. Representation of drum windings. Fig. 8 shows a double-layer drum winding corresponding to the Gramme ring winding in Fig. 3. It has the same number of conductors and the same number of paths through the armature, but only half the number of commutator segments. Conductors in the upper layer are represented by full lines and those in the bottom layer by dotted lines. The radial lines represent face conductors; the connecting lines on the inside represent the connections at the commutator end, and those on the outside represent the connections at the opposite end. For convenience the brushes are shown inside the commutator.

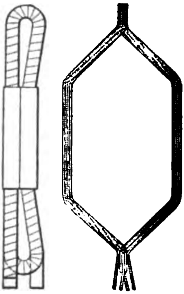

Fig. 7.—Coil group for double layer winding with two turns per coil and eight conductors per slot.

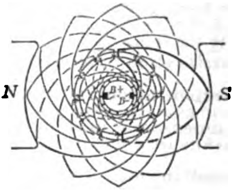

Fig. 8.—Simplex singly re-entrant. drum winding.

18. Multiple winding. Fig. 9 shows a six-pole drum winding with six paths in parallel between the positive and the negative terminals. The three positive brushes are connected together outside of the machine by a copper ring T_+, and the three negative brushes are connected by a similar ring T_-. This winding is of the multiple type, that is, the number of armature circuits between terminals is a multiple of the number of poles.

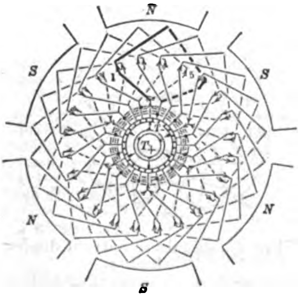

Fig. 9.

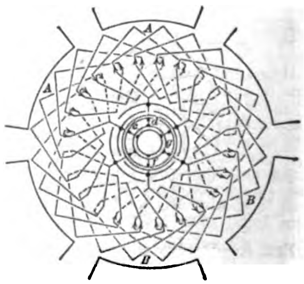

Fig. 10.

Figs. 9 and 10.—Simplex, singly re-entrant, full-pitch multiple winding with equalizers.

19. Equalizers. Fig. 10 shows a multiple-wound armature which is not central with the poles. The flux density in the air gaps A is greater than that in the air gaps B, and the voltage generated in a circuit under poles A is greater than that in a circuit under poles B, so that the generated voltage between c and d is greater than that between f and g; hence a **circulating current** will flow through the winding and brushes, causing sparking, additional loss and additional heating. This circulating current may be minimized by careful centering during erection, while the sparking may be pre-of brushes are required, this type of winding is well suited for direct-current railway motors, inasmuch as the two sets of brushes for a four-pole motor are placed 90 deg. apart so that they may easily be inspected from the car.

25. Lap windings and wave windings. A multiple-wound armature is sometimes said to have a **lap winding** and an armature with a two-circuit winding is said to have a **wave winding.**

26. Dead coils. There are generally more coils than there are slots, and each coil may have more than one turn. A coil in this case is defined as the shortest winding element between two commutator segments. It is not always possible to put a proper two-circuit winding into a given armature. A 110-volt, four-pole machine, with forty-nine slots, forty-nine coils, and two conductors per slot, may have a two-circuit winding because it fulfills the condition that $49 = (24\ p/2) + 1$; when wound for 220 volts, however, four conductors per slot are required, and the number of coils is $98 = (49\ p/2) \pm 0$, which will not give a two-circuit winding. In such a case, one coil, called a dead coil, is not connected into the winding, its two ends being taped so as to completely insulate the coil. The machine, therefore, may have a two-circuit winding with ninety-seven active coils and ninety-seven commutator segments.

27. Turbo-generator windings. In turbo-generators the conductors are long and move at high speed, so that the voltage between adjacent commutator segments is often higher than desirable. For such machines it has been proposed to use the type of winding shown in Fig. 13, the voltage between adjacent commutator segments being that generated in one conductor. To keep the inductance of the return conductors low, it is desirable to group together return conductors in which the currents at any instant are in opposite directions.

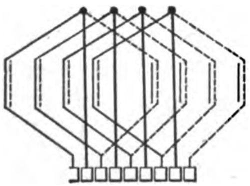

Fig. 13.—Winding with half-turn coil.

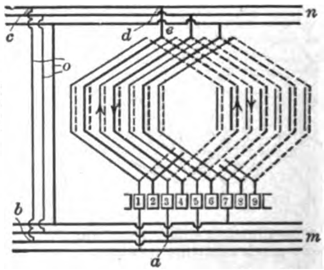

Fig. 14.—Connection of equalizer between parallel windings.

28. Equalizer connections for turbo-generator windings. The normal multiple-circuit doubly re-entrant duplex or multiplex windings can only be used to their full advantage when the voltage between the segments belonging to the different parallel windings is equally distributed, that is to say, the potential between segments 1 and 2 should be exactly half of the potential between segments 1 and 3; but without special means of bringing about this condition it is rather dangerous to use these windings. It may happen that the potential is very unevenly distributed between the segments, and this gives rise to very great equalizing losses over the brushes. The winding shown in Fig. 14 is a multiple-circuit doubly re-entrant duplex winding; the thin lines in the diagram indicate one of the parallel windings, the thick the other. The thin lines at the bottom of the diagram indicate the normal equalizer connections for the winding shown in thin lines, and the thick lines at the top indicate the normal equalizer connections for the winding shown in thick lines. The corresponding equalizer rings of the two parallel windings are connected through the equalizers indicated on the left of the diagram, and by means of these connections equal and the main exciting m.m.fs. exist together. Since the armature teeth are saturated at normal flux densities, the increase in flux density at *f* is less than the decrease at *e*, so that the total flux per pole is diminished by the cross-magnetizing effect of the armature.

33. Demagnetizing effect. Fig. 17 shows the magnetic field produced by the m.m.f. of the armature when the brushes are shifted through an angle

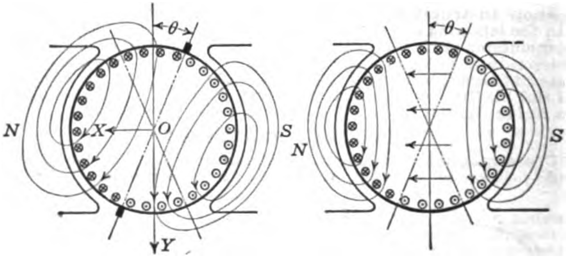

FIG. 17. FIG. 18.

FIGS. 17 AND 18.—Demagnetizing and cross magnetizing effect.

θ so as to improve commutation (Par. 47). The armature field is no longer at right angles to the main field, but may be considered as the resultant of two components, one in the direction OY, called the cross-magnetizing component, the effect of which is discussed in the last paragraph, and the other in the direction OX, which is called the demagnetizing component because it is directly opposed to the main field. Fig. 18 shows the armature divided so as to produce these two components, and it may be seen that the demagnetizing ampere-turns per pair of poles are

$$\left(\frac{ZI_c}{p}\right)\times\frac{2\theta}{180} \quad \text{(ampere-turns)} \quad (2)$$

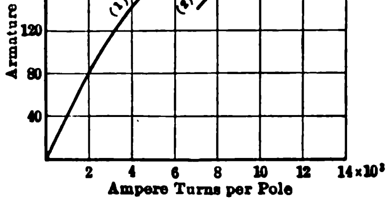

FIG. 19.

where $2\theta/180$ is generally about 0.2. Therefore the demagnetizing ampere-turns per pole are

$$0.1\left(\frac{ZI_c}{p}\right) \text{(ampere-turns)} \quad (3)$$

34. No-load and full-load saturation curves. Curve 1, Fig. 19, shows the no-load saturation curve of a direct-current generator. When full load is put on the generator there is a decrease in flux and therefore a drop in voltage *ab* due to the armature cross-magnetizing effect (Par. 32). A further voltage drop due to the armature demagnetizing effect is counter-balanced by an increase in excitation of $bc = 0.1\ (ZI_c)/p$; also a portion *cd* of the generated e.m.f. is required in overcoming the internal resistance of the machine. With an excitation of 10,000 ampere-turns, the voltage at no load and normal speed equals 240 volts. At full load, with the same excitation, the terminal voltage equals 196 volts. In order that the full-load voltage may be the same as that at no load, the number of ampere-turns per pole which must be supplied by the series field is (13,400 − 10,000) = 3,400 ampere-turns.

divides into two parts which are proportional to the areas of contact between the brush and segments 5 and 6 respectively, and the current density is uniform across the brush surface. In diagram *C* the two contact areas are equal; there is no tendency for current to pass round coil *M*, and the current density is again uniform across the brush surface. In diagram *D* the contact area between the brush and segment 5 is small while that between the brush and segment 6 is large; the larger part of the current therefore enters at segment 6 and the current in coil *M* is reversed, while the current $2I_c$ again divides into two parts which are proportional to the contact areas between the brush and the two commutator segments, and the current density is still uniform across the brush surface.

37. Perfect commutation is defined as such a change of current in the coil being commutated that the current density over the brush contact surface is constant and uniform.

38. The brush contact resistance depends on the brush material and, for carbon brushes, it decreases with increase of current density as shown in Fig. 21. The contact resistance with current flowing from commutator to brush is somewhat higher than with current flowing from brush to commutator.

39. Change of contact resistance with temperature. If the current density in a brush contact be suddenly increased, the contact resistance does not immediately decrease to the value given in Fig. 21, but gradually decreases as the temperature of the contact increases, and reaches a constant value after about 20 min. This explains why a machine will carry a considerable overload for a short time without sparking, whereas, if the overload be maintained, the machine will begin to spark as the brush temperature increases and the contact resistance decreases.

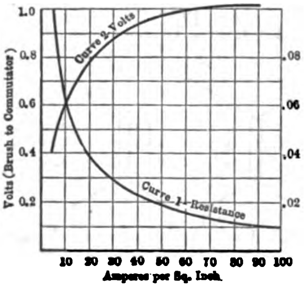

FIG. 21.—Brush contact resistance.

40. Current density in the brushes. For sparkless commutation, (1) the current density in the brush tip must not become infinite, and (2) the average amount of energy expended at the brush contact must be limited. For machines required to operate without sparking up to 25 per cent. overload, a rate of energy dissipation of 35 watts per sq. in. (5.5 watts per sq. cm.) may be allowed at full-load, so that the permissible current density depends upon the voltage drop across the brush contact. The better the commutation, the more nearly uniform is the current density in the brush contact, and the higher the average density which may be allowed.

41. Current density in the brush tip. The effect of coil resistance may generally be neglected, but that of self-induction must be considered. The e.m.f. of self-induction and mutual induction of coil *M* (Fig. 20) opposes the change of current in that coil, so that, in diagram *C*, at the end of half of the period of commutation, the current in the coils *M* has not become zero. When it does become zero, some time later, and the currents entering segments 5 and 6 are equal, the contact area with segment 5 is smaller than with segment 6 and the current density in the brush tip *S* is greater than normal. It may be shown theoretically that the tip density at the end of commutation becomes infinite* when $RT_c/(L+M)$ is less than unity,

where R is the resistance of the brush contact in ohms,
T_c is the time of commutation in seconds,
L is the coefficient of self-induction in henrys of one coil M,
and M is the coefficient of mutual induction in henrys between coil M and coils M_1 and M_2.

* Reid, on "Direct-current Commutation," *Trans.* A. I. E. E., Vol. XXIV.

42. Copper leaf brushes can carry 150 amp. per sq. in. (23 amp. per sq. cm.) with a drop of 0.3 volt at the contact.

Carbon brushes can carry 35 watts per sq. in. (5.5 watts per sq. cm.), Par. 40, for example 35 amp. per sq. in. (5.5 amp. per sq. cm.) with a drop of 1.0 volts at the contact.

43. Average reactance voltage. The criterion for sparkless commutation is, then (Par. 41), that $RT_c/(L+M)$ shall be greater than unity, or that

$$2I_cR > \frac{2I_c}{T_c}(L+M) \qquad (4)$$

where $2I_c$ is the current entering the brush (Fig. 20). The latter quantity is called the average reactance voltage and the former is the voltage drop across one brush contact. It will be found that the higher the contact resistance and the lower the reactance voltage, the better is the commutation.

Fig. 22 shows the magnetic field encircling the short-circuited coils of a full-pitch multiple winding. The reluctance of the magnetic path may readily be calculated from which the value of the flux per unit current and $L+M$, the coefficient of self and mutual induction, are obtained. Deep slots decrease the reluctance of the magnetic path (for the same cross-section of conductor) and increase the reactance voltage, therefore they should be avoided if possible.

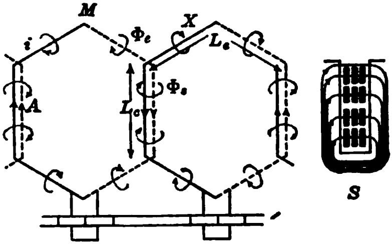

FIG. 22.

44. Effect of type of winding on reactance voltage. In the **short-pitch winding** shown in Fig. 11, the conductors undergoing commutation lie in different slots, and the reluctance of the magnetic path around the coils is greater, and the coefficient of mutual induction smaller, than in a **full-pitch winding**. The use of a short-pitch winding therefore lowers the reactance voltage and improves commutation, but, as shown in Fig. 11, it also reduces the effective interpolar space by the angle θ.

In the **two-circuit winding** with one set of positive and one set of negative brushes, shown in Fig. 12, each brush short-circuits $p/2$ coils in series, so that the reactance voltage is $p/2$ times that of a **multiple winding**. When, however, the number of brush sets is the same as the number of poles, there is a short commutation path around one coil and the commutation is improved.

45. Reactance voltage formula. Approximate results may be obtained by use of the following formula for the average reactance voltage.*

$$E_r = kS(\text{r.p.m.})I_cL_cT^2\left(\frac{\text{poles}}{\text{paths}}\right)10^{-8} \qquad \text{(volts)} \qquad (5)$$

where S is the number of commutator segments,
r.p.m. is the speed of the machine in rev. per min.,
I_c is the current in each armature conductor,
L_c is the frame length in inches (see Fig. 38),
T is the number of turns per coil between segments,
$\left(\frac{\text{poles}}{\text{paths}}\right) = 1$ for multiple windings and $p/2$ for two-circuit windings,
$k = 1.6$ for two-circuit windings and for full-pitch multiple windings,
and
$k = 0.93$ for short-pitch multiple windings.

Deep slots increase the reactance voltage above this value.

* Gray. "Electrical Machine Design," p. 84.

46. Effect of brush arc. An increase in the brush arc has no effect on the reactance voltage because, while it increases the number of coils in series at short circuit, it decreases the time of commutation in the same ratio, and the reactance voltage remains unchanged. On the other hand, a wide arc may cause sparking by starting commutation in the coils before they are in a reversing field, or by keeping them short-circuited until they are in too strong a field. To minimise this trouble make the proportions such that,

$$\text{brush arc} < \left(\frac{\text{pole pitch}}{12}\right) \times \left(\frac{\text{commutator diameter}}{\text{armature diameter}}\right) \qquad (6)$$

where all dimensions are in inches. Furthermore, the brush should not cover more than three commutator segments except in machines of low reactance voltage, otherwise there will be large circulating currents in the brush face.

47. Shifting of brushes. To improve commutation, the brushes are shifted from the neutral position, so that the short-circuited coils are in a magnetic field and an e.m.f. (E_s) is generated in them which opposes the reactance voltage and improves commutation. As the current in the machine increases, the reactance voltage increases with it. To have perfect commutation at all loads, the voltage E_s must maintain an unvarying ratio to the current. This is only possible when the distance by which the brushes are moved from the neutral position increases as the current increases. Modern machines must operate from no load to 25 per cent. overload without sparking and without shifting of the brushes during operation. In these machines the brushes are permanently shifted (at the time of erection) from the neutral position until the voltage E_s is so large that sparking takes place at no load.

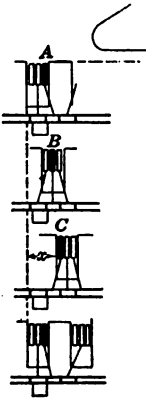

FIG. 23.—Commutation with several coils per slot.

48. Number of slots per pole. Fig. 23 shows three of the stages in the commutation of a machine with six coil sides per slot. The commutator segments are evenly spaced while the coils, being in slots, are not. Between the instant when the brush breaks contact with coil A, and the instant it breaks with coil C, the slot has moved through a distance x, so that if the magnetic field in which the coils are commutated is suitable for coil A, it is too strong for coil C, and the latter will therefore be badly commutated, every third commutator segment being blackened. The distance x is equal to the slot pitch minus the width of one commutator segment. To minimize this trouble, a machine should have more than twelve slots per pole. Large machines have generally more than fourteen slots per pole.

49. Limits of reactance voltage. Experience shows that when the following conditions are fulfilled, namely:

(1) Number of slots per pole is greater than twelve,

(2) Brush arc is less than one-twelfth of the pole pitch measured at the commutator surface,

(3) Pole arc is less than seven-tenths of the pole pitch, and

(4) Ampere-turns for air-gap and teeth are greater than 1.2 to 1.5 times the armature ampere-turns per pole (Par. 35): then the reactance voltage calculated by Eq. 5 (Par. 45) should be

(1) Less than seven-tenths of the voltage drop per pair of brushes, with brushes in neutral position, and

(2) Less than the full voltage drop per pair of brushes, with the brushes shifted to improve commutation.

A machine with a two-circuit winding will commutate about 20 per cent. better than would be indicated by the value of reactance voltage obtained from Eq. 5 (Par. 45), while the commutation of a machine with a short-pitch winding will be about 30 per cent. worse than indicated, because of the reduction of the effective interpolar space (Par. 44).

50. Shunt, compound and series machines. Due to armature reaction, the flux at the pole tip toward which the brushes are shifted decreases with increase of armature current (Par. 31). This decrease is kept within reasonable limits by the use of a strong exciting field (Par. 35) and is less in a compound machine than in a shunt machine operating on constant excitation. In the series machine the main exciting m.m.f. and the armature m.m.f. increase together, and the flux at the commutating pole tip may increase or decrease, depending on the relative strength of field and armature.

51. Interpoles. An interpole generator is shown diagrammatically in Fig. 24, where n and s are auxiliary poles which have a series winding so connected that their strength increases with the armature current. To improve commutation in a non-interpole generator, the brushes are shifted forward in the direction of motion, so that B_+ would come under the tip of the N pole and B_- under the tip of the S pole. In the interpole machine the auxiliary pole n is placed opposite the brush B_+ and the auxiliary pole s opposite the brush B_-.

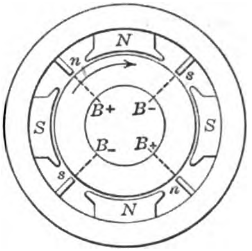

Fig. 24.—Magnetic circuit of interpole generator.

52. Interpole excitation. The interpole must have a m.m.f. equal and opposite to that of the cross-magnetising effect of the armature, namely, $ZI_c/2p$ ampere-turns per pole (Par. 30) and, in addition, a m.m.f. which can send across the gap a flux large enough to generate in the short-circuited coil an e.m.f. equal and opposite to the reactance voltage. In order that the interpole flux may be always proportional to the current, the interpole magnetic circuit must not be allowed to become saturated.

53. The effective interpole arc is represented by the expression $W_{ip}+2\delta$ (see Fig. 25) and should be of such proportions that while the current in a conductor is being commutated, the slot carrying that conductor is in the interpole field. The distance moved by the coil A (Fig. 23) while short-circuited equals the brush arc multiplied by the armature diameter and divided by the commutator diameter and the effective interpole arc must exceed this by the distance x (Fig. 23).

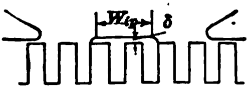

Fig. 25.—Interpole width.

54. The reluctance of the interpole air-gap should vary as little as possible for different positions of the armature, otherwise the interpole field will be pulsating. The effective interpole arc should therefore be a multiple of the slot pitch; it is generally made about 15 per cent. of the pole pitch and, to minimize the interpole leakage flux, the main pole arc is not more than about 65 per cent. of the pole pitch.

55. The axial length of the interpole in inches is given by the formula,*

$$L = \frac{24 \times \text{core length in inches} \times \text{amp. cond. per in.}}{\text{interpole gap density in lines per sq. in.}} \qquad (7)$$

The ampere-conductors per in. (Par. 59) seldom exceed 900, and, with an interpole gap density of 45,000 lines per sq. in. (7,000 lines per sq. cm.), the interpole circuit will not be saturated up to 50 per cent. overload; the interpole length, therefore, need not exceed half the frame length, if there are as many interpoles as there are main poles and if the overloads do not exceed 50 per cent.

56. The interpole ampere-turns per pole for a newly designed machine are usually made equal to 1.4 times the armature ampere-turns per pole (Par. 52). This is generally too large, so adjustment must be made after the machine is erected.

57. Flashing over is generally caused by a sudden change of load. Fig. 26 shows a representation of the armature cross-field in a loaded machine. A sudden change of load alters the value of the cross-flux, and a voltage

*Gray. "Electrical Machine Design," p. 94.

proportional to the rate of change of flux is generated in coil *a*. This may increase the voltage that already exists between adjacent segments to such a value that arcing starts, and then the machine flashes over from brush to brush, particularly if the commutator is dirty. Machines with badly distorted fields and a high average voltage between commutator segments are especially likely to flash over.

58. Compensating windings. For such service as the operation of reversing rolling mills, the current in the motors may change suddenly from full-load value in one direction to three times full-load value in the opposite direction. For such machines the average voltage between adjacent commutator segments, which is equal to the terminal voltage divided by the number of commutator segments per pole, should not exceed

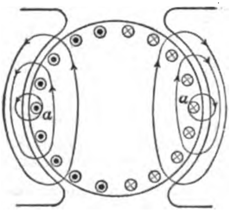

FIG. 26.

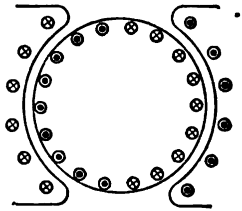

FIG. 27.

FIGS. 26 AND 27.—Armature field with and without compensating windings.

about 15, otherwise compensating windings will be required to prevent flashing over. The compensating winding is carried by the pole face, and is in series with and has the same number of ampere-turns per pole as the armature. However, the current passes in the opposite direction to that in the armature and thus, as shown in Fig. 27, the armature field is completely neutralized. For further discussion of the subject of commutation see the references below.*

ARMATURE DESIGN

59. Output equation. The output of a machine is proportional to the armature volume, and the output equation is

$$D_a^2 L_c = \frac{\text{watts} \times 60.8 \times 10^7}{\text{r.p.m.} \times \mathcal{B}_g \times q \times \Psi} \quad \text{(cu. in.)} \qquad (8)$$

where D_a is the armature diameter in inches,
L_c is the frame length in inches (Fig. 38),
$\mathcal{B}_g$ is the apparent gap density in lines per sq. in.,
Ψ is the per cent. enclosure (= pole arc pole ÷ pitch), and
q is the ampere-conductors per in. ($= ZI_a/\pi D_a$).

60. The e.m.f. equation for all types of direct-current generators is:

$$E = Z\phi_a\left(\frac{\text{r.p.m.}}{60}\right)\left(\frac{\text{poles}}{\text{paths}}\right)10^{-8} \quad \text{(volts)} \qquad (9)$$

where E is the generated voltage between terminals,
Z is the total number of face conductors,
ϕ_a is the flux per pole which crosses the air-gap and is cut by the armature conductors,
r.p.m. is the armature speed in revolutions per min.
"paths" refer to the number of parallel circuits (electric) through the armature.

* Arnold, "Die Gleichstrommaschine," Vol. I and II; Hawkins and Wallis, "The Dynamo," Vol. II; Baily and Cleghorne, *Journal* of Inst. of Elec. Eng.; Vol. XXXVIII; Gray, "Electrical Machine Design;" Hobart, "Dynamo Design," Lamme, *Trans.* of A. I. E. E., Vol. XXX, p. 2359.

61. Another output equation, readily obtained from the e.m.f. equation, is given by

$$\frac{\text{watts}}{\text{r.p.m.}} = \left(\frac{ZI_a}{\text{paths}}\right)(\phi_a \times \text{poles})\frac{1}{60 \times 10^8} \qquad (10)$$

where (ZI_a/paths), called the **electric loading**, is the total number of ampere-conductors on the armature periphery. The larger the electric loading, the more copper and the less iron there is in the machine. The **magnetic loading,** as the quantity $(\phi_a \times \text{poles})$ is termed, is the total flux entering the armature. The larger the magnetic loading, the more iron and the less copper there is in the machine.

62. The gap density ($\mathfrak{B}_g$) is limited by the density at the bottom of the teeth; the greater the diameter, the less the tooth taper, and the higher the gap density for a given tooth density at the root. The relation between $\mathfrak{B}_g$ and D_a is given in Fig. 28.

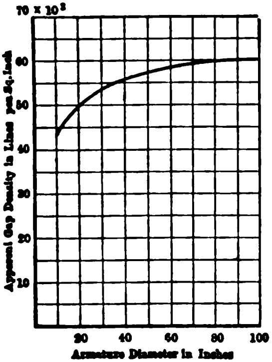

FIG. 28.

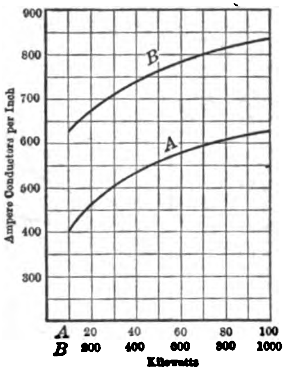

FIG. 29.

63. The ampere-conductors per in. (q) are limited by heating and by commutation. If q is large, the copper section must be large and the slots deep in order to keep down the temperature, but deep slots tend to cause sparking. It is found that q depends principally on the output of the machine, as shown in Fig. 29.

If the speed for a given output be increased, a smaller diameter can be used, and the peripheral velocity will not be greatly increased. Since the small machine is not so well ventilated as the large machine, see Fig. 31, the same value of q should be used in each case.

64. Relative cost factor. A certain ratio k, which is equal to the magnetic loading divided by the electric loading, will give the cheapest machine. Then

$$\frac{\text{watts}}{\text{r.p.m.}} = \text{a const. (electric loading) (magnetic loading.) Par. 61.}$$

$$= \text{a const. (electric loading)}^2 \qquad (11)$$

and the relation between the watts per rev. per min. and the electric loading, given in Fig. 30, may be used in preliminary design. The value of k is affected by the cost of labor and material and by the conditions of manufacture.

65. Number of poles. A pole of circular cross-section has the largest section for the shortest mean turn. If the pole be rectangular, then that with a square section has the largest area for the shortest mean turn. For economy in copper, the ratio of pole pitch to frame length will generally have a value between 1.1 and 1.7.

66. The armature ampere-turns per pole seldom exceed 7,500 in non-interpole machines. A larger number requires a long pole pitch, long end connections, a large number of exciting ampere-turns per pole, long poles, and a yoke of large diameter. For interpole machines, the main field need not be so strong relatively to the armature field as in non-interpole machines, and a reasonable limit for the armature ampere-turns per pole is 10,000.

67. A simple procedure for armature design is given in the following:

ZI_c, the number of ampere-conductors, is obtained from Fig. 30.
$q = ZI_c/\pi D_a$, the number of ampere-conductors per in., is obtained from Fig. 29.
D_a, the armature diameter, is next determined.
$\mathfrak{B}_g$ is obtained from Fig. 28.
L_c is found by substitution in Eq. 8, Par. 59.
p, the number of poles, is so chosen that the pole pitch divided by L_c equals 1.1 to 1.7.
ϕ, the flux per pole $= 0.7$ (pole pitch) $\times L_c \times \mathfrak{B}_g$, assuming the pole enclosure $= 0.7$.
Z, the number of armature conductors, is found from Eq. 9, Par. 60.

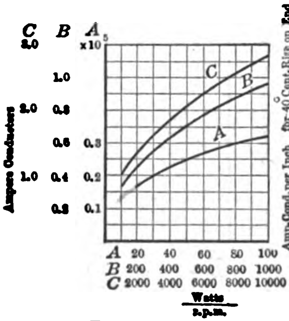

FIG. 30.

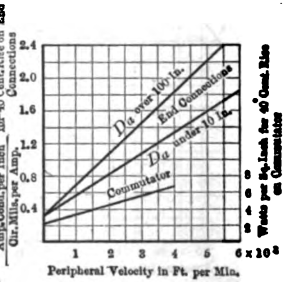

FIG. 31.

The winding is then so chosen that the reactance voltage will be below the desired limit. A two-circuit winding is the cheapest, and a winding with two turns per coil is cheaper than one with only one turn per coil.

68. The commutator diameter (D_c) is made equal to six-tenths of the armature diameter so as to have reasonably long "necks" (coil leads), but a peripheral velocity greater than 3,500 ft. per min. (1,070 m. per min.), is undesirable. One objectionable feature of the turbo-machine is that its commutator speed may run as high as 7,000 ft. per min. (2,140 m. per min.).

69. Brush design. The brush arc should not exceed the value $\left(\frac{\text{pole pitch}}{12}\right)\left(\frac{\text{comm. dia.}}{\text{arm. dia.}}\right)$. The volts drop per pair of brushes should be chosen to suit the reactance voltage (Par. 49). The energy at the brush contacts is limited to 35 watts per sq. in. (5.5 per sq. cm.) (Par. 40).

70. Example of armature design. It is required to determine approximate dimensions for a direct-current generator of the following rating: 400 kw., 240 volts, 1,670 amp., 200 rev. per min. The results, determined in consecutive order, are as follows:

ZI_c, ampere-conductors,	$= 1.33 \times 10^5$
q, ampere-conductors per in.,	$= 733$
D_a, armature diameter,	$= 58$ in.
B_g, apparent gap density,	$= 58,000$ lines per sq. in.
L_c, frame length,	$= 12$ in.

p, poles,		= 10	
τ, pole pitch,		= 18.2 in.	
ϕ, flux per pole,		= 8.8×10^6	
Z, total face conductors,	= 164	= 820	= 820
Winding,	1-turn ser.	2-turn mult. short pitch	1-turn mult. short pitch
S, commutator segments,	= 82	= 205	= 410
RV, reactance voltage,	= 13	= 3.1	= 1.5
D_c, commutator diameter,			= 35 in.
Brush arc,			= 0.91 in.
Volts per pair of brushes,			= 2
Amp. per sq. in. brush contact,			= 35
Brush length,			= 10.5 in.
F, commutator face,			= 13 in.

If the winding were series, or two-turn multiple, the reactance voltage would be too high and interpoles would be required.

Comparative designs should be worked out with both larger and smaller armature diameters and with different numbers of poles; then a choice should be made, and the design completed as below.

The final or **detailed design** is worked out in the following order. The probable number of total face conductors is 820, from the preliminary design. The number of slots per pole should be greater than fourteen and the total number of slots greater than 140; the nearest number of slots that will give an even number of conductors per slot is 200. Therefore

Slots	= 200
Conductors per slot	= 4
Coils	= 400
Commutator segments	= 400
Winding	1-turn multiple

Ampere-conductors per in. $= 167 \times 800/\pi \times 58 = 730$

$$\frac{\text{Ampere-conductors per in.}}{\text{Cir. mils per amp.}} = 1.3 \text{ for 40 deg. cent. rise, from Fig. 31.}$$

Cir. mils per amp.	= 560
Amp. per conductor at full load	= 167
Section of conductor	= 93,000 cir. mils = 0.073 sq. in.

Slot opening = 0.47 × (slot pitch) in large machines
= 0.52 × (slot pitch) in small machines

For a first approximation, therefore

Slot pitch = 0.91 in.

Slot opening = 0.43 in.

0.064 width of slot insulation (Fig. 47)
0.04 clearance between coil and core
0.326 available space for copper and conductor insulation.

Use flat strip, as in Fig. 47, with two conductors in the width of the slot; make the strip 0.14 in. wide and insulate it with half-lapped cotton tape.

Depth of conductor = 0.073/0.14 = 0.52 in.; increase this to 0.55 in. to allow for rounding of the corners.

Slot depth is found as follows:

0.55 = depth of each conductor
0.024 = insulation of each conductor
0.084 = depth of slot insulation (Fig. 47)
0.658 = depth of each insulated coil
2 = number of coils in depth of slot
1.316 = depth of coil space
0.2 = thickness of stick at top of slot
1.516 = necessary slot depth; make it 1.6 in.

The tooth flux density should now be checked to make sure that it is not too high, see Par. 123, and the internal diameter of the armature made such that the flux density in the armature core shall not exceed 85,000 lines per sq. in.

71. Effect of interpoles. When interpoles are used, the reactance voltage is no longer a limiting factor in the design, so that deep slots may be used and a large amount of copper put on each inch of the periphery. For interpole machines, the value of q, the ampere-conductors per in., will generally be 20 per cent. greater than given in Fig. 29. The commutating fringe under the pole tip is not used, so that the ratio of the exciting ampere-turns per pole for gap and teeth to the armature ampere-turns per pole, which is seldom less than 1.2 for non-interpole machines, is generally made about 0.8 for similar machines with interpoles. There is therefore a large saving in field copper, and in pole and yoke material.

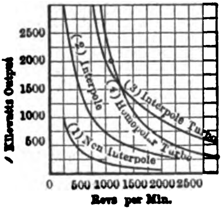

FIG. 32.—Maximum output curves.

72. Speed limitations in design.* If the peripheral velocity of a machine is fixed, the output can be increased only by increasing the frame length, the number of conductors, or the current per conductor, all of which increase the reactance voltage; so that, after a certain output has been reached, interpoles must be supplied or the peripheral velocity increased.† Fig. 32 shows the maximum output that can be obtained for a given speed, the peripheral velocity being taken as 6,000 ft. per min. (1,830 m. per min.) for machines of ordinary construction, and 15,000 ft. per min. (4,600 m. per min.) for turbo-machines. The high-speed turbo-machine is not too satisfactory as regards efficiency, commutation, and heating and the tendency is to gear a high-speed turbine to a moderate speed generator through a **Melville-Macalpine reduction gear.**

FIELD DESIGN

73. The magnetic circuit is well shown in general in Fig. 38, where the closed dot-and-dash line indicates the complete path through one pair of poles, two air-gaps, the armature and the yoke, all in series. There are as many paths similar to this one, in a multipolar machine, as there are poles. This path, of course, is the path of the useful flux, and does not take into consideration the leakage flux.

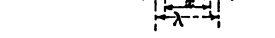

FIG. 33.

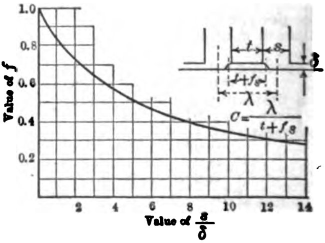

FIG. 34.

FIGS. 33 AND 34.—Fringing constant.

74. The fringing constant.‡ The actual air-gap area per pole equals $(\psi_T L_c)x/\lambda$, Par. 75, where λ/x (Fig. 33) is the fringing constant C. Now $x = t + fs$ where f depends on the slot width s and on the air-gap clearance δ and may be obtained from Fig. 34. Then

$$C = \lambda/x = (t+s)/(t+fs) \tag{12}$$

For the machine shown in Fig. 35:

$s/\delta = 0.43/0.3 = 1.44$
$f = 0.78$ from Fig. 34.
$C = (0.48+0.43)/(0.48+0.78 \times 0.43) = 1.12$

* Hobart and Ellis. "High Speed Dynamo-electric Machinery."
† Gray. "Electric Machine Design," p. 142.
‡ Carter, *Electrical World and Engineer*, Nov. 30, 1901; Hele-Shaw, Hay and Powell; *Jour.* of Inst. of Elec. Eng., Vol. XXXIV, p. 21.

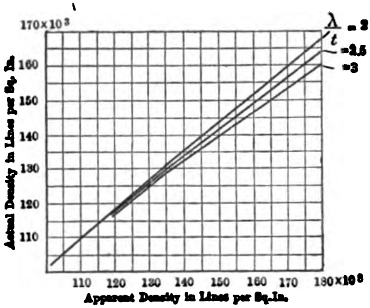

Fig. 36.—Armature tooth densities.

ϕ_m, the total flux per pole, consists of the flux ϕ_a which crosses the air-gap and is cut by the armature conductors, and the leakage flux ϕ_e which crosses between the poles but does not enter the armature. The ratio ϕ_m/ϕ_a, called the leakage factor, is greater than unity; its value may be calculated with a fair degree of accuracy if the dimensions of the magnetic circuit are known, but for direct-current machines it is usual to assume a value of leakage factor and, for a first approximation, the following table may be used for the type of machine shown in Fig. 38.

	Leakage factor
Four-pole machines up to 10 in. armature diameter....	1.25
Multipolar machines between 10 in. and 30 in. diameter..	1.2
Multipolar machines between 30 in. and 60 in. diameter..	1.18
Multipolar machines greater than 60 in. diameter......	1.15

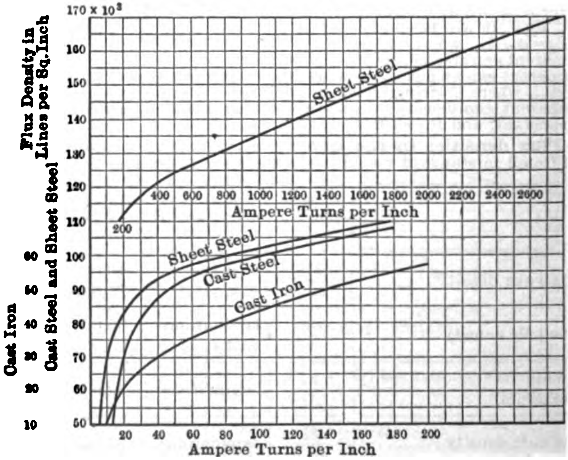

Fig. 37.—Magnetization curves.

80. Calculation of the leakage factor.* Fig. 39 shows part of a machine with a large number of poles. The total leakage flux per pole is

$$\phi_e = \phi_1 + \phi_2 + \phi_3 + \phi_4 \qquad (13)$$

*The derivation of these formulæ is given in Gray, "Electrical Machine Design," page 51, for other cases see Hawkins and Wallis, "The Dynamo," Vol. I, p. 471.

where

$$\phi_1 = 13k(nI)_{g+t}\ \frac{L_s h_s}{l_1} \qquad (14)$$

$$\phi_2 = 19k(nI)_{g+t}\ h_s \log_{10}\left(1 + \frac{\pi W_s}{2l_1}\right) \qquad (15)$$

$$\phi_3 = 6.5k(nI)_{g+t}\ \frac{L_p h_p}{l_3} \qquad (16)$$

$$\phi_4 = 9.5k(nI)_{g+t}\ h_p \log_{10}\left(1 + \frac{\pi W_p}{2l_3}\right) \qquad (17)$$

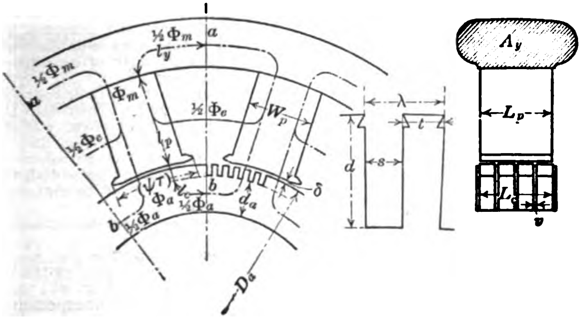

Fig. 38.—The paths of the main and the leakage fluxes.

and k is equal to unity for inch units and to $1/2.54 = 0.3937$ for centimeter units. For a given value of ϕ_a, the flux crossing the air-gap, the value of $(nI)_{g+t}$, the necessary ampere-turns per pole for gap and teeth, may be found; and, substituting this value in the above formulas, the corresponding value of ϕ_e may be found. The leakage factor $= 1 + \phi_e/\phi_a$.

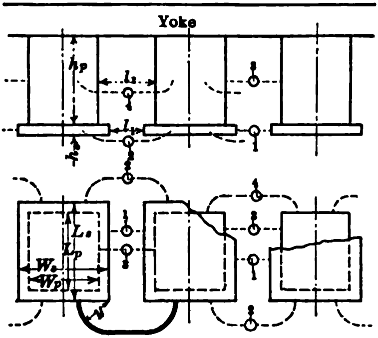

Fig. 39.—The leakage paths.

81. Calculation of field ampere-turns per pole. The total ampere-turns per pole required to establish the necessary flux in the magnetic circuit may be analysed into a series of components. The natural subdivision follows the several different members or elements which go to make up the complete circuit. These would include the yokes, the field cores, the air-gaps, the armature teeth and the armature core. Since the field poles are structurally duplicates of each other, except where interpoles are used, it is natural to confine the calculations of required ampere-turns to a single field pole. Fig. 40 shows the unit magnetic circuit for a multipolar machine, or that part of the total magnetic structure which corresponds to one field pole and simply needs repeated application to build up the whole structure. This unit magnetic circuit comprises one complete field core, one complete air-gap, one complete group of armature teeth under a single pole face, two half-yokes in parallel and two half-armature cores in parallel. The total number of ampere-turns, at no load, may be expressed as

$$nI = (nI)_y + (nI)_c + (nI)_p + (nI)_t + (nI)_g \qquad (18)$$

where the several quantities in the formula are as follows:

$(nI)_y$ represents the number of ampere-turns required to establish the flux $\phi_m/2$ through a length of yoke equal to l_y in Fig. 38; this length is one-half the total length of the yoke circuit from pole to pole. In a single-yoke machine, such as the horse-shoe bipolar type, with two field coils, the full value of flux, or ϕ_m, should be assumed instead of $\phi_m/2$.

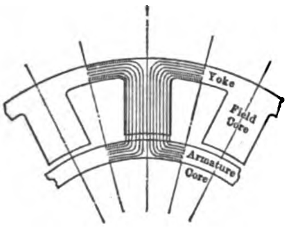

Fig. 40.—Unit magnetic circuit of multipolar machine.

$(nI)_c$ represents the number of ampere-turns required to establish the flux $\phi_a/2$ through a length of armature core equal to l_c in Fig. 38.

$(nI)_p$ represents the number of ampere-turns required to establish the flux ϕ_m through the field core, which has a length of l_p as shown in Fig. 38.

$(nI)_t$ represents the number of ampere-turns required to establish the flux ϕ_a through one set of armature teeth under one pole face.

$(nI)_g$ represents the number of ampere-turns required to establish the flux ϕ_a through one air-gap.

The calculation of ampere-turns in each case, except for the air-gap, is carried out by taking different values of flux density $\mathcal{B}$ and obtaining the proper value of ampere-turns per in. from the curves in Fig. 37; the latter is then multiplied in each instance by the length of the corresponding portion of the magnetic circuit, in inches.

The required number of ampere-turns for the air-gap, in terms of inch units, is given by

$$(nI)_g = \frac{C\,\mathcal{B}_g\delta}{3.20} \qquad (19)$$

and in terms of centimeter units, by

$$(nI)_g = \frac{C\,\mathcal{B}_g\delta}{1.26} \qquad (20)$$

The quantity C is the fringing constant (Par. 75).

82. Excitation for tapered teeth. When the armature teeth are tapered, the flux density is not uniform throughout the total depth of the tooth. The tooth length must therefore be divided into a number of short lengths, the flux density and the corresponding ampere-turns per in. length found in each case, and the average value multiplied by the tooth length to give $(nI)_t$. This process can be shortened by use of the series of curves shown in Fig. 41; if k, the ratio between the actual flux densities at the bottom and at the top of the tooth, is known, the average ampere-turns per in. can be found directly.

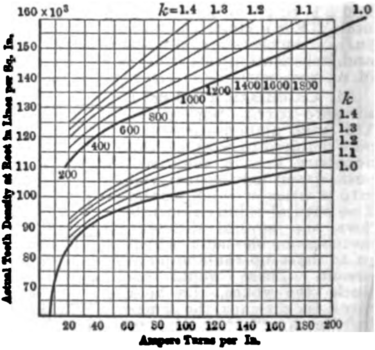

Fig. 41.—Magnetization curves for tapered teeth.

83. Calculation of the no-load saturation curve. Taking the example of the ten-pole machine shown in Fig. 35, the following calculations must be carried out in order to obtain a series of points from which to plot the no-load saturation curve.

L_n = the net axial length of armature core = $0.9\,(12 - 3 \times 0.5) = 9.45$ in.
A_y = the yoke area = 136 sq. in.

87. The minimum length of field coil to give the necessary radiating surface for cooling is given by the formula*

$$L_f = \frac{n_f I_f}{1{,}000}\sqrt{\frac{\text{length of mean turn}}{\text{external periphery} \times \text{watts per sq. in.} \times d_f \times sf \times 1.27}} \quad (22)$$

where L_f is the length of the field coil in inches, Fig. 42,
d_f is the depth of the field coil in inches,
sf is the space factor of the winding and may be found from Fig. 43.

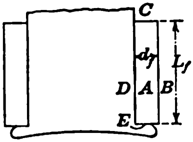

FIG. 42.—Field coil length.

The allowable watts per sq. in. of surface B, Fig. 42, may be found from Fig. 44.

88. The weight of field coil for a given machine is equal to $\sqrt{d_f}$ multiplied by a constant. The larger the value of d_f, the shorter the length L_f, the smaller the radiating surface and the lower the permissible loss in the coil. Since the section of the field coil wire is fixed (because it depends only on the ampere-turns and the voltage per coil, Par. **86**), a lower permissible loss can be obtained only by the use of a smaller current I_f, a larger number of turns n_f, and therefore a more expensive coil. It must not be overlooked, however, that when d_f becomes smaller and the field coil becomes cheaper, the value of L_f increases and therefore the cost of the poles and the yoke increases. The most economical value for d_f must be determined by trial; an average value is 2 in.

89. Example of field system design. The armature of a ten-pole, 240-volt no-load, 240-volt full-load, 1,670 amp., 200 r.p.m. generator is shown drawn to scale in Fig. 35; it is required to design the field system, which is not supposed to be given.

The following data are taken from Par. **83**.

$\phi_m = 10.5 \times 10^6$
$\phi_a = 9 \times 10^6$
$nI_t = 2{,}080$
$\mathcal{B}_g = 59{,}000$ lines per sq. in.

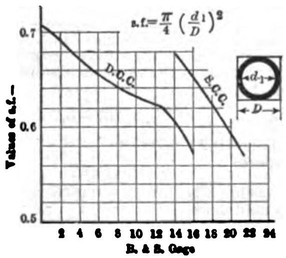

FIG. 43.—Space factor for wire.

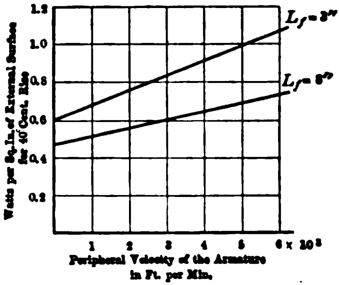

FIG. 44.—Field-coil heating constant.

(a) Calculation of the air-gap clearance.

$(nI)_g + (nI)_t = 1.2$ times the armature ampere-turns per pole, from Par. **85**,
$= 1.2\ (800 \times 167/2 \times 10) = 8{,}100$
$(nI)_t = 2{,}080$ see above
$(nI)_g = 6{,}020$,
$C\delta = 3.2 \times 6{,}020/59{,}000$, from Par. **81**,
$= 0.328$ in.,
$C = 1.12$ from Fig. 34,
$\delta = 0.29$ in. (make it 0.3 in.).

* Gray. "Electrical Machine Design," p. 66.

(b) Calculation of approximate dimensions for the magnetic circuit.

Assume the no-load excitation $= 1.25[(nI)_g + (nI)_t]$
$= 10{,}100$ ampere-turns per pole.

Next find L_f for the shunt coil from eq. 22 (Par. 87), where d_f is assumed to be 2 in.; sf is assumed to be 0.6, from Fig. 43; the allowable watts per sq. in. $= 0.6$ from Fig. 44; the external periphery of the field coil equals 1.2 times the length of the mean turn, approximately; therefore $L_f = 10$ in., approximately; the latter should be increased 30 per cent. to allow for the series coil.

The pole area $= \phi_m/\mathfrak{B}_p = 10.5 \times 10^6/95{,}000 = 112$ sq. in.

The yoke area $= \phi_m/2\mathfrak{B}_y = 10.5 \times 10^6/2 \times 40{,}000 = 132$ sq. in.

(c) Saturation curves. From these dimensions the magnetic circuit is drawn to scale and the no-load and the full-load saturation curves are determined and plotted. For the machine in question, the curves are given in Fig. 19.

(d) Design of the shunt coils. The details are as follows:

The no-load excitation $= 9{,}990$ ampere-turns per pole, Fig. 19, or Par. 82.

E_f, the volts per coil, equals $0.8 \times 240/10 = 19$ volts; this leaves 20 per cent. of the terminal voltage to be absorbed by the field rheostat.

M, the mean turn, equals 53 in. The external periphery equals 61 in.

The size of wire equals $9{,}990 \times 53/19$, from Par. 88, or 28,000 cir. mils. The proper size of wire is No. 5.5 A.W.G., a special size between Nos. 5 and 6, which has a section of 29,500 cir. mils and a diameter when insulated with double cotton of 0.19 in. When such odd sizes are not available, the coil can be made with the proper number of turns of No. 5 wire in series with the proper number of turns of No. 6, so as to have a field coil of the proper resistance.

The number of layers of wire in a 2-in. depth equals $2/0.19 = 10$.

The number of turns per layer in a 10-in. length equals $10/0.19 = 53$.

n_f, the number of turns per coil, equals 530.

I_f, the shunt current, equals $9{,}990/530 = 18.8$ amp.

The current density equals $29{,}500/18.8 = 1{,}570$ cir. mils per amp.

(e) Design of the series coils. The details are as follows:

Excitation at full load and normal voltage	= 13,400 ampere-turns, Fig. 19.
Shunt excitation at normal load	= 9,990 ampere-turns.
Series ampere-turns per pole at full load	= 3,410
Series turns per pole	= 2.5
Series current = 3,410/2.5	= 1,370 amp.
Current in series shunt	= 300 amp.

The current density is taken 20 per cent. greater than in shunt coils because the series coils are better ventilated.

Current density	= 1,300 cir. mils per amp.
Size of wire = 1,300 × 1,370	= 1,780,000 cir. mils = 1.4 sq. in.
Resistance of 2.5 turns	$= 7.4 \times 10^{-6}$ ohms.
Loss in one series coil	$= 1{,}370^2 \times 7.4 \times 10^{-6} = 140$ watts.

The permissible watts per sq. in. is taken 20 per cent. greater than in shunt coils.

Watts per sq. in.	= 0.72
Necessary radiating surface	= 140/0.72 = 195 sq. in.
Length L_f of series coil	= 195/61 = 3.2 in.
Depth of wire = wire section/L_f	= 0.45 in.

Size of wire = 3 strips (3.2 in. × 0.15 in.).

GENERAL DESIGN AND CONSTRUCTION

90. Type of construction for small machines. Fig. 45 shows the type of construction generally adopted for machines up to 100 h.p. at 600 rev. per min.

91. The armature core (M in Fig. 45) is built of laminations of sheet steel 14 mils (0.35 mm.) thick, which are separated from one another by layers of varnish and have slots F punched to carry the armature coils G.

92. A marking notch is punched at one side of the key-way K (Fig. 45) and these notches must line up when the punchings are assembled, to ensure that the burrs at the edges all lie in the same direction.

93. Brass vent segments (*P* in Fig. 45), about ⅜ in. (1 cm.) wide, separate the core into sections about 3 in. (7.5 cm.) wide. The core and the vent segments are clamped between end heads *N* which carry coil supports *L* attached by arms shaped like fans. The coils are held in place against centrifugal force by steel band wires.

94. The poles (*B* in Fig. 45), are of circular cross-section in order to give the required area for the magnetic flux with the minimum length of mean turn of field coil *A*. They are made of forged steel and have laminated pole faces *E* made of sheet steel 25 mils (0.63 mm.) thick.

95. End play is provided for by making the axial length of the pole face ⅜ in. (1 cm.) shorter than that of the armature core. This enables the revolving part of the machine to oscillate axially and so prevent the journals, bearings and commutator from wearing in grooves.

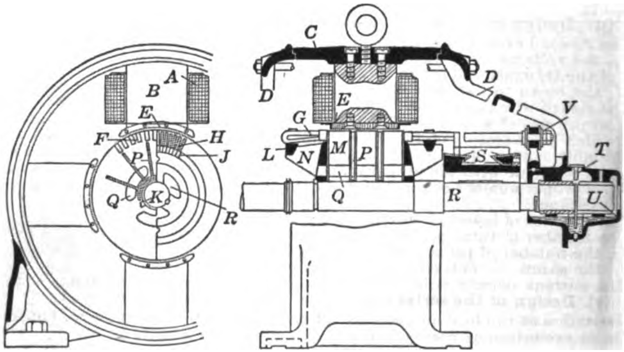

FIG. 45.—Small direct-current motor.

96. The yoke (*C* in Fig. 45) carries the bearing housings *D* which stiffen the whole machine. The housings can be rotated with respect to the yoke through 90 deg. or 180 deg., so that the machine may be mounted either on a wall or a ceiling. This rotation of the bearings is necessary because the machine is lubricated by **oil rings** and the **oil wells** must always be below the shaft.

97. The commutator segments (*J* in Fig. 45) are of hard-drawn copper and have a wearing depth of from 0.5 in. (1.25 cm.) on a 5-in. (12.5-cm.) commutator to 1.0 in. (2.5 cm.) on a 50-in. (125-cm.) commutator. The commutator shell, as the clamps and their supports are called, is provided with air passages *R* which help to keep the machine cool.

98. The bearing construction is shown in detail in Fig. 45. The projection *T* on the oil-hole cover keeps the oil ring from rising and resting on the bushing; the oil slingers prevent the oil from creeping along the shaft. The liner of special bearing metal is given a snug fit in the bearing shell, and can be removed when worn and another put in its place. A small overflow at *U* makes it impossible to fill the bearing too full.

99. The brushes are carried on studs which are insulated from the rocker arm *V*. The rocker arm is carried on a turned seat on the bearing and can be clamped in a definite position.

100. Type of construction for large engine-type generators. For large direct-connected engine-type units the type of construction shown in Fig. 46 is generally adopted. The **armature core** is built of segments carried by dovetails on the spider. The segments of alternate layers overlap so as to break joints and give a solid core. The **poles** are of rectangular cross-section and are built of laminations 25 mils (0.63 mm.) thick, of the shape shown at *P*, and assembled so that the rounded pole tips point in opposite directions and a saturated tip is produced which helps commutation. The **shaft, base and bearings** are generally supplied by the engine builder, so that the commutator must be supported from the armature spider; the **brush rigging** must also be supported by the machine.

101. Mechanical design.* The **yoke** should be heavy and, in engine-type units, is often made with a large section of cast iron rather than a smaller section of cast steel; it must be stiff enough to prevent undue sagging even when there is a large unbalanced magnetic pull. The **shaft** should be stiff enough to limit the deflection to 5 per cent. of the air-gap clearance and, along with the **spider**, should have a **factor of safety** of 12 to take care of short-circuits.

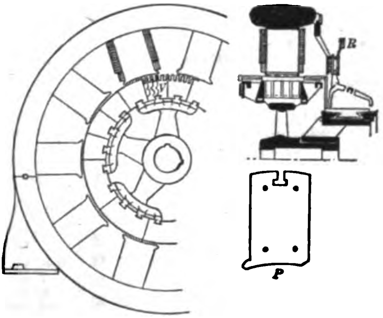

Fig. 46.—Large engine-type generator.

102. Unbalanced magnetic pull.† If the armature of a machine is x cm. out of centre, the flux density under the poles where the gaps are smallest will be greater than under the poles where the gaps are largest, and the pull on one side of the machine will be greater than on the other by an amount

$$kS\mathfrak{B}^2\frac{x}{\delta} \qquad (23)$$

where $\mathfrak{B}$ is the effective gap density,
$S = \pi D_a L_a$, the total armature-core surface,
x = armature displacement,
δ = length of air-gap,
$k = \dfrac{1}{7.2\times 10^7}$ if inch units are used and the pull is in pounds,
$k = \dfrac{1}{2.47\times 10^7}$ if centimeter units are used and the pull is in kilograms.

The above formula holds for a two-circuit winding; if a multiple winding is used, the e.m.fs. in the different paths will be unequal, and circulating currents will flow tending to keep the flux densities under the poles nearly equal, so that the pull will be less than that given by the formula.

INSULATION

103. General requirements. A good insulator for electrical machinery must have high dielectric strength and high electrical resistance, should be tough and flexible, and should not be affected by heat, vibration, or other operating conditions.

104. The insulating materials generally used for revolving machinery are as follows:

(a) **Micanite,** which is easily bruised and should be protected by a tougher material.

(b) **Varnished cloth,** which must be carefully handled to prevent cracking or scraping of the varnish film.

(c) **Paper,** which is chosen for its toughness and should be baked dry when tested.

* Livingstone, "Mechanical Design and Construction of Commutators;" Livingstone, "Mechanical Design and Construction of Generators;" Hawkins and Wallis, "The Dynamo;" Hobart and Ellis, "Armature Construction."

† Behrend, B. A. *Trans.* A. I. E. E., Vol. XVII, p. 617.

120. Intermittent ratings. Suppose that a machine is operating on a continuous cycle, x min. loaded and y min. without load. The temperature of the machine will vary during each cycle between the values θ_x and θ_y (Fig. 50), where the temperature increase in the interval x is equal to the temperature decrease in the interval y. Under these service conditions, θ_x, the highest operating temperature, is less than θ_m, the maximum temperature that would be obtained on continuous operation under load. For this service, therefore, a machine may be designed with higher copper and iron densities than otherwise it would have if designed for the same load but for continuous operation. It must be noted that, if the machine is stationary during the period of no load, the drop in temperature is small, and the rating of the machine cannot be made much greater than if it were operating on continuous load.

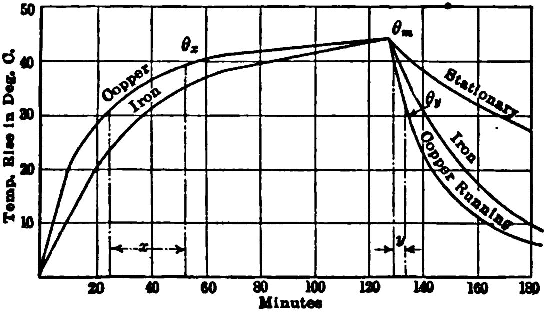

FIG. 50.—Heating and cooling curves of a direct-current motor.

121. Heat conduction in the armature core. The hottest part of the core is at A, Fig. 51; consequently the heat has to be conducted along the laminations and dissipated from surfaces B, and also across the laminations and layers of varnish and dissipated from surfaces C. The conductivity along the laminations is about fifty times that across the laminations, but the end surface of the laminations is small compared with the surface of the vent ducts, so that **radial ducts** are effective and necessary.

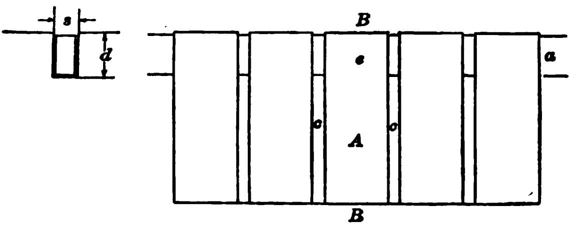

FIG. 51.—Heat conduction in armature core.

122. Flux density and peripheral velocity. The peripheral velocity of a machine in ft. per min. is

$$v = 10 \times \text{pole pitch in inches} \times \text{frequency in cycles per sec.}$$

Hence for a given frequency, the peripheral velocity of the machine is proportional to its pole pitch. The flux in the armature core of a direct-current machine is always alternating, and the **frequency** is equal to the product of the revolutions per sec. and the number of pairs of poles (interpoles excluded).

130. Semi-enclosed machines have the frame openings screened with perforated sheet metal. This prevents free circulation of air through the machine and causes the temperature to rise, on an average, about 20 per cent. higher than if operating as an open machine.

131. In totally enclosed machines, the temperature rise of the core and the coils is proportional to the total loss in the machine (neglecting bearing friction); it is independent of the distribution of this loss and may be found from Fig. 54. The rating as an enclosed machine will be considerably lower than that as an open machine. A casing around the machine makes it equivalent to an enclosed machine with an extra large radiating surface; the casing should be of heat-conducting material such as sheet metal and should not be of wood. Fans on the armature help in the cooling of enclosed machines by blowing the hot air against the casing.

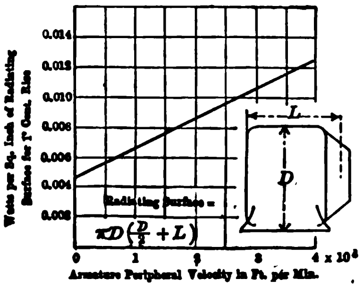

FIG. 54.—Temperature rise of enclosed motors.

132. Forced ventilation,* whereby air is blown through a machine by an external fan or by a fan attached to the armature, allows the machine to have the same rating as it would have when operating as an open machine; 100 cu. ft. (2.8 cu. m.) of air per kw. loss should be supplied for a temperature rise of the windings and the core of 40 deg. cent.

EFFICIENCY AND LOSSES

133. The iron losses† consist of hysteresis and eddy-current losses in the armature teeth and core; these may be kept small by the use of special grades of iron (Sec. 4) and by the use of thin and well-varnished laminations. There are losses also in the end heads and spider due to leakage flux; losses due to filing of the slots which short-circuits the laminations; losses due to the fact that the core flux takes the shortest path and crowds in behind the teeth, so that the core density is not uniform; and pole-face losses‡ due to the movement of the armature teeth past the faces of the poles. In order to minimize the pole-face losses, the pole faces should be laminated if the slot opening is greater than twice the air-gap clearance.

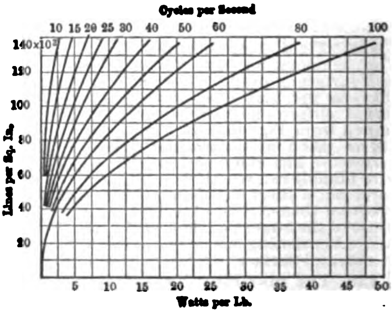

FIG. 55.—Iron-loss curves for direct-current machines.

134. The iron losses increase with the load if the flux per pole is kept

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* Gray. "Heating of Pipe-ventilated Machines," London Electrician, Jan. 16, 1914.

† Thornton. "Distribution of Magnetic Induction in Armatures," *Journal* of Inst. of Elec. Eng., Vol. XXXVII, p. 125.

‡ Wall and Smith. "Pole-face losses," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 577.

constant, because of field distortion, as the densities are then very high under alternate pole tips.

135. The individual iron losses cannot be calculated separately, and curves such as those in Fig. 55, obtained by tests on completed machines, must be used as follows:

Taking the machine shown in Fig. 35:	
Actual maximum tooth density	= 150,000 lines per sq. in.
Average core density	= 84,000 lines per sq. in.
Weight of armature teeth	= 385 lb.
Weight of armature core	= 2,300 lb.
Frequency = $p \times$ r.p.m./120	= 16.6 cycles per sec.
Tooth loss per lb.	= 6 watts, from Fig. 55.
Core-loss per lb.	= 1.8 watts.

Total iron loss = $(385\times 6)+(2{,}300\times 1.8) = 6{,}450$ watts.

136. The armature copper loss is given by the formula

$$\frac{ZLI_c^2}{\text{c.m.}} \qquad \text{(watts)} \qquad (27)$$

where Z is the number of conductors, L is the length of one conductor in in. (Fig. 56), I_c is the current in each conductor, or the total current divided by the number of armature paths, and c.m. is the cross-section of each conductor in cir. mils.

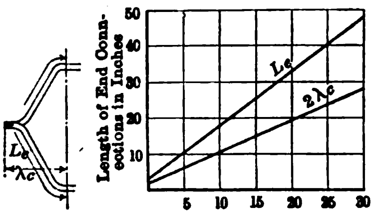

FIG. 56.—Dimensions of coils.

137. The shunt excitation loss equals E_tI_f watts, where E_t is the terminal voltage and I_f the shunt current. In a generator, about 20 per cent. of this loss will be in the shunt-field rheostat.

138. The series excitation loss equals $I_a^2R_s$ watts, where I_a is the total current in the machine and R_s is the combined parallel resistance of the series field coils and the series shunt.

139. The brush contact resistance loss has been discussed in Par. 38 and equals E_bI_a watts, where E_b is the voltage drop per pair of brushes and I_a is the total current of the machine.

140. The bearing friction loss for moderate-speed bearings with ring lubrication and light machine oil is given by the formula

$$0.8dl\left(\frac{v}{100}\right)^{\frac{3}{2}} \qquad \text{(watts)} \qquad (28)$$

where d is the bearing diameter in inches, l is the bearing length in inches, and v is the rubbing velocity in feet per min.

141. The brush friction loss, assuming the coefficient of friction to be 0.28 and the brush pressure to be 2 lb. per sq. in., is given by the formula

$$1.25\,A\frac{V}{100} \qquad \text{(watts)} \qquad (29)$$

where A is the total brush rubbing surface in square inches, and V is the rubbing velocity in feet per min. The brush pressure is generally less than 2 lb. per sq. in. (0.14 kg. per sq. cm.) except for railway motors, where it may be twice as large in order to keep the contact firm in spite of the vibration of the machine.

142. The windage loss cannot be accurately calculated and, with peripheral velocities less than 6,000 ft. per min., is so small that it may be neglected.

143. The efficiency of a generator is given by the expression

$$Eff_g = \frac{\text{output}}{\text{output}+\text{losses}} \qquad (30)$$

ance is reduced below this value, the machine becomes completely demagnetized (except for the residual magnetism), and the terminal voltage and the armature current both become practically zero.

147. When a shunt generator is short-circuited the machine is demagnetized and the current becomes negligible (Fig. 59). At the instant of short-circuit, however, the flux in the pole cannot reduce suddenly to zero, and the voltage due to this flux will send a large current through the circuit; at the end of a few seconds, however, the current will have become zero.

148. Instability of unsaturated shunt generators. If the no-load, normal voltage point on the saturation curve is *a*, Fig. 60, below the point of saturation, then the overload capacity of the machine will be small, and the change of voltage with load will be large. Furthermore, a slight decrease in speed will cause a decrease in the generated voltage, which will decrease the shunt field current and cause the voltage to drop still further. If *ac* is tangent to the saturation curve at point *a*, then the ratio of voltage change to the change of speed producing it, is *ab/oc*.

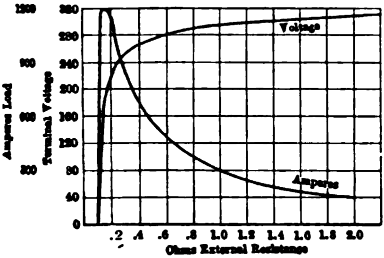

FIG. 59.—Shunt characteristics on a resistance base.

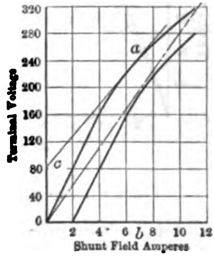

FIG. 60.—No-load and full-load saturation curves.

149. The regulation of electrical machinery is defined in the A. I. E. E. Standardization Rules (Sec. 24). The **voltage regulation** of a separately excited generator is *bc/bh* (Fig. 58); for a shunt generator it is *ec/eh* (Fig. 58); for a flat-compounded generator it is *fg/ch*; and for an overcompounded generator it is *mn/hk* (Fig. 58). The **current regulation** of a constant-current generator depends largely on the type of regulator used and is defined as the ratio of the maximum difference of current from the rated load value (occurring within the range from rated load to short-circuit, or minimum limit of operation) to the rated load current.

150. To maintain the terminal voltage constant, shunt generators may be operated with an adjustable resistance in series with the shunt field coils; this resistance may be reduced automatically, or by hand, as the load increases. Automatic regulators for this purpose generally consist of a solenoid connected across the terminals of the machine, acting as a relay which will open or close an operating circuit and vary the resistance of the field circuit as required.

151. The Tirrill Regulator, described in Sec. 10, periodically short-circuits part of the field rheostat by means of light vibrating contacts of small inertia; the time during which the rheostat is short-circuited or is active determines the average field current and therefore the voltage of the machine.

152. Compound machines, operated without a regulator, keep the voltage approximately constant from no load to full load because, due to the series field coils, the total excitation increases with the load; the machine is then said to be **flat-compounded.** By the use of an extra strong series field, the voltage may be made to increase with the load; the machine is then said to be **overcompounded.** Curves 3 and 4, Fig. 58, show the characteristic curves for compound generators. The compounding of a machine may be reduced by shunting the series field coils with a resistance; this resistance is called a "series shunt."

153. Series generators. Curve 1, Fig. 61, shows the relation between voltage and current if there is no armature resistance or armature reaction. This is really the no-load saturation curve of the machine and is determined by separately exciting the field coils so that no current flows in the armature. Curve 2 shows the actual relation between terminal voltage and load current.

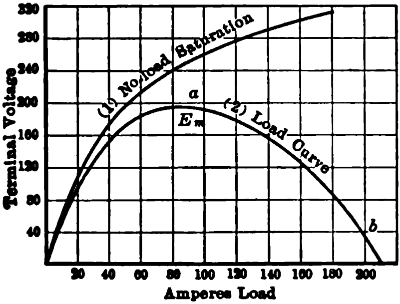

FIG. 61.

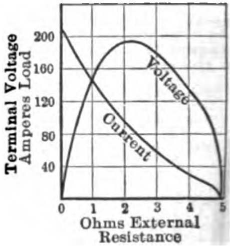

FIG. 62.

FIGS. 61 AND 62.—Characteristic curves of a series generator.

The total voltage drop consists of that portion due to the decrease in flux caused by armature reaction, and that required to send the current through the armature, brushes and series field coils.

154. Critical resistance of series generators. The values of current in a series generator and the resistance of the external circuit are plotted in Fig. 62. The critical resistance of the machine is 4.9 ohms; with an external resistance greater than this, the machine will not excite, or build up.

155. Series machines were formerly used as **constant-current generators** for the operation of **arc lamps** in series, but few of them are now in service. Specially designed machines were operated with automatic regulators so as to have the line *ab* (Fig. 61) nearly vertical, and the current practically constant for all voltages up to E_m (Fig. 61).

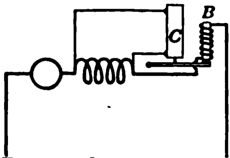

FIG. 63.—Constant-current regulator.

156. The Brush regulator, shown diagrammatically in Fig. 63, has been used as a **constant-current regulator.** The carbon pile *C* has the property that its resistance decreases through a wide range as the pressure between the ends increases. If the current in the external circuit increases, the pull of the solenoid *B* also increases, and the carbon pile is compressed and its resistance reduced so that it shunts more of the current from the series field coils; the flux in the machine is therefore reduced and the voltage drops until the current reaches the value for which the regulator was set. Other types of constant-current regulators are described in Par. **209** and **212.**

MOTOR CHARACTERISTICS AND REGULATION

157. Counter e.m.f. It was pointed out in Par. **6** that, since a motor armature revolves in a magnetic field, an e.m.f. is generated in the conductors which is opposed to the direction of the current and is called the counter e.m.f. The applied e.m.f. must be large enough to overcome the counter e.m.f. and also to send the armature current I_a through R_m, the resistance of the armature winding, the brushes and the series field coils; or

$$E_a = E_b + I_a R_m \quad \text{(volts)} \quad (32)$$

where E_a is the applied e.m.f. and E_b, the counter e.m.f., is given by Eq. 9, Par. 60.

158. Shifting of the brushes. It may be seen from Fig. 2 that, while the brushes of a generator are shifted forward in the direction of motion to help commutation, those of a motor have to be shifted backward. In each case, however, the armature reaction reduces the flux per pole.

159. The torque equation. The torque of a motor is proportional to the number of conductors on the armature, to the current per conductor and to the total flux in the machine. The formula for the torque is

$$\text{torque} = 0.1175\, Z\phi I_a \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(lb. at 1 ft. rad.)} \quad (33)$$

where Z is the total number of armature conductors, ϕ is the total flux per pole, and I_a is the armature current taken from the line.

160. The speed equation is

$$E_b = E_a - I_a R_m = Z\phi \left(\frac{\text{r.p.m.}}{60}\right)\left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(volts)} \quad (34)$$

or

$$\text{r.p.m.} = 60 \left(\frac{E_a - I_a R_m}{Z\phi}\right)\left(\frac{\text{paths}}{\text{poles}}\right) 10^{8} \quad (35)$$

For a given motor the number of armature conductors Z, the number of poles, and the number of armature paths, are constant. The torque can therefore be expressed as

$$\text{torque} = \text{a constant} \times \phi I_a \quad (36)$$

and the speed, likewise, is expressed

$$\text{r.p.m.} = \text{a constant} \times \left(\frac{E_a - I_a R_m}{\phi}\right) \quad (37)$$

161. Shunt-motor speed and torque. In this case E_a, R_m and ϕ are constant, and the speed and torque curves are shown in curves 1, Fig. 64; the effective torque is less than that generated, by the torque required for the windage and the bearing and brush friction. The drop in speed from no load to full load seldom exceeds 5 per cent.; indeed, since ϕ, the flux per pole, decreases with increase of load, due to armature reaction, the speed may remain approximately constant up to full load.

162. Effect of field-coil heating on speed. The field-coil resistance increases and the exciting current decreases about 20 per cent. as the field coils increase in temperature. The flux per pole is therefore less and the speed greater when the machine is hot than when cold, unless a field rheostat is manipulated to keep the exciting current constant. The effect of change of exciting current on speed is minimized by having the magnetic circuit well saturated, so that a large change in current will produce only a small change in flux.

163. Variable-speed operation of shunt motors can best be investigated by means of Eq. 37, Par. 160. In order to increase the speed, ϕ must be reduced by inserting a resistance in series with the field coils. In order to decrease the speed below the value which it has with full field, the quantity $(E_a - I_a R_m)$ must be decreased by placing a resistance in series with the armature. The latter resistance must be able to carry the armature current, but the starting resistance must not be used for this purpose since it is designed for starting duty only, and would burn out if allowed to carry full-load current for more than a few minutes.

164. Speed control of shunt motors by armature resistance is not very satisfactory, since the speed regulation is bad. If a motor is operating with full-load current at half speed, about 50 per cent. of the applied voltage is consumed in the resistance, but if the load were decreased, so that only half of full-load current was required, then only 25 per cent. of the applied voltage would be consumed in the same external resistance, and the motor speed would increase to 75 per cent. of normal speed, unless the external control resistance were automatically increased with decrease of load. Due to the large voltage drop across the external resistance, the efficiency of the system is low.

165. When the speed of shunt motors is controlled by field resistance, the speed regulation and the efficiency are both good, but the commutation is generally poor because, at high speeds, the main field is weaker than normal while the armature field is unchanged, so that the field distortion is excessive and the commutating field under the pole tip consequently disappears (Par. 35). The reactance voltage also is increased (Par. 45). With standard shunt motors without interpoles, it is generally impossible to increase the speed more than 60 per cent. by field weakening without having trouble due to sparking, the output of the machine being the normal full load.

166. Speed changes of shunt motors under rapidly fluctuating loads.* When the load on a shunt motor increases slowly, the flux per pole decreases due to armature reaction, and the speed (Eq. 37, Par. 160) remains approximately constant. If, however, the load changes rapidly, the flux per pole cannot change rapidly due to the self-induction of the field coils; the machine then operates for the instant as a constant-flux machine, and the speed drops rapidly to allow the counter e.m.f. to decrease and the necessary current to flow.

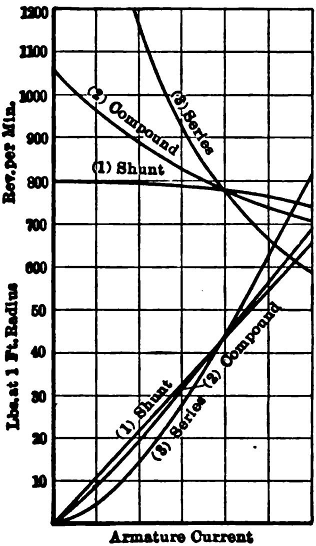

FIG. 64.—Motor characteristics.

167. Speed and torque of series motors. The speed equation (Eq. 37, Par. 160) and the torque equation (Eq. 33, Par. 159) apply to motors of all continuous-current types. In the case of series motors the flux ϕ increases with the armature current I_a; the torque would be proportional to I_a^2 were it not that the magnetic circuit becomes saturated with increase of current. Since ϕ increases with load, the speed drops as the load increases. The speed and torque characteristics are shown in curves 3, Fig. 64.

168. Excessive speeds of series motors on small loads. If the load on a series motor becomes small, the speed becomes very high, so that a series motor should always be geared or direct-connected to the load. If it were belted, and the belt broke, the motor would run away and would probably burst.

169. Speed adjustment of series motors. For a given load, and therefore for a given current, the speed of a series motor can be increased by shunting the series winding or by short-circuiting some of the series turns, so as to reduce the flux. The speed can be decreased by inserting resistance in series with the armature.

170. The compound motor is a compromise between the shunt and the series motor. Because of the series winding, which assists the shunt winding, the flux per pole increases with the load, so that the torque increases more rapidly and the speed decreases more rapidly than if the series winding was not connected, but the motor cannot run away on light loads, because of the

* Short, E. W. "Inherent Regulation of Direct-current Motor;" *Journal* of Inst. of Elec. Eng., Vol. XLVI, p. 171.

shunt excitation. The speed and torque characteristics for such a machine are shown in curves 2, Fig. 64. The speed of a compound motor can be adjusted by armature and field rheostats, just as in the shunt machine (Par. 163).

171. Automatic speed regulation. To keep the speed constant under all conditions of load some kind of centrifugal governor may be used to operate on the shunt-field rheostat. A piece of apparatus of this kind now on the market* is an adaptation of the Tirrill voltage regulator, in which a centrifugal control device mounted on the motor shaft performs the functions of the main control magnet in the standard regulator. The regulator periodically short-circuits part of the shunt-field rheostat by means of light vibrating contacts of small inertia. The time during which the rheostat is short-circuited, or is active, determines the average field current and the flux per pole, and therefore the speed of the machine. When the speed is too high, the centrifugal device short-circuits the rheostat for a long period and allows the flux per pole to increase and the speed to decrease.

172. The differential motor is a compound-wound machine with the series winding opposing the shunt winding, so that the flux will decrease as the load increases and the speed be constant from no load to full load, or actually increase with increase of load. The series winding of such a motor should be short-circuited when starting the machine, so that the starting current will not be excessive. Differential motors are rarely used, because the speed of the shunt motor is so nearly constant from no load to full load that the extra complication of the differential winding is rarely necessary. Differential windings are used to some extent for small motors, in order to secure constant speed with variable load.

173. Unstable operation with rising-speed characteristic. Upon suddenly increasing the load torque on a differential motor, designed for a rising-speed characteristic, the speed for a brief instant decreases. This results in a momentary drop of counter e.m.f., which admits a larger armature current, in turn weakening the resultant field strength and further reducing the counter e.m.f. The attendant increase in armature current increases the armature torque, and the reactions are such that the latter continues to increase until it exceeds the load torque and commences to accelerate the armature. The increase in speed continues until the rising counter e.m.f. finally limits the armature current to a value at which the armature torque equals the load torque, and the speed becomes constant. These reactions, with change of load, occur quite rapidly; if, however, the field cores are large and massive, changes in flux attendant upon sudden changes in m.m.f. will lag by an appreciable time interval, on account of eddy currents in the cores. The presence of an appreciable flux lag, with very rapidly changing loads, results in unstable operation; for example, when the load is suddenly increased, the speed will drop appreciably before it commences to accelerate, and when the load is suddenly removed, the speed will rise appreciably before it commences to decrease. The effect of the armature inertia will accentuate these defects in speed regulation. Such defects are not found in motors whose speed decreases with increasing load, *i.e.*, which have a drooping speed characteristic.

174. Interpole motors have a commutating field which increases with the current and is not affected by armature reaction (Par. 52). Motors which are subjected to excessive overloads, and adjustable-speed motors operating at high speeds with a weak main field, give little trouble due to sparking if supplied with interpoles. **Hunting**† takes place in interpole machines which have a **rising-speed characteristic**. Such a characteristic may be obtained by working with a weak main field and with a short air-gap under the main poles, so that the field distortion under load is large and the flux per pole decreases with increase of load due to the cross-magnetizing effect of the armature (Par. 32).

Such a characteristic may also be obtained by making the interpoles too strong. If commutation is perfect, the current in the short-circuited coil will be zero when that coil is in the geometrical neutral position. If, however,

* General Electric Company's Bulletin on "Automatic Voltage Regulators," 1913.

† Rosenberg, *Electrician*, Aug. 4, 1911.

the commutating field is too strong, the reversal of this current will be advanced, so that the true neutral will be shifted backward. The flux per pole will therefore decrease with increase of load, due to the demagnetizing effect produced, and the speed will increase with load.

Due to saturation of the interpole core, the interpole field will be too strong at light loads, if of the proper strength at full load. Hunting is therefore likely to occur at light loads, particularly if the main field is so weak that the effect of the brush currents in demagnetizing the machine is proportionately large.

175. Non-inductive shunts should not be used with interpole windings if the load fluctuates rapidly, because then the current, which is rapidly changing, will pass through the shunt rather than through the interpole coils, since the latter have considerable inductance, and the commutation will therefore be poor. To make the shunt take its proper share of the current under all conditions of load, it should be made inductive by winding it on an iron core, and the ratio of the shunt reactance to the interpole-coil reactance should be equal to the ratio of the shunt resistance to the interpole-coil resistance.

176. Reversal of direction of motion. In order to reverse a motor it is necessary to reverse the current in the field coils, or in the armature, but not in both. In an interpole machine, the interpole winding must be considered as part of the armature and not as part of the field system.

WEIGHTS AND COSTS

177. Weights and costs. The cost figures given by different manufacturers on a large generator may vary as much as 50 per cent. One manufacturer may build an entirely new machine and charge part of the cost or development to the order; another may offer a standard machine of larger capacity, with a lower rating for the particular case; while still another manufacturer may increase the rating of a machine of smaller capacity, adding fans if necessary to keep the machine cool.

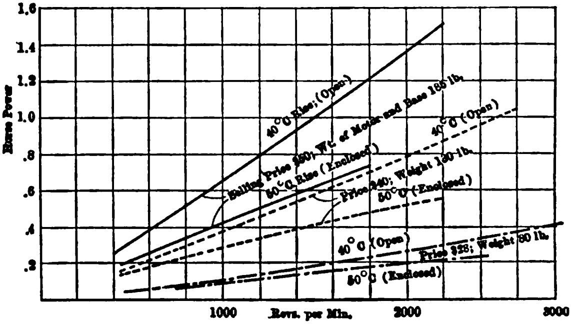

FIG. 65.—Cost of small direct-current motors without base or pulley.

178. Varying costs of labor and material. The cost of large units depends largely on the cost of material, while that of small motors depends largely on the cost of labor. These costs are continually changing, so that it is impossible to give figures which are always reliable. The curves in Figs. 65, 66 and 67 are average figures for standard machines.

The curves in Fig. 66 are interpreted as follows: A machine which weighs 2,000 lb. will cost $380 and will have a rating of 12 h.p. at 500 r.p.m. as an enclosed machine on continuous duty; or 19 h.p. at 500 r.p.m. as an open machine on continuous duty; or 31 h.p. at 500 r.p.m. with a 1-hr. rating; or 40 h.p. at 500 r.p.m. with a half-hour rating. The temperature rise on full load is 40 deg. cent. as an open machine, and 50 deg. cent. as an enclosed machine. The horse-power is proportional to the speed over a range of 30

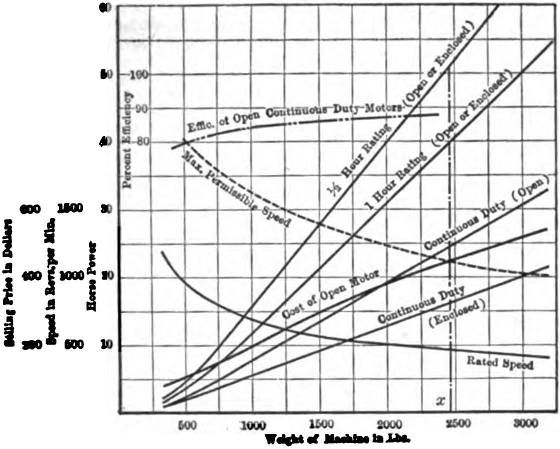

FIG. 66.—Weight and cost of standard 220-volt direct-current motors without base or pulley.

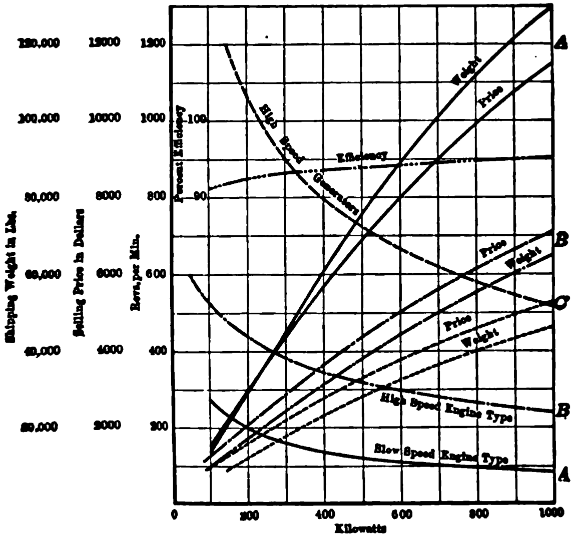

FIG. 67.—Weight and cost of standard 550-volt direct-current generators without base or bearings. *A*, Slow-speed engine type; *B*, high-speed engine type; *C*, high-speed generators.

per cent. above or below the rated speed. The maximum permissible speed is the highest that can be used for variable-speed operation with the particular line of machines on which data is given.

179. Effect of voltage on weight, cost and efficiency. If two machines are built on like frames for the same output and speed but for different voltages, the number of commutator segments will be proportional to the voltage and the commutator length will be proportional to the current. The low-voltage machine will be the heavier because of the long commutator, but, for moderate outputs, there will not be much difference in cost between a 120-volt and a 600-volt machine; the cost of the extra copper on the low-voltage machine is compensated for by the cost of the extra labor on the high-voltage commutator.

The losses will be affected in the following way: The windage, bearing friction, excitation and iron losses will be unchanged; the brush friction loss will be the smaller in the machine with the higher voltage; the contact resistance loss will be the smaller in the machine with the higher voltage because the contact drop is the same in each case and the loss is therefore proportional to the current. The armature copper loss will be unchanged if the same amount of armature copper is used in each machine, because, since the number of conductors is directly proportional to the voltage, the section of each conductor will be proportional to the current and the current density will be the same in each machine. If, however, due to the space taken by the insulation on the large number of conductors, the total amount of copper is the smaller in the machine with the higher voltage, then the copper loss will increase with the voltage and, for the same copper loss in each machine, the output of the high-voltage machine will be less than that of the low-voltage machine.

180. Effect of speed on weight, cost and efficiency. The output of a machine equals the product of (volts per conductor)×(current per conductor)×(number of conductors). For a given frame, the volts per conductor is directly proportional to the speed, and the product of (the current per conductor)×(number of conductors) is constant for a constant current density and a constant weight of armature copper. The output is therefore directly proportional to the speed. As a matter of fact the flux density must decrease as the speed and the frequency increase, in order to keep down the iron loss; but the current density may increase with speed due to better ventilation. However, the output is directly proportional to the speed, over a considerable range. The higher the speed, the larger the output, and therefore the longer the commutator and the heavier the machine.

At very low speeds the number of conductors becomes large and, on account of the amount of insulation required, the total amount of copper is less than normal; the rating of such machines must therefore be reduced in faster ratio than the speed is reduced.

The total armature loss for a given frame and a given temperature rise is equal to $k(A+B\times\text{r.p.m.})$ (see Fig. 52) so that while the output is directly proportional to the speed, the losses do not increase so rapidly; and, until turbo-speeds are reached, at which the windage losses become excessive, the efficiency increases with the speed.

STANDARD CONSTANT-POTENTIAL GENERATORS

181. Generators for power and lighting service are usually wound for 125 volts or 250 volts and are either flat-compounded or slightly over-compounded, so that the voltage at the lamps varies but little with change of load. The efficiency, weight, cost and speed may be obtained from Figs. 66 and 67. The regulation should be less than 2 per cent.

182. Generators for railway service are subject to rapidly fluctuating loads and to sudden and excessive overloads. The engine speed will drop considerably on an excessive overload unless a large flywheel is supplied, since the generator will not have the necessary flywheel effect in itself. The machines are generally wound for 550 volts at no load and 600 volts at full load, and have one terminal grounded. In order to secure proper commutation under all load conditions, interpole machines are often employed.

183. Generators for electrolytic work are usually low-voltage machines of large current capacity. When the terminal voltage is very low, the exciting current will be large if the machine is shunt wound, and the field rheostat between brushes *BB* and a current *I* in the external circuit. This current *I* sets up a flux ϕ_3, which opposes ϕ_1, but can never exceed ϕ_1, so that *I* cannot exceed that value at which the armature ampere-turns per pole equal the shunt-field ampere-turns per pole. The relationship between current and speed for different shunt excitations is given in Fig. 69. The direction of the current *I* is independent of the direction of rotation of the machine.

188. A system of car lighting by a shunt generator driven from the car axle is shown diagrammatically in Fig. 70. The diagram shows the conditions at standstill; the switch *S* is open, the generator is cut out and the battery supplies the lamps. As the car speeds up, the generator voltage increases and, when the value is reached for which solenoid *F* was set, the pull of the magnet closes the switch and connects the generator in parallel with the battery. The generator then delivers current to the battery and to the lamps, which current, flowing through coil *H*, helps to keep the switch closed. As the speed increases, the voltage of the generator and the battery current

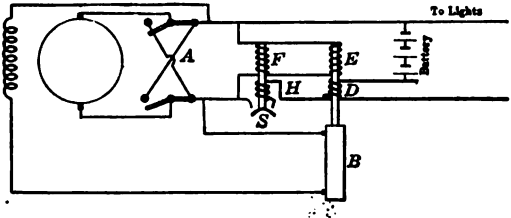

FIG. 70.—Car-lighting system.

both increase, but when full-load battery current is reached, the pull of coil *D* acts to lessen the pressure on the carbon pile *B* and the generator voltage decreases; coil *D* therefore limits the battery charging current. When the battery reaches full charge, its voltage rises to the maximum value and then the pull of coil *E* acts to lessen the pressure on the carbon pile, preventing further rise of voltage and permitting the generator to supply only the current for the lamps. When the speed drops below a certain value, the battery voltage is higher than that of the generator; current then flows back through the coil *H*, thus releasing the switch *S* and disconnecting the generator from the circuit.

Since the generator current should always be in the same direction no matter what the direction of motion of the car, a pole changer *A* is supplied; this consists of a double-throw switch operated by means of a mechanism on the shaft, which mechanism reverses the switch when the rotation of the generator reverses.

189. The windmill generating plant consists of a storage battery operated in parallel with a shunt generator driven by a windmill, an automatic cut-in being used to connect or disconnect the generator from the battery at the proper times. The cut-in is similar to the switch *S* in Fig. 70 and is equipped with a shunt coil connected across the generator terminals and a series coil in the line between the generator and the battery. When the windmill speed and the generator voltage are high enough to give a charging current, the shunt coil pulls up the plunger and closes the switch; the charging current then flowing in the series coil holds the switch closed. The series coil has a second plunger which is attracted downward by the charging current and, in its downward movement, opens the circuit of the shunt coil, allowing the first plunger to drop to normal position. Current cannot again flow in the shunt coil until the battery current has fallen to about 0.5 amp., when the battery switch opens, and the shunt circuit is again closed and ready to operate. See Sec. 22.

THREE-WIRE CONSTANT-POTENTIAL GENERATORS

190. The early three-wire systems were operated with two similar generator units connected in series and the neutral connected to the centre nected permanently across diametrically opposite points on the armature. The voltage between a and b is alternating and, even at no load, or when the load is perfectly balanced, an alternating current flows in this reactance coil. This current, however, is extremely small because the reactance is large. The center o of the coil is always midway in potential between the brushes c and d, and is connected to the neutral of the system. When the loads on the two sides of the system differ, the difference between the currents in the outside lines flows in the neutral wire and through the reactance coil, which offers only a small resistance to direct current.

194. The current distribution in the Dobrowolsky machine* may be considered as that due to the average current $(i_1+i_2)/2$ and a superimposed unbalanced current $(i_1-i_2)/2$, as shown in Fig. 75. The former of these currents flows in the outside lines, but does not pass through the neutral line, and so does not affect the potential of the point o. The unbalanced current is that which affects the voltages on the two sides of the system and this current is shown separately in Fig. 76.

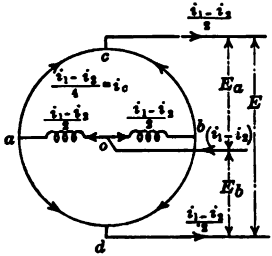

Fig. 76.

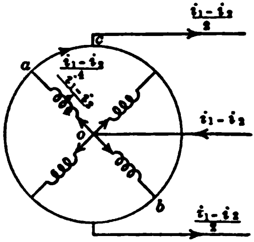

Fig. 77.

Figs. 76 and 77.—Unbalanced currents in three-wire generators.

If R_a is the resistance of the armature from brush to brush, then the resistance from a to c varies from O to $2R_a$ and, in the position shown in Fig. 76, it is equal to R_a. If R_b is the resistance of each of the two legs of the balance coil, the voltage drop from o to a is equal to $(i_1-i_2)R_b/2$; the drop from a to c equals i_cR_a and is alternating, with an average value of $(i_1-i_2)R_a/6$. The average drop from o to c is expressed by

$$\frac{(i_1-i_2)}{2}\left(\frac{R_a}{3}+R_b\right) \qquad \text{(volts)} \qquad (38)$$

195. The unbalanced current (i_1-i_2) is generally limited to 25 per cent. of the full-load current in the outside lines and, since the armature drop at full load equals the product of full-load current and R_a, and seldom exceeds 3 per cent. of E, it follows that the average voltage from a to c seldom exceeds 0.25 per cent. of E_a for 25 per cent. unbalanced current. Therefore the regulation of each side of the system is determined principally by the drop in the balance coil and can readily be kept within 2 per cent.

196. The use of two balance coils connected as shown in Fig. 77 results in a slight improvement in the machine. The average voltage drop from o to c in this case is

$$\frac{(i_1-i_2)}{4}\left(\frac{R_a}{3}+R_b\right) \text{ approx.} \qquad \text{(volts)} \qquad (39)$$

and is apparently less than it would be with only one coil. But when two coils are used, as in Fig. 77, each one carries half of the current carried by the single coil in Fig. 76; therefore the wire used has half the section and each of the coils in Fig. 77 has twice the resistance of the coil in Fig. 76, and the drop from o to a is the same in each case. The drop from a to c is less in Fig. 77 than in Fig. 76, but the difference is so small that it has little effect on

* Hawkins. *Journal* of Inst. of Elec. Eng., Vol. XLV, p. 704.

will have 240 segments and, with a minimum segment and mica of 0.2 in. (0.5 cm.) thickness will have a commutator diameter of about 15 in. (38 cm.). For further information see Sec. 16.

202. Mill motors for rolling-mill work are built like street railway motors set on feet, and are constructed in a similar manner in order that they may be readily repaired. The shafts are made stiffer than usual, which results in greater bearing friction and smaller efficiency than in standard motors. These motors weigh and cost about 20 per cent. more than standard motors of the same rating.

203. Mine motors are designed to operate in a damp atmosphere and must therefore be specially impregnated with waterproof compound.

204. Flame-proof motors,* for operation in explosive atmospheres, must have the current-carrying parts completely enclosed in flame-tight enclosures of non-inflammable material of sufficient strength so as not to be endangered by an explosion in the motor interior. The housings of such motors should never be opened in service except when the motor is completely disconnected from the supply circuit.

It is impossible to construct motors which are **gas-tight.** When the machine becomes heated, any gas which is in the case expands and some of it is forced out along the shaft. When the motor cools again, a fresh supply of gas will be drawn into the case. **Flame-tight** motors, wherein the transmission of an inside explosion to the outside is prevented, have proved feasible. There are two types: (a) Totally enclosed machines, constructed to withstand a pressure of 110 lb. per sq. in. (7.7 kg. per sq. cm.), are built in capacities up to about 25 h.p., but become large and expensive for greater outputs. (b) **Plate-protected motors** have openings which are filled with plates about 0.02 in. (0.5 mm.) apart so as to form a labyrinth passage for the gases; the function of this labyrinth is to cool the products of combustion.

205. Adjustable-speed motors are efficient only when operated by field control (Par. 164). For a wide range in speed, interpoles are required (Par. 165). The size and cost of the machine depend on the minimum speed at which it is necessary to supply the rated output, and the maximum speed is that at which the peripheral velocity reaches a safe limit. By the use of interpoles, deep slots may be employed, and the output for a given weight increased 10 per cent. over that for a non-interpole machine, but the cost per horse-power is not reduced. The following table gives a list of ratings that may be obtained from a machine of weight x (Fig. 66), suitable windings being supplied; a speed range of 3 to 1 is ample for most purposes:

46 h.p. at 800 to 1,200 rev. per min.
40 h.p. at 700 to 1,200 rev. per min.
34 h.p. at 600 to 1,200 rev. per min.
29 h.p. at 500 to 1,200 rev. per min.
20 h.p. at 350 to 1,050 rev. per min.
17 h.p. at 300 to 900 rev. per min.
14 h.p. at 250 to 750 rev. per min.
11 h.p. at 200 to 600 rev. per min.

STANDARD CONSTANT-CURRENT GENERATORS

206. Open-circuit windings. Fig. 79 shows an armature with two open coils and four commutator segments. The voltage between A and B varies as shown in Fig. 80; the current is pulsating and only half of the armature is in use at any given instant.

207. In the Brush arc machine the commutator segments are made to overlap as shown diagrammatically in Fig. 81 and the brushes are wide enough to cover two overlapping segments. During the first one-eighth rev., coil C alone is active and the e.m.f. in that coil passes through its maximum value. During the next one-eighth rev., coils C and D are in parallel; the e.m.f. in C is decreasing and that in D is increasing. During the next one-eighth rev., coil C is cut out and coil D alone is active. When two coils are in parallel the higher e.m.f. in one coil tends to reverse the current in the coil of lower

* Baum. "Fire Damp-proof Apparatus," *General Electric Review*, Vol. XIII, p. 402.

is obtained by shifting the brushes. When the brushes are in the position shown in Fig. 82, large e.m.fs. are being generated in the coils connected in series; when the brushes are shifted through 90 deg. these coils are generating low e.m.fs. and the terminal voltage is a minimum. The mechanism which shifts the brushes also varies the angle θ between brushes so as to secure good commutation with all brush positions.

211. Rating of Thomson-Houston arc machines.* A 2,500-volt, 10-amp., 829 rev. per min. Thomson-Houston machine weighs 5,975 lb. (2,700 kg.), occupies a floor space of 64 in. by 52 in. (1.6 × 1.3 m.) and requires 38 h.p. to drive it.

212. The Thomson-Houston regulator is shown diagrammatically in Fig. 83. The electromagnet *M* is short-circuited through the contact *S*. When the line current is too strong, contact *S* is opened by the magnet *N* and the main current passes through *M*, which raises a lever and increases the

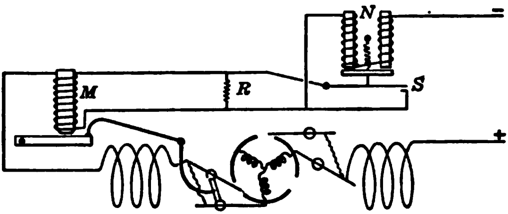

FIG. 83.—Thomson-Houston regulator.

brush arc. At the same time the brushes are shifted from the position of maximum e.m.f. The arcing at the commutator is suppressed by a mechanically-operated blower, and the arcing at the switch *S* is minimised by the discharge resistance *R*.

213. The Wood arc machine has a Gramme-ring winding with a large number of commutator segments. The current is kept constant by shifting the brushes, the voltage being a maximum when the brushes are in the neutral position and zero when the brushes are under the centres of the poles. The regulator is operated by an electromagnet which lifts a lever against the pull of a spring; when the line current is too large, the magnet pulls the lever in such a manner as to engage reduction gearing with the revolving armature and cause the brushes to move to a position of lower voltage; if the current is too small, the spring pulls the lever in the opposite direction and the gearing then moves the brushes to a position of higher e.m.f.

As in the Thomson-Houston machine, the brushes of the Wood arc machine are split into two parts separated by an angle θ (Fig. 82). As the brushes move under the poles, for the purpose of reducing the terminal voltage, the e.m.f. generated in the short-circuited coils increases, and must be counterbalanced by a higher reactance voltage; this is readily obtained in a Gramme winding by reducing the brush arc so as to decrease the time of commutation. For sparkless operation, the brush angle θ should decrease as the brushes move under the poles; this is accomplished automatically by the brush-rocking device.

214. Rating of Wood arc machines.* A 6,250-volt, 9.6-amp., 500 rev. per min. Wood arc machine weighs 14,600 lb. (6,600 kg.), occupies a floor space of 82 in. by 80 in. (2.1 m. by 2 m.) and requires 90 h.p. to drive it.

215. Constant-current generators for series arc lighting are nearly obsolete, although the Rosenberg machine (Par. 187), is coming into use for the operation of searchlight arcs. Direct-current series lighting systems are now in use, but in most cases are supplied from rectifiers (Sec. 6).

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* Houston and Kennelly, "Recent Types of Dynamo-electric Machinery," 1898.

224. Standard balancer sets,* as used for three-wire operation, consist of two like units coupled together, each wound for half of the total voltage and connected in series as shown in Fig. 85. On balanced load, they both run "light" as motors; but with unbalanced load, the currents flow as shown in Fig. 85 and machine M acts as a motor and drives G as a generator. The current in M is greater than that in G by that amount required to supply the armature losses. The motor speed drops with increase of load, and the generator voltage drops due to the decrease in speed and in excitation, so that E_g is less than $\frac{1}{2}E$. By crossing the shunt coils, as in Fig. 86, the regulation is improved. The motor field decreases with decrease of E_g and the speed of the set increases with load; furthermore, the generator excitation, being taken from E_m, increases with load, so that with this connection the voltages are more nearly equal under all conditions.

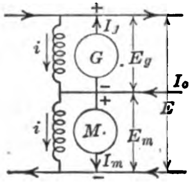

FIG. 85.

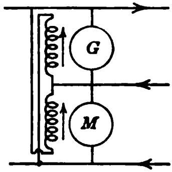

FIG. 86.

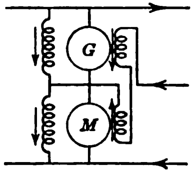

FIG. 87.

FIGS. 85, 86 AND 87.—Balancer sets.

225. Compound balancers are connected as in Fig. 87, so that the generator is always cumulatively compounded and the motor is compounded differentially, no matter in which direction the unbalanced current flows. This connection causes the balancer speed and the generator voltage to increase with the unbalanced load.

The generator current is expressed by the formula,

$$I_g = I_o \frac{\eta_m \times \eta_g}{1 + \eta_m \eta_g} \qquad (40)$$

and the motor current by

$$I_m = I_o \frac{1}{1 + \eta_m \eta_g} \qquad (41)$$

The efficiency in each case being given with the shunt-excitation loss neglected. The actual combined efficiency of the set is

$$\text{Eff.} = \frac{I_g}{I_m + 2i} \qquad (42)$$

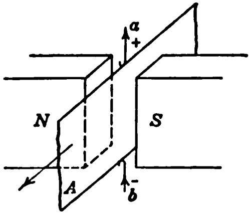

FIG. 88.—Faraday's demonstration.

HOMOPOLAR MACHINES

226. Theory of Operation.† Faraday showed that, if the metal strip A, Fig. 88 be moved so as to cut lines of force, an e.m.f. will be established between the brushes a and b and a continuous current sent round the external circuit connecting them.

227. The radial type, shown in Fig. 89, consists of a metallic disc, rotating between poles which are excited by field coils wound concentric with the shaft. The brushes are placed at a and b, and holes are cast in the yoke to allow access to the brushes. In Fig. 90, there are two discs mounted on the same shaft so that they are electrically connected

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* Budd Frankenfield, *Electrical World*, Dec. 23, 1905; Lanier, *Electrical Journal*, Vol. IX, p. 1036.

† Gray. "Impossible Homopolar Machines," *Canadian Elec. News*, Mar. 15, 1913.

Now the flux density in section A, Fig. 91, is limited to about 130,000 lines per sq. in. (20,000 per sq. cm.) so that $D_a = 1.7\,L_c$ approximately, and therefore $D_a^2 = 76$ watts/rev. per min., with the above limitations.

231. Weight and cost.* Because of the low value of ampere-conductors per in., made necessary by the brush rigging, the value of $D_a^2L_c$ for a homopolar machine will generally be greater than for a machine of the standard type and the machine will be much heavier and more expensive. Therefore, until suitable brushes are found, this type of machine is not likely to be widely used except in the case of machines for low voltages and large currents.

232. The maximum output that can be obtained for a given number of revolutions per minute may be found by assuming a limiting peripheral velocity of 15,000 ft. per min. (77 m. per sec.). Then the output in watts is equal to $D_a^2 \times$ r.p.m./76 and

$$\text{kw} = 0.72\,\frac{(\text{perip. vel.})^2}{\text{r.p.m.}^2} \times \frac{1}{1000} \tag{45}$$
$$= 2.5 \times 10^9/(\text{r.p.m.})^2$$

The maximum output and the speed are plotted in curve 4, Fig. 32. The points shown on the curve give the ratings of two machines now in operation.

233. Compound-wound homopolar machines. The idea underlying the compounding is explained by the diagram in Fig. 92, which relates to a machine having six conductors. The brushes E are connected to the stationary conductors H by means of connection pieces G. Only a portion of the whole length of G is actually employed to carry current, and the amount of this active portion can be varied by the brush rocker F. In practice it is sufficient to have a flexible lead instead of the fixed conductor G.

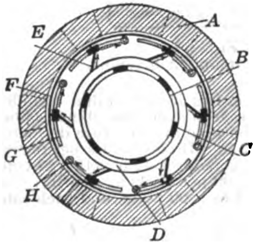

FIG. 92.—Compounding of homopolar machines. B, armature conductors; C, insulation between conductors; D, slip rings.

234. Homopolar machines may be made self-exciting and Noeggerath points out that homopolar machines may even be operated without the use of a field coil.

235. Standard lines of homopolar machines are not on the market; the machines are heavy and expensive if the ampere-conductors per in. are kept low so as to have a reasonably satisfactory brush rigging (Par. 230), and are troublesome in operation unless they are excessively large. The troubles encountered in the construction and operation of a homopolar machine are described by Lamme† in connection with a 2,000-kw., 260-volt, 7,700-amp., 1,200-rev. per min. machine which had 16 slip-rings operating at a peripheral velocity of 13,200 ft. per min. (67 m. per sec.) and copper leaf brushes set against the direction of rotation, the rings being lubricated with graphite.

OPERATION OF GENERATORS AND MOTORS

236. Shunt-wound generators in parallel. A and B, Fig. 93, are two similar generators feeding the same bus bars C and D. If machine A tends to take more than its proper share of the total load, the voltage of A falls, and the load is automatically thrown on B, the machine with the higher voltage. Furthermore, if the engine connected to B fails for an instant, that machine slows down, its generated e.m.f. falls, and current flows back from the line to operate it as a motor. Since the excitation remains unchanged, the machine will run at normal speed and in the same direction as before, and, as soon as the engine recovers, will again take its share of the load.

237. Division of load between shunt generators in parallel. The external characteristics of the two machines are shown in Fig. 95. At

* Pohl. "The Development of Tubo-generators," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 239.

† Lamme. *Trans.* of A. I. E. E., Vol. XXXI, p. 975.

voltage E, the currents in the machines are I_a and I_b, and the line current is I_a+I_b. To make machine A take more of the load, its excitation must be increased, in order to raise its characteristic curve. If a 100-kw. machine and a 500-kw. machine have the same regulation, and therefore the same drop in voltage from no load to full load, then, as shown in Fig. 96, the machines will divide the load according to their respective capacities.

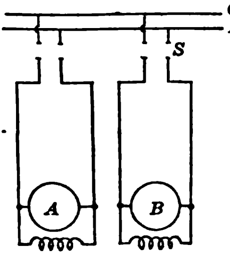

FIG. 93.—Shunt.

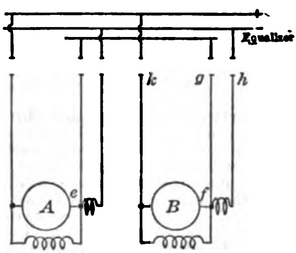

FIG. 94.—Compound.

Connections for parallel operation.

238. Compound-wound generators in parallel. A and B, Fig. 94, are two compound-wound machines. If machine A tends to take more than its proper share of the load the series excitation of A increases, its voltage rises and it takes still more of the load, so that the operation is unstable. Furthermore, if the engine on B fails for an instant, that machine slows down, its generated voltage falls and current flows back from the line to operate it as a motor. Under these conditions the shunt excitation remains unchanged, but the current in the series coils is reversed, so that, running as a motor in a weak field, the machine will tend to increase in speed and possibly run away.

239. Equalizer bus. To prevent instability when compound-wound machines are operated in parallel, a bus bar of large section and negligible resistance, called an equalizer bus, is connected from e to f as in Fig. 94. Points e and f are then practically at the same potential; therefore the current in each series coil is inversely proportional to the resistance of that coil, is independent of the armature current, and is always in the same direction. The machine ammeter, which indicates (at the switchboard) the current output, should always be connected in series with the lead k, Fig. 94. In **interpole machines**, the interpole winding is considered as part of the armature.

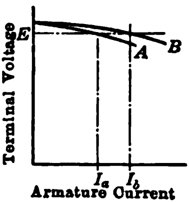

FIG. 95.

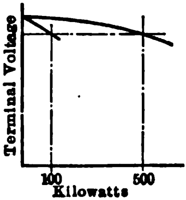

FIG. 96.

FIGS. 95 AND 96.—Division of load between two shunt generators in parallel.

240. Series shunt. When a single compound generator has too much compounding, a shunt in parallel with the series field coils will reduce the current in these coils and so reduce the compounding. When compound machines are operating in parallel, using an equaliser bus, the current in the series field coils depends only on the resistance of these coils; and a series shunt connected to one machine does not reduce the compounding of that machine alone, but also that of all the other machines with which it is operating in parallel. In order to reduce the compounding of a single machine, a resistance must be placed in *series*, and not in parallel with the series field coils. A combination of series and shunt resistances can also be employed. This adjustment is made after erection. If one machine is found to take more than its share of the load, then its compounding must be reduced by means of a resistance placed in series with its series field coils.

241. Starting and stopping a single shunt-wound generator. It is generally safest to start with the machine entirely disconnected from the external circuit and with the field rheostat all in circuit. Then bring the generator up to speed and cut out the field resistance until the voltage of the generator is normal. The main line switch may then be closed and further adjustment of voltage made if necessary.

To stop the machine, open the feeder switches, insert all the resistance in the field-coil circuit, then open the main switch and shut down the engine.

242. Starting and stopping shunt-wound generators in parallel. Assume that machine A, Fig. 93, is running; it is required to throw machine B in parallel with it. This latter machine must on no account be connected to the line while coming up to speed, otherwise it will form a short circuit across the machine which is already in operation. To place machine B in operation, bring it up to speed with the switch S open, adjust the shunt rheostat until $E_b = E_a$, then close switch S and increase the excitation of B until it takes its share of the load. To disconnect this machine, its excitation should be reduced until machine A carries the entire load; the switch S may then be opened. When shunt machines are being connected in parallel for the first time, the polarity of the switches should be carefully tested with a voltmeter or its equivalent.

243. Starting and stopping compound-wound generators. A single machine is started and stopped in the same way as a shunt machine (Par. 241). To place machine B, Fig. 94, in parallel with machine A, which is already running, bring the machine up to speed and excite it to give normal voltage; first close switches g and h in order to excite the series coils, then make E_b equal to the bus-bar voltage and close switch k; the machine may then be made to take its share of the load by increasing the shunt excitation. To disconnect the machine, reduce its load to zero as in the shunt generator, and open the three switches in the reverse order.

Three separate switches are necessary for large machines, because of the large currents. For smaller machines, one double-pole switch for g and h, and a single-pole switch k, are sometimes used. For small machines, a three-pole switch is often used, but then the main switch is closed before the series field has its proper value and there is a momentary disturbance.

244. Starting and stopping motors. All except small motors, rated at a small fraction of a horse power, should be provided with a **starting box** or **starting rheostat.** Such starters, on constant-potential systems, consist in general of graded resistance connected in series with the armature, and eliminated step by step as the motor comes up to speed. The starting torque, as well as the running torque, is given by Eq. 36, Par. 159; therefore in order to keep the starting current as small as possible, the magnetic flux should be as large as possible and the field coils should be fully energized before the armature receives any current. The counter e.m.f. at standstill is zero, and therefore the series starting resistance is necessary to limit the starting current to a safe value. Starters should be equipped with an **automatic release** which will operate under the conditions of no terminal voltage, or no current in the shunt field coils, so that the motor will not be burnt out when the terminal voltage is re-established or when the field circuit accidentally opens. For further information on starters see Sec. 5, and for information on motor control see Sec. 15.

Shunt motors may be stopped by merely opening the line switch; such motors should not be stopped by returning the handle of the starting box to the "off" position, because this method requires the opening of the field circuit while energized and gives rise to a momentary but very severe induced e.m.f. The handle of the starting-box should automatically return to the "off" position before the motor finally comes to a dead standstill.

245. Field discharge. If the field circuit be suddenly opened while carrying current, then, due to the rapid decrease of flux through the large number of field-coil turns, a large e.m.f. will be induced between the two open ends. This may be sufficient to break down the insulation between the field coils and the poles. To prevent this, when a motor is disconnected from a line, the field coils should be short-circuited through the armature winding at the instant the line circuit is opened, the necessary connections being made by the starter.

246. Installation of motors and generators. The machine should, if possible, be placed in a cool ventilated position which is free from dirt, dust, or moisture. Machines required to operate in damp places should have the coils specially treated. The foundation should be solid to prevent vibration. If the machine is belted, the belt tension should not be too great, the distance between belt centres too short, or the pulley too small; the pulley should not have a diameter less than that recommended by the manufacturer. The belt should be flexible and without lumpy joints and the bottom side should be the tight side. After erection, clean the bearings by pouring in gasoline, drain this off through the drain cocks and then fill the bearings with light mineral oil. Before starting, see that there are no loose parts and that the brushes are making firm contact.

247. Starting generators for the first time. Bring the generator slowly up to speed with the field circuit open and see that the oil rings operate properly; then close the shunt field switch and bring the voltage up to normal. Run the machine without load for an hour, after which the load may gradually be increased. Generators should be thoroughly dried out in every instance before they are placed in commission.

248. Starting motors for the first time. Check the connections to make sure that they are correct and secure. See that the controller handle is in the starting position, then close the line switch. If the motor does not start on the first or second notch of the controller, open the line switch and look for the trouble. When starting, bring the controller handle over slowly to the running position, allowing the motor to gather speed, but do not run on the starting notches for any length of time. Run the motor without the belt for half an hour (this cannot be done with a series motor) and then put on the load. When shutting down, open the line switch and see that the controller handle returns to the starting position before the motor finally stops.

249. Operating instructions. Keep oil away from the commutator, brushes and windings. Do not allow dirt or dust to accumulate in or around the machine. Do not lubricate the commutator with oil; a piece of muslin moistened with vaseline may be used to clean the commutator. Emery is a conductor and should not be used in fitting brushes or cleaning the commutator; use sandpaper and do not use it on the commutator too frequently. Do not use greater brush tension than necessary; tension greater than 2 lb. per sq. in. (0.14 kg. per sq. cm.) is seldom required. When replacing brushes, use the quality and size originally supplied with the machine, and fit them to the commutator with sandpaper before use; a strip of sandpaper should be placed on the commutator below the brushes, sand side up, and pulled through in the direction of motion of the commutator. Do not open generator-field circuits quickly (Par. 118); open the switch slowly, permitting the arc to extinguish gradually, which should take about 5 sec. On large generators use a field discharge resistance, which is connected across the terminals as soon as the field switch opens; see Fig. 97.

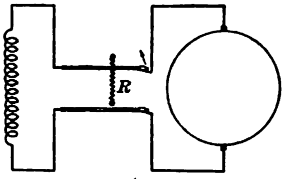

Fig. 97.—Field discharge resistance.

Do not stop quickly on account of a hot bearing, but slow down the machine and apply good clean oil. A quick shut-down will cause the bearing to "freeze." Inspect and clean the machine periodically.

250. Poor commutation is generally due to one or more of the following causes:

(a) Brushes not in the proper position.

(b) Bad spacing of the brush sets. This may be checked by counting the number of commutator segments between adjacent brush sets.

(c) Projecting mica. This cause may be removed by cutting out the mica between segments for $\frac{1}{16}$ in. (0.16 cm.) below the commutator surface.

(d) Rough commutator, generally caused by sudden rushes of current. When such current rushes are inherent under the operating conditions, and interpoles are not employed, it may be advisable to use abrasive brushes to keep the commutator free from rough spots.

(e) Flat bars, produced because some of the commutator segments are softer than others.

(f) High bars, generally due to soft spots in the mica clamping cones.

(g) Grooved commutator, may be prevented by staggering the brush sets so that the space between two brushes of one set is covered by a brush of the next set and the commutator wears down evenly.

(h) Poor brush contact, due to imperfect bedding of the brushes, to dirt, or to burning of the contact.

(i) Worn brushes being replaced by others of the wrong quality or size.

(j) Sticky brushes, which do not move freely in box holders and so do not follow irregularities of the commutator.

(k) Vibration due to want of balance in the armature, to poor foundations, or to a badly laced belt.

(l) Chattering of the brushes, which can generally be cured temporarily by cleaning the commutator with a piece of muslin moistened with vaseline, and may be cured permanently by changing the brush angle.

251. Armature winding troubles are generally due to the following causes:

(a) A broken coil, generally at the commutator end, caused by the wire connected to the commutator being too tight, excessive vibration, poor soldering at the commutator neck, or the use of copper which was not properly annealed. This trouble causes a bad arc at the instant the brush breaks contact with the segment connected to the broken coil. The trouble can be fixed temporarily by short-circuiting the commutator segments connected to the damaged coil, thereby cutting it out, care being taken not to short-circuit the coil itself.

(b) A short-circuited armature coil may be due to damaged insulation between turns or to an accumulation of copper dust in the commutator necks. A large local current will flow in this coil and cause it to become hot and to smoke.

(c) An armature coil may be reversed during repairs. The e.m.f. of the reversed coil opposes that of the other coils so that one circuit in the armature will generate less than normal voltage (Par. 19). At the moment of commutation, the conductors of this coil will be under the wrong pole tips and local sparking will take place.

252. Field-coil troubles are generally due to the following **causes:**

(a) An open circuit: If the motor is series wound, the machine will stop and cannot be started again; if a shunt motor, the machine will speed up as the flux decreases (Par. 162) and the line current will increase as the back e.m.f. diminishes, until the circuit-breakers open. If the machine is a shunt or compound generator, the generated e.m.f. will greatly decrease and a large current will flow into the machine from other generators which are operating in parallel with it, and open the circuit-breakers.

(b) A short circuit will reduce the field-coil resistance and in the case of a shunt machine, will cause the exciting current to increase and the temperature to rise. The m.m.f. of the damaged coil will be reduced and that of the other coils increased, so that the strengths of the poles will be different (Par. 19). The average flux per pole will be unchanged in a shunt machine, but will be reduced in a series machine.

(c) Reversed field coils will cause adjacent poles to have the same polarity. The polarity can be tested with a compass or, if that is not available, with a piece of soft iron which will lie along the lines of force and therefore bridge the poles if the polarity is correct, but will tend to lie axially in the direction of the shaft if the polarity is wrong.

253. The effect of wear in the bearings is to throw the armature out of centre with respect to the pole-pieces and cause an unbalanced pull (Par. 19).

254. End thrust causes heating of the bearings and is generally due to projection of the armature core beyond the magnetic field (Par. 95). End thrust may also be due to the fact that the shaft is not horizontal.

mately the same value and at least the same current-carrying capacity, and comparing the drops of potential across each, in which case the current need not be measured.

262. The field-coil resistance is determined by passing a known current through the coils and measuring the drop of potential across the field terminals.

263. Load tests on machines of considerable size must be made by some method whereby the power developed by the machine is not dissipated, but is made available for the test; otherwise the power-house capacity may not be large enough to test many machines and the cost of the test will be excessive.

264. Blondel's loading-back method. Two identical machines are required for this test. They are separately excited, connected together mechanically to run at the same speed, and their armatures are connected electrically in opposition as in Fig. 101 so that, when equally excited, there is no current in the armature circuit. An auxiliary motor M is belted to the set

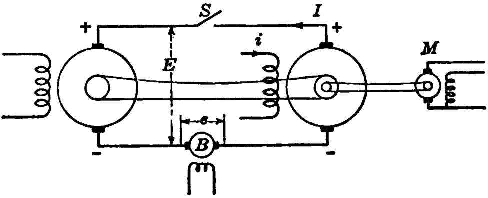

Fig. 101.—Blondel method.

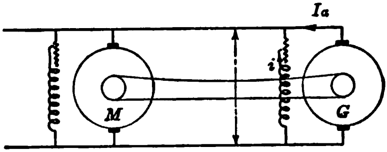

Fig. 102.—Kapp method.
Loading back tests.

and should have a capacity large enough to supply the no-load losses of both machines. The booster B must carry full-load current and is used to circulate the current through the armatures of both machines. The set is brought up to speed by the auxiliary motor, the switch S being open. The fields are then excited until the voltage E is normal and the voltage across the switch S is zero. This switch may then be closed and, by suitably exciting the booster, any desired armature current may be made to circulate. The booster supplies the copper-loss and the motor M supplies the other armature losses of both machines so that EI is the generator output; one-half the output of M is equal to the sum of the windage, friction and iron-losses of one machine; one-half of eI is the copper-loss of one machine; and Ei equals the excitation loss of one machine, from all of which the efficiency may be found.

265. The regulation of a generator, or of a motor, may be determined from Blondel's test. The machines in this case need not be identical, but they must be of the same voltage, and the output of the testing machine must not be less than that of the machine to be tested. In the test for generator regulation, start with normal voltage E and no circulating current; then excite the booster to give the desired current I_a and measure E_t, the terminal voltage. Plot E_t and I_a as in Fig. 58. In the test for motor-speed regulation, keep the voltage across the motor terminals constant by means of the booster, and vary the speed of the auxiliary motor M until the circulating current has the value desired. Plot the speed and I_a as in Fig. 64.

266. Hopkinson's test. This test is similar to Blondel's, but the booster is eliminated and the auxiliary motor is used to supply all the losses, the current in the armatures being circulated by weakening the field of one machine and strengthening that of the other. The iron-losses in the two machines are different because the fields have different excitations, so that, while the method is satisfactory for regulation and heating, it is not satisfactory for efficiency.

267. Kapp's method is preferred to Hopkinson's and is the one generally adopted in commercial work for regulation and heating tests; the efficiency of a machine is generally calculated from the losses. The diagram of connections is shown in Fig. 102. The losses are supplied from the testing circuit and are easily measured, but, since the copper-losses in the two machines are different, as also are the iron-losses, the method should not be used for an accurate determination of efficiency.

268. Load tests on series motors. When a large number of **railway motors** have to be tested the loading-back method of test is used. Two motors are connected together as shown in Fig. 101 and are geared to the same countershaft so as to run at the same speed. This countershaft, driven by an auxiliary motor supplies the mechanical losses. The field coils are connected in the armature circuit and a booster is also placed in this circuit to supply the copper losses.*

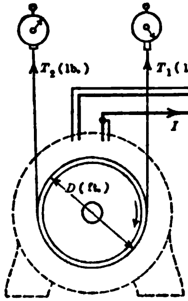

Fig. 103.—Prony-brake test.

269. Prony brake test. The efficiency is seldom determined by direct measurement of input and output except in the case of small motors which are connected directly to the line and the load then measured by means of a water-cooled **prony brake** as in Fig. 103.

$$\text{Eff.} = \frac{746\pi\, D\,(\text{r.p.m.})(T_1 - T_2)}{33{,}000\, EI} \tag{46}$$

270. In constant-current arc generators, the load losses are generally large, and the efficiency of such machines is obtained by measuring the output electrically, and the input by means of a driving motor whose efficiency is known.

271. Load saturation test. The generator is driven by a motor of the same voltage and of larger output, and the machines are connected to the testing circuit as in Fig. 102. Starting at about 20 per cent. above normal voltage and with full-load circulating current, the excitations of the two machines are gradually reduced and a series of readings of E_t and i are taken, I_a being constant. The results are plotted as in curve 2, Fig. 19.

272. Heat run. The machine is connected as in Fig. 102 and operated at rated speed and voltage, with the desired circulating current. The suggestions contained in the A. I. E. E. standardization rules, Sec. 24, regarding measurement of temperature and conditions of test, should be followed.

273. Insulation resistance may be measured with a megger (Sec. 3) or by means of a high-resistance voltmeter connected as in Fig. 104. In the latter case the insulation resistance equals the resistance of the voltmeter multiplied by the ratio $(E-e)/e$, where E, the voltage of the testing circuit, should be the same as the normal voltage of the machine being

*For modifications of this test see:
Workman, R. E. "Factory Testing," *Electric Journal*, Vol. I, p. 551.
Fay, C. J. "Testing Large Motors," *Electric Journal*, Vol. III, p. 525.

tested, and e is the voltmeter reading or the drop in voltage across the voltmeter resistance.

274. Puncture test. To test the insulation, a high voltage is applied between the armature winding and the frame, between the field windings and the frame, and also between the shunt and the series field coils with the shunt winding disconnected from the armature. The test voltage is obtained from a small testing transformer of adjustable ratio and should be raised to the desired value smoothly and without sudden large increments; the maximum should be applied for 1 min. unless otherwise specified, and then gradually decreased. The recommendations given in Sec. 24, should be followed.

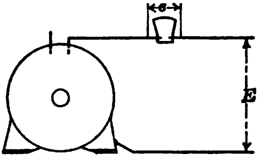

FIG. 104.—Measurement of insulation resistance.

275. Acceptance tests. A compound generator to be tested for efficiency, regulation, temperature, commutation and insulation would be handled as follows:

(a) Grind the brushes in place with sandpaper.

(b) Measure the armature and the field coil resistances.

(c) Place full load on the machine (Par. 272). Adjust the brush position so that the machine is sparkless over the desired range of operation. The brushes should not be set further forward than necessary, otherwise the armature reaction will be greater than it need be. Adjust the current in the series coils with a temporary shunt to give the required voltage at no load and at full load.

(d) Keep the machine on full load until the temperatures, as indicated by the field coil resistance, have become approximately stationary; then shut down and take temperatures.

(e) Measure the armature and the field coil resistances before the machine has time to cool.

(f) Give the machine an overload run, if that is desired.

(g) Make the regulation test (Par. 265 and 267); then since the machine is properly connected, a full-load saturation test may be made for the information of the designer, if required.

(h) The no-load loss may be determined by running the machine idle as a motor (Par. 260), but the designer will probably want information in regard to the separate losses (Par. 258). The test results are then worked up, and, if the machine is satisfactory, the insulation resistance is measured and the puncture test made.

276. Commercial or shop tests. For standard machines on which the designer has all the information he requires, such a complete test (Par. 275) is not necessary. The machine should be run idle at normal speed and voltage to make sure that the no-load losses are not too high due to poor material or poor construction, and that the excitation is not too large or too small. The armature and field coil resistances are checked with the calculated values. The machine is run for an hour at 25 per cent. overload to test the mechanical construction and then run idle at 50 per cent. above normal voltage to test the insulation between turns. The speed may be increased during this latter test. The insulation resistance is then measured and the puncture test made. For further information see the series of articles on shop testing by R. E. Workman in Vol. I of *Electric Club Journal*.

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SECTION 9

CONVERTERS AND DOUBLE-CURRENT GENERATORS

SYNCHRONOUS CONVERTERS

BY F. D. NEWBURY, M.E.

GENERAL THEORY

1. Comparison with separate synchronous motor and direct-current generator. The theory of the synchronous converter is best explained by the similarity of the converter to a synchronous motor driving a direct-current generator. The converter combines the characteristics of both motor and generator in the single armature winding. This winding is provided on one end with a commutator as in a direct-current generator, and on the other with collector-rings and taps to the winding as in a revolving-armature synchronous motor. Alternating current is supplied through the collector-rings, and with no direct-current load the synchronous converter operates purely as a synchronous motor. Its speed is determined by the frequency and number of poles and the flux is fixed by the impressed voltage, just as in a synchronous motor.

2. Excitation. In the synchronous converter, as in the synchronous motor, the magnetic flux and the corresponding net exciting ampere-turns are determined solely by the impressed voltage. If it is attempted to vary the exciting ampere-turns and flux by variation of the main field excitation, the latter variation is neutralized by an equivalent change in excitation brought about by a change in phase and value of the armature current, so that the flux and net excitation remain constant. Increased excitation in the main field winding produces a leading current in the armature (leading with respect to the line voltage) which, in the majority of transmission lines serving synchronous converters, is beneficial to line power-factor and voltage. Conversely, under-excitation produces a lagging current which is detrimental to the power-factor and voltage of such lines.

3. Ratio of alternating voltage to direct-current voltage. Assuming the synchronous converter to be operating without direct-current load, it will be clear that the direct-current voltage between brush arms will, through the action of the commutator, have a value equal to the maximum instantaneous value of the alternating voltage, giving proper consideration to the relative points in the armature winding to which, at any instant, the brushes and collector-rings are connected. In the single-phase, two-phase and six-phase diametrically connected converters, the direct-current brushes and collector-rings are connected to equivalent points on the armature winding, so that the ratio between the alternating and direct-current voltages is simply the ratio between the effective and the maximum alternating voltages. In the three-phase converter, the collector-rings are connected to points 120 electrical degrees apart, while the direct-current brushes are connected to points 180 electrical degrees apart, so that the voltage ratio is affected by this difference. The theoretical ratios are shown in Par. 4. See Par. 35 and Figs. 9 to 14, inclusive, for further information.

These theoretical ratios are based on the assumptions that the impressed alternating-current wave form and the counter e.m.f. wave form of the converter are both sine-waves, that there is no loss in the converter, and that the direct-current brushes are at the no-load neutral position. Variations in wave form are small in commercial circuits and apparatus. The effect of the resistance of the windings, brushes, and brush contact is appreciable, and may vary the ratios (Par. 5) from 2 to 4 per cent. Changes in brush position, even within the small limits permitted by commutating conditions, may affect the ratio 1 per cent. A lagging current in the converter winding has the same effect as narrowing the pole-face and will thus increase the ratio of alternating voltage to direct-current voltage. In general, therefore, actual ratios are slightly higher than the theoretical ratios (Par. 4), assuming conversion from alternating to direct-current.

4. Table of Theoretical Voltage Ratios

Number of converter phases	Ratio of alternating voltage
Single-phase..................	0.71 of direct voltage
Two-phase.....................	0.71 of direct voltage
Three-phase...................	0.61 of direct voltage
Six-phase double delta..........	0.61 of direct voltage
Six-phase diametrical..........	0.71 of direct voltage

5. The theoretical current ratio, neglecting the losses and assuming 100 per cent. power-factor is the inverse ratio of the alternating and direct-current voltages (Par. 4). This follows from the equality of the alternating-current input and direct-current output. From this standpoint, but including the effect of the losses, the current ratios are given by the following formula:

$$I_a = \left(\frac{1}{Eff}\right) Y I_d \qquad \text{(amps.)} \qquad (1)$$

in which expression the symbol I_a represents the value of the alternating current and I_d the value of the direct current. Eff represents the efficiency. Y is equal to twice the square root of two divided by the number of collector-rings. Values of Y are given as follows:

No. of phases	Value of Y
Single-phase............................	1.41
Two-phase............................	0.707
Three-phase............................	0.940
Six-phase............................	0.470
(Both double-delta and diametrical transformer connections.)	....

For all practical purposes an average efficiency of 94 per cent. may be assumed, in which case the current ratios will be as shown in Par. 6. These simple ratios are very easily remembered and are convenient for approximate calculations.

6. Table of Approximate Current Ratios

No. of phases	Alternating current per terminal
Single-phase...	1.50 times direct current
Two-phase.....	0.75 times direct current
Three-phase....	1.00 times direct current
Six-phase......	0.50 times direct current

7. Actual current ratio. Since the current ratios given in Par. 6 are based on theoretical voltage ratios (Par. 4) the actual ratios will vary from 2 to 4 per cent. from those of Par. 6. In specific cases where exactness is desired, the current can be determined most conveniently from the direct-current output, actual alternating voltage, actual efficiency and power-factor using the following formula:

$$\text{alternating current (per terminal)} = \frac{K.W. \times 1000}{E_a \times Eff \times Y \times P.F.} \qquad \text{(amp.)} \qquad (2)$$

Where E_a is the alternating voltage. Values of Y are given as follows:

Number of phases	Value of Y
Single-phase..........	1.00
Two-phase	2.00
Three-phase..........	1.73
Six-phase	3.00

If the efficiency and power-factor are not known, see Par. **28, 38,** and **39** for probable values.

8. Armature currents and heating. The current in the converter armature may be considered as made up of: (a) an alternating current, uniformly dividing among the various conductors of the winding, which is necessary to drive the converter as a synchronous motor, and which is determined by the magnitude of the losses; (b) a current flowing from the collector-ring taps to the direct-current brushes, varying widely in value in the different conductors at different positions of the armature with respect to the field poles. The first component is small and in theoretical discussions is usually neglected. The second component for convenience in calculation, may be considered to be a resultant of the instantaneous values of alternating current and direct current in any individual conductor. Fig. 1 illustrates the

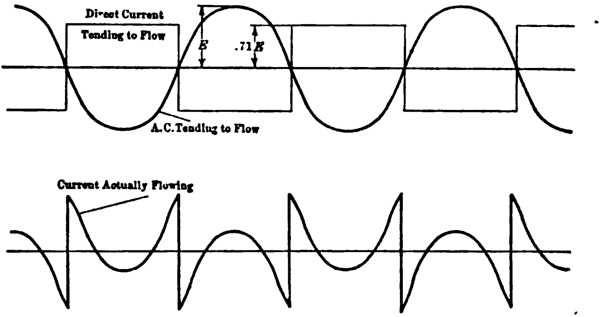

FIG. 1.—Armature current in conductor, 100 per cent. power-factor.

simplest case, namely, that of a conductor midway between alternating-current taps, which are equidistant from pole centres, and with 100 per cent. power-factor alternating-current input. This diagram clearly shows the relation between the effective current actually flowing and the alternating current and direct currents that would flow in separate motor and generator windings, and indicates the fundamental reason for the economy of the synchronous converter due to its single winding.

9. The ratio of the effective or resultant armature current to the external direct current varies with the number of phases, or more properly, with the number of connections per pole to the armature winding. The larger the number of such connections, the smaller will be the effective current.

10. The distribution of the current among the different conductors at 100 per cent. power-factor is such that the maximum loss occurs in the tap coils and the minimum loss in the coils midway between taps. This is shown in Fig. 3.

11. The effect of diminishing power-factor on the effective current is to increase the latter greatly, even with small reductions in power-factor. The effect of decreased power-factor on the distribution of current is greatly to increase the current and loss in conductors near one side of the tap coils and to reduce the loss in conductors on the other side of the same tap coils. The average effective current and the loss are considerably increased. The effects of power-factor are illustrated by Fig. 2 which shows the same conditions as Fig. 1, except that the power-factor is 86.5 per cent. instead of 100 per cent. It will be seen that the alternating-current wave has been shifted with respect to that of the direct current, thus causing an increase in the effective current. Fig. 3 shows the difference in distribution of losses and difference in average losses with 100 per cent. and 95 per cent. power-factors.

12. Table showing Relative Converter Losses on Basis of Direct-current Generator Losses taken as Unity

Calculations based on 3 per cent. rotational losses
(Calculated by C. E. Wilson)

	Relative armature loss in complete winding					Relative maximum loss in one conductor				
No. of collector rings	P.F. 100 per cent.	P.F. 98.5 per cent.	P.F. 94 per cent.	P.F. 86.6 per cent.	P.F. 76.6 per cent.	P.F. 100 per cent.	P.F. 98.5 per cent.	P.F. 94 per cent.	P.F. 86.6 per cent.	P.F. 76.6 per cent.
2	1.451	1.522	1.734	2.160	2.940	3.121	3.653	4.358	5.342	6.808
3	0.587	0.627	0.753	1.005	1.468	1.249	1.594	2.048	2.673	3.596
4	0.391	0.426	0.532	0.746	1.137	0.751	1.017	1.367	1.861	2.596
6	0.274	0.304	0.400	0.589	0.935	0.430	0.614	0.874	1.249	1.825
12	0.209	0.236	0.326	0.500	0.824	0.249	0.354	0.525	0.792	1.232

13. Losses affecting rating. Par. 12 shows the relative average losses and maximum loss per conductor compared with those of the equivalent direct-current generator for various phases and power-factors. It shows a large increase, particularly in the maximum loss due to small changes in power-factor. It is this characteristic that limits the use of synchronous converters to operating power-factors near 100 per cent. This table also shows the advantage of a large number of rings. Practically all converters above 200 or 300 kw. are now built with six collector-rings and phases, while 12 rings have been considered for the largest ratings. A distinction must be made, however, between copper loss and rating. This table does not represent relative capacities of the various armatures, since the rating depends on many other factors besides armature coil heating. In general, the **current capacity** of a given armature will be increased by increasing the number of rings and will be reduced by a reduction in power-factor, even slightly below 100 per cent. power-factor, although not to so great an extent as is indicated by a direct comparison of the losses.

14. The armature reaction of the synchronous converter is relatively small compared with that of the equivalent direct-current generator on account of the relatively small effective armature current. In this characteristic the converter is very nearly equal to the compensated direct-current generator. In a six-phase converter, the effective armature reaction varies from 7 per cent. to 20 per cent. of the armature reaction in an equivalent uncompensated direct-current generator.*

15. Commutation in the synchronous converter offers the same problem as in the direct-current generator, differing only in degree. Due to the smaller effective current the armature reaction and, to a lesser extent, the self-induction, are smaller than in the direct-current generator of equal rating, so that allowable commutation limits are much higher. The synchronous converter, without commutating poles, holds a position between the simple direct-current generator and the direct-current generator with commutating poles and with a compensating pole-face winding. For this reason the commutating poles with their attendant complications were not added to the synchronous converter until long after they had been success-

* Lamme, B. G. and Newbury, F. D. "Interpoles in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXIX, page 1625.

same number of poles as the converter and having its armature winding connected in series with the converter armature winding. This booster alternator, by a change in its own excitation, varies the voltage applied to the terminals of the converter. The excitation is so arranged that the booster fields and voltage may be reversed without opening the field circuit. The possible variation in voltage is double the rated booster voltage, since it may be added to or subtracted from the line voltage. The connections are shown in Fig. 5. The voltage may be controlled automatically through relays and regulator, or the booster may be series wound, thus automatically compounding the converter. This method of voltage variation has largely superseded the methods previously described, particularly in the larger installations.

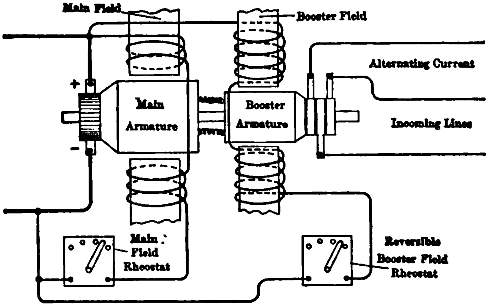

FIG. 5.—Synchronous booster converter.

21. Types of synchronous booster. The booster may be a revolving-armature generator located between the collector-rings and main armature, or it may be a revolving-field generator located outside of the collector-rings. The revolving-armature construction is the more usual since it eliminates additional collector-rings and external wiring, and the large number of parallel circuits in the converter winding favorable to low-voltage generation may be conveniently used in the booster winding. The rotating-field booster is sometimes preferable since it may be added to a standard converter with less change in existing parts. There is also less interference with the ventilation of the main armature.*

22. The application of commutating poles to the booster converter involves new features due to the motor action, or the generator action, of the converter when the booster is excited. The converter acts as a motor to the extent of the booster output plus all losses, when the booster is excited to increase the direct-current voltage, and, conversely, the converter acts as a generator to the same extent when the booster is excited to lower the voltage. Due to this motor or generator action the effective current in the converter armature varies with the booster excitation as well as with the output of direct current.† If the effective armature current varies, the commutating-pole flux must vary correspondingly if the commutating poles are to be of benefit. This variation is accomplished approximately in one method by providing two windings on the commutating poles, one in series with the armature as in other commutating-pole machines, and the other in series with the booster field winding. The windings are so connected as to assist one another when the direct-current voltage is decreased and to oppose one another when the direct-current voltage is increased. This arrangement of windings provides approximately equal commutating-pole flux and armature flux under all operating conditions except that of no external load coincident

* Newbury, F. D. "Voltage Regulation of Rotary Converters;" *Electric Journal*, Vol. V, page 616.

† Yardley, J. L. McK. "Efficiency of Synchronous Booster Converters;" *Elec. Journal*, Feb., 1913.

25. Conditions affecting direct-current voltage regulation of the compound converter.* It is apparent that the direct-current voltage regulation of the compound-wound converter depends on many elements internal and external to the converter, and that the change in voltage is limited by the inability of the converter to operate at low power-factor and heavy load. The range of voltage is more restricted and the results are much more difficult to predetermine than in the compound-wound direct-current generator. The voltage range is affected by certain factors which are as follows: (a) the resistance drop between the point of constant voltage and the converter; (b) the reactance drop between the same points; (c) the ratio of armature ampere-turns to shunt-field ampere-turns; (d) the ratio of series-field ampere-turns to shunt-field ampere-turns; (e) the setting of the shunt-field rheostat; (f) the transformer secondary voltage; (g) the total drop through the converter.

26. Customary values for these factors (Par. 25) are as follows: (a) the full-load armature ampere-turns are approximately equal to the no-load shunt-field ampere-turns; (b) the full-load series-field ampere-turns are approximately one-half the armature of shunt-field ampere-turns; (c) the shunt-field rheostat is so set that the lagging component of the line current will be approximately 25 per cent. of the full-load energy component; the shunt-field current will then be about 75 per cent. of its normal no-load 100 per cent. power-factor value under the previous assumptions: (d) the transformer secondary voltage usually is chosen somewhat higher than the correct no-load value to assist in holding up the voltage at overloads.

Under the above conditions, an approximately flat direct-current voltage regulation curve will be obtained with the following values of resistance and reactance measured from the point in the circuit having constant voltage, to the converter collector-rings:

Resistance drop, per cent.	Reactance drop, per cent.
0	4
2	8
4	12
6	16

27. Relation between power-factor and load in compound converters. With the average conditions stated in Par. 26, the power-factor will vary with the load approximately as is shown, Par. 28. With larger overloads—carried for a sufficient length of time to make heating a consideration—the shunt field winding should be further under-excited in order to bring the power-factor nearer unity at the extreme overloads, or the series field should be shunted to reduce the change in power-factor with load.

28. Table of Power-factor Variation with Load in Compound Converters

Load	Power-factor
	Per cent.
$\frac{1}{8}$	70 lag
$\frac{1}{4}$	93 lag
$\frac{1}{2}$	100 lag
$\frac{3}{4}$	99 lead
Full	98 lead
$1\frac{1}{4}$	97 lead

29. The reactance necessary for compounding may be in the step-down transformers or in separate reactance coils. Where possible, the transformers are designed with the necessary reactance, as this method is

* Bache-Wiig, J. "Voltage Regulation of Compound-wound Rotary Converters;" *Elec. Journal*, Vol. VIII, page 860.

lower in cost and requires less floor space and wiring; it is, however, difficult so to design the transformers when the required reactance is more than 10 per cent. It is also more difficult to obtain high reactance in 25-cycle than in 60-cycle transformers, and in the core type than in the shell type (Sec. 6).

30. The split-pole method of voltage control utilizes a different principle from any previously discussed. Variation of direct-current voltage is secured, not by a variation in the impressed alternating voltage, but by a change in the shape of the magnetic field, such that the total flux and the direct-current voltage are changed, while the alternating voltage remains substantially unchanged. This is possible because of the fact that in polyphase windings in which the phases are tapped 120 electrical degrees apart, third harmonics and multiples thereof cancel out and do not appear at the 120-deg. terminals. The action of the split-pole converter therefore depends on variations in the field flux distribution which produce third harmonics, in conjunction with taps on the alternating-current side 120 deg. apart. The reason for this will be understood by reference to Fig. 7. It is evident that the armature coils between the 120-deg. taps on the alternating-current side will always include two equal and opposite areas of the third-harmonic variation of flux which neutralize each other and so produce no change in alternating-current wave form. On the other hand, the armature coils between the brushes on the direct-current side, which are 180 electrical degrees apart, will always include three areas of the third harmonic variation in flux, only two of which neutralize each other, leaving one to change the average ordinate of the field flux curve, and, consequently, the direct-current voltage.

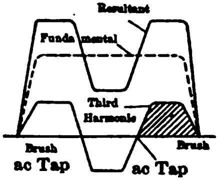

FIG. 7.—Flux distribution in three-part pole, split-pole converter.

With the split-pole converter, the 120-deg. connection on the alternating-current side is preferable; consequently the three-phase delta connection or the six-phase double-delta connection should be used. However, any secondary connection of transformers may be used providing the primary is Y connected and the neutral is not fixed.

Harmonics other than the third and multiples thereof will appear at the alternating-current terminals and will cause a corrective current to flow from the supply circuit through the converter windings so as to neutralize the flux producing these harmonics in the converter. It is desirable, therefore, so to design the converter that the wave form will be as nearly as possible a combination of the fundamental, third and ninth harmonics. In practice this is so nearly accomplished that the effect of the split-pole converter on the supply circuit wave form is negligible.*

31. Action of the split-pole converter. When the split-pole converter is operated at a higher voltage than that corresponding to the alternating line voltage, the additional output due to the increased direct-current *voltage* is supplied by an increased *current* on the alternating-current side. This current moreover is a "motor" current dividing in the converter in the same way as the motor current necessary to supply the losses. The value of the effective current is, therefore, considerably increased. At lower voltages the converter acts as an alternating-current generator decreasing the line alternating current, but due to the distribution of the current in the armature the effective current is increased.

32. Two types of split-pole converter. The first converters of this type were designed with two regulating poles for each main pole. This arrangement resulted in symmetrical flux and voltage wave forms through-

* (a) Stone, C. W. "Some Developments in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXVII, p. 181.
(b) Steinmetz, C. P. "Variable Ratio Converters;" *G. E. Review*, 1908, pages 26–84, 1909.
(c) Burnham, J. L. "Modern Types Synchronous Converters;" *G. E. Review*, page 74, 1912.

out the entire voltage range, and was favorable to commutation but required machines of comparatively large diameter. The split-pole converters as built at present have a single regulating pole for each main pole. This construction obviously permits a considerable reduction in diameter and cost for a given output, and the detrimental effect of the varying magnetic field in the commutating zone can be compensated for by providing favorable commutating conditions in other respects. The field-flux wave forms and the corresponding voltage wave forms for various voltages, with both the three-part pole and the two-part pole constructions, are shown in Fig. 8.

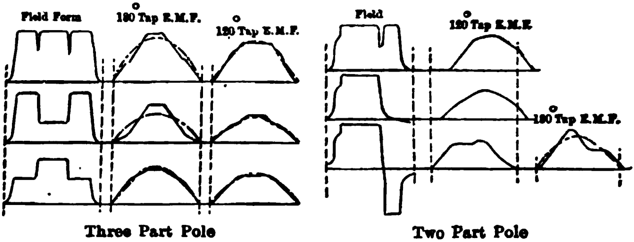

Fig. 8.—Flux-distribution and alternating voltage wave forms in split-pole converter.

Upper curves, max. voltage. Middle curves, mid. voltage. Lower curves, min. voltage.

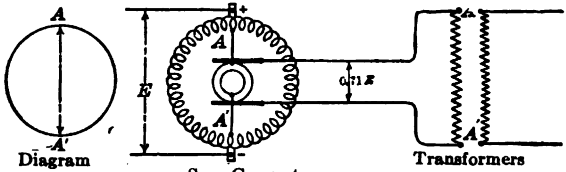

Fig. 9.—Single-phase connections.

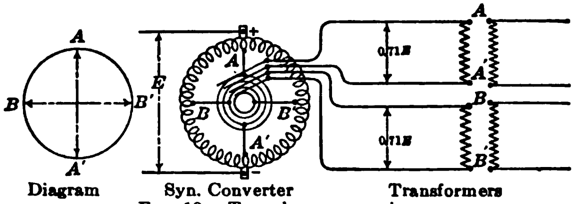

Fig. 10.—Two-phase connections.

33. Limits of voltage variation with the split-pole converter. In varying the voltage, the excitation of the regulating poles is increased in the same direction as the excitation of the main poles to increase the voltage, and is reversed to decrease the voltage. The split-pole converter is limited to approximately 20 per cent. variation in either direction, but this is sufficient to cover the majority of applications.

34. Direct-current booster.—The direct-current voltage can be varied directly by inserting a booster in the direct-current circuit. This booster may be direct-connected to the converter or driven by a separate motor. It is generally used in the latter form as an addition to existing equipment, since it does not affect the converter either structurally or in respect to operating voltage. All methods involving change in alternating voltage necessitate the operation of the converter at the highest voltage.

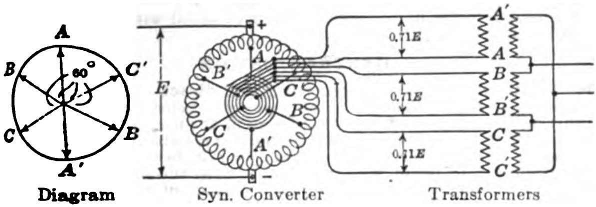

FIG. 11.—Six-phase diametrical connections.

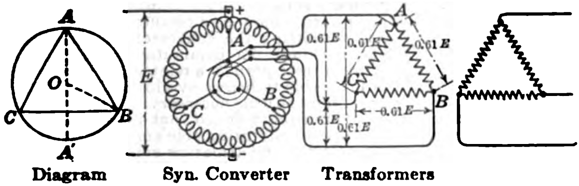

FIG. 12.—Three-phase delta connections.

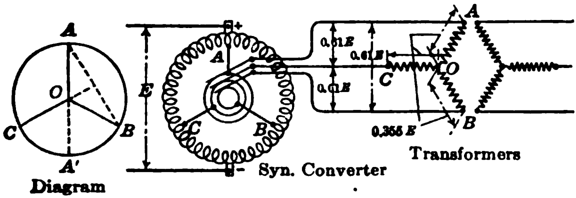

FIG. 13.—Three-phase Y connections.

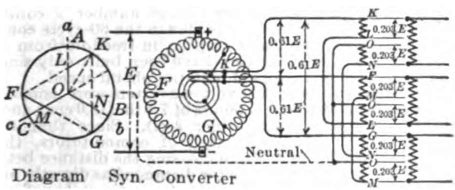

FIG. 14.—Three-phase interconnected Y connections (for 3-wire direct-current circuits).

The weight, floor space and cost of a converter with a direct-connected direct-current booster are greater than the same factors in a converter with an alternating-current booster. A further serious disadvantage of the direct-current booster is the additional commutator, which is equal in current capacity to the converter commutator.

35. Transformer voltages and connections. The various transformer connections with voltages commonly used are shown in Figs. 9 to 14, inclusive. Fig. 14 shows the transformer connections necessary when the converter is used to supply three-wire direct-current circuits; this modification in the transformer windings is necessary to avoid magnetic unbalance due to the unbalanced currents obtained with unbalanced loads on the direct-current circuits.

GENERAL DESIGN

36. Similarity between converter and direct-current generator. The general design of the synchronous converter closely resembles that of the direct-current generator. The design of the magnetic circuit is identical; the types of armature and field windings are the same, except for the taps to the collector-rings; the number of armature slots per pair of poles must be some multiple of the number of phases; the design of the electric circuit is the same, except for the reduced value of the effective current. This reduction of effective armature current permits smaller conductors and smaller armature slots—a condition favorable to commutation; it also permits a higher ratio of armature ampere-turns to shunt-field ampere-turns, resulting again in a smaller armature core; and furthermore, it reduces the flux distortion on overload, permitting the converter to carry large momentary overloads without flashing. In commutating-pole converters, the reduced effective armature current permits a relatively small commutating-pole winding, which is favorable to heavy overloads. With the small number of commutating-pole ampere-turns necessary, it is easy to provide sufficient section in the commutating pole so that large overloads can be carried without saturating the commutating pole and thus destroying the equivalence of commutating-pole flux and armature-coil flux. In the direct-current generator this is not true, and commutating-pole saturation is usually a limit to the overloads that can be carried.

There are, however, various requirements in design, due to the rigid relationship between poles and speed, that do not enter into direct-current generator design. Following directly from this relationship, the maximum distance between adjacent neutral points on the commutator of any synchronous converter is a direct function of the frequency and the peripheral speed of the commutator. The peripheral speed of the commutator, in feet per min., is equal to the alternations per min. (cycles per sec. times 120) multiplied by the distance in feet between adjacent neutral points on the commutator surface.

37. Comparison between 25-cycle and 60-cycle converters. This simple relationship between poles and speed (Par. 36) is responsible for most of the difference between high-frequency and low-frequency converters. It follows from this law that the distance between neutral points in a 25-cycle converter is 2.4 times the distance in a corresponding 60-cycle converter for the same commutator speed. Thus while ample room is available in the 25-cycle converter for a large number of commutator bars at a low peripheral speed, the reverse is true in the 60-cycle converter. The 600-volt 60-cycle converters that compare in freedom from flashing and sensitiveness with 25-cycle converters have been built only since it became possible to construct commutators of high peripheral speed.

Up to the year 1909, 60-cycle 600-volt converters were usually built with a maximum distance between neutral points of 7.5 in. (19.0 cm.) and a peripheral speed of 4,500 ft. per min. (22.9 m. per sec.). Since that time, through improvements in the mechanical design of commutators, the peripheral speed has been increased to 5,500 ft., increasing the distance between neutral points to 9 in. (22.9 cm.). This greater distance has directly and indirectly improved the operating characteristics. As a direct benefit there is less chance that a flash under a brush will reach to the adjacent brush arm, causing the converter to buck; and, indirectly, the greater distance permits the use of more commutator bars, reducing the maximum voltage between bars and so reducing the danger of an arc spreading from bar to bar. With 9 in. (22.9 cm.) available between neutral points, it is possible to proportion 60-cycle converter commutators as conservatively as those of 25-cycle converters and direct-current generators.

The distance between neutral points becomes a design limitation only with the higher line voltages. At 250 volts the design of the 60-cycle converter has not been handicapped as it was at 600 volts, although it has unjustly suffered in reputation.

At the higher voltages now being used in railway work, the 25-cycle converter approaches the same limiting conditions as the 60-cycle at 600 volts. At 1,500 volts, the 25-cycle converter is theoretically equivalent, in commutator proportions, to the 60-cycle converter at 625 volts.

8. Table of Weights, Speeds, and Efficiencies for 600-volt 25-cycle and 60-cycle Converters

Kw.	Frequency	R.p.m.	Approximate net weight (lb.)	Approximate efficiency at full load, per cent.
*300	25	750	10,100	95
*500	25	750	15,500	96
1,000	25	500-750	23,000	96
1,500	25	500	39,000	96
2,000	25	375	57,000	96
3,000	25	214-250	92,000	96
4,000	25	187	158,000	96
†200	60	1,200	10,500	91
†300	60	1,200	12,200	93
†500	60	720-900	18,000	94
750	60	720-900	20,000	94
1,000	60	600	35,000	94
1,500	60	514	47,000	94
2,000	60	400	60,000	94

Where two speeds are given, the weights and efficiencies apply to the higher speeds.

39. Table of Weights, Speeds and Efficiencies for 250-volt, 25-cycle and 60-cycle Converters

(b) 25 and 60-cycle—250-volt converters

Kw.	Frequency	R.p.m.	Approximate net weight, lb.	Approximate efficiency at full load, per cent.
200	25	750	14,300	93.0
300	25	750	20,000	94.0
500	25	500-750	35,000	94.5
750	25	375-500	45,000	95.0
1,000	25	300-375	66,000	95.5
100	60	1,200	5,700	90.5
200	60	1,200	13,500	91.5
300	60	900	14,000	92.5
500	60	720	19,500	93.5
750	60	600	32,000	93.7
1,000	60	514	42,000	94.0

All designs are of the non-commutating-pole type and will stand 100 per cent. momentary overload.

Where two speeds are given, the weights and the efficiencies apply to

* Will stand 200 per cent. overload momentarily—all other designs will stand 100 per cent. overload.

† Non-commutating-pole type; in all other cases commutating poles are employed.

the *lower* speeds. The difference, however, will not be of material importance.

40. Commutator design for synchronous converters follows that for direct-current generators except that long high-speed commutators are more frequently used. The longest commutators are built with three V-ring supports, or with two V-ring supports and a central shrink ring. Shrink rings alone are not as effective as either of these constructions for the majority of cases, on account of the large diameters involved. With large diameters, large tangential stresses are produced in the shrink ring by relatively small radial forces. The V-ring construction without shrink rings is generally to be preferred since the commutator can be readily taken apart for repairs and also can be more easily insulated from adjacent parts. A construction embodying four V-rings has been employed to a limited extent; this consists, in effect, of two separate commutators flexibly connected together. The inaccessibility of the middle V-rings is a serious objection to this construction.

Long commutator necks must be braced from each other. This is done by fibre plugs set into each neck, by interlacing heavy twine between the necks, or by roping wooden spacing blocks to each neck.

41. The ventilation of commutators, in cases where the necks do not provide sufficient cooling surface and windage, has been most successfully accomplished by attaching radiating vanes about 2 in. square to the outer end of each bar. These vanes not only provide additional cooling surface at the most effective point, but considerably increase the air circulation.

42. Armature equalizer connections are used in synchronous converters just as in direct-current generators (Sec. 8) to equalize the effect of the flux under all poles. The collector-rings are also equalizing rings, so that the equalizers are usually spaced with respect to the collector-rings. To secure greater accessibility, the equalizer rings are generally located on the collector end of the armature. Special constructions have been developed in order to place the equalizing connections in such a manner that there will be no interference with the collector connections and no increase in the length of the commutator.

43. Damper windings. Almost without exception synchronous converters are provided with damper or **amortisseur windings** to prevent hunting (Par. 61). These are usually of the built-up grid type, commonly employed on the rotors of induction motors, consisting of a large number of bars located in slots in the pole-face, and connected on the ends by continuous rings. A cast-copper damper winding is sometimes employed, consisting of relatively few bars of large cross-section in the pole face. In the commutating-pole converters, the end rings are sometimes made in disconnected segments—one for each pole—so that the commutating poles will not be enclosed by the damper winding. If the commutating poles are individually enclosed, changes in the commutating-pole flux are damped, thus preventing the commutating-pole flux from changing as rapidly as the armature current and flux when sudden changes in load occur.

44. The machine ventilation problem varies widely in converters for different frequencies and voltages. In high-speed 25-cycle converters of medium output, the armatures are small in diameter and relatively long. Every means is used to increase the natural air circulation. In these machines, heating and commutation are of approximately equal effect in limiting the output. In large 25-cycle converters of both voltages (250 and 600) and in 60-cycle converters for 250 volts, the natural air circulation is ample for the dissipation of the losses, but not excessive. In 60-cycle 600-volt converters and particularly in those of large size, the armatures are of large diameter and narrow, and the peripheral speeds are high. Under these circumstances, the natural air circulation is much greater than is necessary and greatly increases the windage loss. In such machines the natural air circulation is restricted as much as possible by stopping the air entrances in order to eliminate the unnecessary windage loss.

CHARACTERISTICS

45. The no-load saturation curves are very similar to the same curves for direct-current generators. There are two such curves—one with direct-current volts and one with alternating volts as ordinates. From these curves the actual no-load voltage ratio may be determined for any desired voltage.

46. **Heating of synchronous converters** occasions practically no difficulty either in design or in operation under proper conditions of power-factor, etc. The problem, however, varies with converters of different frequencies and voltages (Par. 44).

47. **The overload capacity,** as determined by heating and by flashing, is inherently large, due in great measure to the small armature reaction. The latter is particularly important since it results in small field distortion due to load. Consequently, on sudden changes in load, there is very little increase in voltage between commutator bars or shifting of the flux in the commutating zone, both of which, if present, would tend to cause flashing.

48. **The losses** may be divided into constant losses (with varying load) and variable losses. The constant losses are: core loss; friction and windage losses (including commutator and collector friction); and shunt field and rheostat loss (assuming that rheostat resistance and direct-current voltage remain fixed). The variable losses are: armature copper loss; series-field copper loss; commutating-field copper loss; brush I^2R and surface-contact losses; and load loss.

49. **Additional losses in the synchronous booster converter.** In the synchronous booster converter, the only additional losses at the mid-voltage are the booster armature copper loss and the load loss. At higher voltages, the converter core loss is increased due to the larger "motor" current, and the booster core loss and field copper loss are added. At lower voltages the converter core loss is reduced, since the flux is reduced; the converter copper loss is increased due to the larger "generator" current, and the booster losses are the same as for a corresponding increase in voltage.

50. **Additional losses in the split-pole converter.** In the split-pole converter there are no additional losses at the mid-voltage, but at either lower or higher voltages the converter core-loss is increased, since the flux density is increased (Par. 32 and Fig. 8). The converter copper loss is increased, as in the booster converter, at higher and lower voltages (Par. 31).

51. **Hunting of synchronous converters,** as in other forms of synchronous apparatus, is the periodic variation of the rotor from the true synchronous position with respect to the supply system. During hunting, the rotor is alternately ahead and behind its true synchronous position. In forging ahead, energy is expended in the converter, the latter acting as a motor; in dropping behind, the converter acts as a generator and gives up energy. This alternate motor and generator action is accompanied by a variation in the value of the flux due to the armature reaction, by a fluctuation of alternating-current and power-factor, and by a shifting of the commutating field which causes periodic sparking at the brushes. The frequency of the hunting cycle may often be determined from the frequency of the sparking. Hunting may be caused by periodic variation in the supply frequency, by sudden changes in load, or by excessive line drop. It is more likely to occur in 60-cycle than in 25-cycle converters, because of the greater number of poles and consequently smaller actual angular variation corresponding to the limiting electrical angular variation.*

52. **Hunting may be practically eliminated** by providing suitable **damper** or **amortisseur windings** in the pole faces. Since hunting is accompanied by a shifting of the flux across the pole face, the winding placed in the path of this flux will oppose any such change, and will tend to damp out the oscillations as soon as they begin. Practically all converters are now built with such windings (Par 42). Hunting troubles have also been greatly reduced by the use of generators driven by steam turbines or water turbines in which the angular velocity is much more uniform than in reciprocating engines.

53. **Interruption of energy supply.** If a converter is operating alone

* (a) Steinmetz, C. P. "Hunting;" *G. E. Review*, May, 1913.
(b) Newbury, F. D. "Hunting of Rotary Converters;" *Elec. Journal*, June, 1904.
(c) Lamme, B. G. "Causes of Hunting;" *Elec. Journal*, June, 1911.

or in parallel with other converters supplied from the same alternating-current feeders, the interruption of the alternating-current supply will bring the voltage on the direct-current side to zero, and the converters will stop. If, however, there is another source of direct-current connected to the same direct-current bus and not dependent on the same alternating-current feeders, interruption of the alternating-current supply will not cause the converter to stop; the direct-current voltage will be maintained and the converter will be driven as an inverted converter. If the shunt field happens to be weak or is interrupted, or if the converter should supply energy to an inductive load on the alternating-current side (such as a short-circuit on the high-tension side of the transformers) the speed will greatly increase. To guard against danger under such conditions, converters are usually provided with a speed-limit device, and the alternating-current and direct-current breakers are so interlocked that opening the alternating-current breaker opens the direct-current breaker. In addition, the direct-current breakers are sometimes provided with a reverse-current tripping relay. When the alternating-current supply is subject to serious drop in voltage due to short-circuits or other cause, it may be advisable to provide the alternating-current breakers with low-voltage tripping coils. This is particularly necessary with commutating-pole synchronous converters due to the flashing that would occur should the converter drop out of step as a result of low voltage, and later start with the brushes down when the voltage resumes normal value.

54. The speed-limit device (Par. 53) consists of a pivoted weight rotating with the converter shaft; the centrifugal force acting on the weight is counter-balanced by a spring. The weight moves outward and operates a switch when the predetermined overspeed is reached. The switch closes (or opens) the circuit of the shunt tripping coil of the direct-current breaker.

GENERAL APPLICATIONS

55. Comparison of efficiency with that of a motor-generator set. The efficiency of a 60-cycle converter including its transformers will be from 3 per cent. to 5 per cent. higher than an equivalent synchronous motor-generator set without transformers. The 25-cycle converter shows a further gain in efficiency over the motor generator set of from 0.5 to 1.0 per cent. If the line voltage is above 13,200 volts, transformers will usually be required with the motor-generator set as well as with the synchronous converter, so that the difference in efficiency in favor of the latter will be further increased by 2 per cent. This higher efficiency of the converter is such an important advantage that it is sufficient alone to justify the use of synchronous converters wherever possible.

56. Comparison of required floor space with that of a motor-generator set. The floor space required by 60-cycle converters and transformers is approximately equal to the floor space required by 60-cycle motor-generator sets of compact design. The fact, however, that the transformers may be placed in some remote location makes the arrangement of synchronous converters and transformers more flexible and gives them in many cases the advantage of reduced floor space.

57. Comparison of cost with that of a motor-generator set. The combined cost of synchronous converters and transformers is approximately equal to the cost of synchronous motor-generator sets without transformers, assuming a motor voltage of 2,300 volts or lower. For higher alternating voltages the motor cost increases appreciably, making the comparison favorable to the converter equipment. With alternating pressures above 13,200 volts, transformers are necessary with the motor-generator set as well as with the synchronous converter, so that the cost of the converter equipment is relatively still lower. With 60-cycle apparatus under 200 kw. capacity and alternating voltages of 2,300 volts and lower, the comparison is somewhat in favor of the motor-generator set, while with larger apparatus the comparison is somewhat in favor of the synchronous converter. In few cases, however will there be sufficient difference in cost alone to determine the choice of the apparatus.

58. Comparison of reliability with that of a motor-generator set. The design and construction of synchronous converters has been standardised to such an extent that in respect to reliability the comparison is mainly concerned with the number of machines involved. Compared with a three-unit motor-generator set consisting of a synchronous motor, direct-current generator and direct-current exciter, the single unit converter has a decided advantage. The comparison between the motor-generator set and the booster converter is apparently less favorable on account of the additional booster generator, but there are so few troubles that can reasonably be expected in a relatively small low-voltage alternator that the difference is more apparent than real.*

59. Comparison of voltage control with that of a motor-generator set. In this characteristic the synchronous motor-generator set has an advantage over the synchronous converter. The independence of alternating and direct-current voltage in the motor-generator set may justify its use on alternating-current circuits in which the voltage fluctuates badly and where it is essential to maintain steady direct-current voltage. Even under such conditions of fluctuating alternating voltage it is considered preferable, by some engineers, to employ the converter and obtain the desired steady direct-current voltage by means of a regulator.†

60. Comparison of power-factor control with that of a motor-generator set. The motor-generator set, including a synchronous motor, may be designed to correct power-factor more economically than can the synchronous converter. For this reason, the motor-generator set is usually employed where considerable power-factor correction is necessary.

61. For railway service compound-wound synchronous converters are generally used, sufficient reactance being placed in the alternating-current supply circuit to obtain the necessary voltage regulation. For this service on 25-cycle systems, synchronous converters are used to the practical exclusion of motor-generator sets and other forms of conversion apparatus. On 50-cycle and 60-cycle systems, the use of motor-generator sets, and in Europe the use of motor converters has, in the past, been more general; but even for these higher frequencies the use of the synchronous converter is rapidly growing.

62. For lighting and power service, the shunt-wound converters with induction regulators or the more specialized forms of split-pole and booster converters are used. On the larger 25-cycle systems, the use of converters is general. On 60-cycle systems, their use, particularly in the booster form, is rapidly growing, due mainly to the gain in efficiency.

63. The synchronous converter can be used to supply 3-wire direct-current circuits without any structural change, except in the case of compound-wound or commutating-pole converters, in which the series windings on alternate poles are connected in the positive and negative leads so that unequal currents in these leads will not affect the magnetization of the converter. See Par. 35 and Fig. 14 for the transformer connections necessary to obtain the neutral lead. The synchronous converter will operate under extreme differences of current value in positive and negative leads with very small differences in voltage between the outside leads and the neutral lead. For example, a 1,000-kw., 60-cycle, 280-volt commutating-pole booster converter, operated with full-load current in the positive lead and half-load current in the negative and neutral leads, had a difference of only 1 volt in the pressures from neutral to positive and neutral to negative leads. The same converter, operated with full-load current in the positive and the neutral leads and zero current in the negative lead, had a difference of 4 volts in the pressures from neutral to positive and neutral to negative leads. Without the resistance drop of the booster armature winding, the voltage balance would have been still better.

64. For electrolytic work, either shunt-wound converters without means for varying the voltage, or the same types of variable voltage converters as used for lighting service, are generally employed.

OPERATION

65. Alternating-current self-starting. The synchronous converter may be started as an induction motor if alternating current at reduced vol-

* Lincoln, P. M. "Motor Generators versus Synchronous Converters;" *Proc.* A. I. E. E., March, 1907.

† Walker, Miles. "Rotary Converters versus Motor-Generators;" *Jour.* I. E. E. (London), Discussion, Vol. XXXVIII, page 428.

tage is applied to the collector-rings. The armature winding acts as the primary and the squirrel-cage winding imbedded in the pole faces acts as the secondary. For the smaller converters one starting voltage only is required. The middle terminals of a double-throw switch are connected to three of the collector-rings, one set of outer terminals is connected to the starting-voltage taps of the transformers and the other set of outer terminals is supplied with the full voltage of the line. With six-phase converters three leads are carried direct from the transformer to the converter, and three through the main and

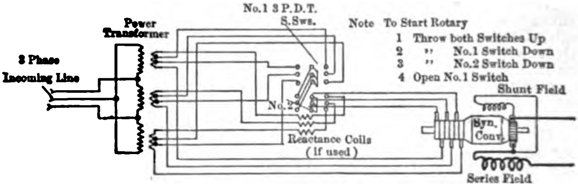

Fig. 15.—Alternating-current self-starting connections with two starting voltages.

starting switches. With the largest converters, it is usual to employ two starting voltages for which two double-throw three-pole switches are required. The connections for this arrangement are shown in Fig. 15.

66. Field "break-up" switch. During the starting period the field winding has voltages induced in it of magnitudes depending upon the ratio of armature and field turns. To prevent a dangerous induced voltage in the field winding, it is usual to open the field circuit in several places during the starting period by means of a multi-point double-throw switch, which is usually located on the frame of the converter. Appreciable voltage rise in the field circuit may also be prevented by closing the field circuit during start-

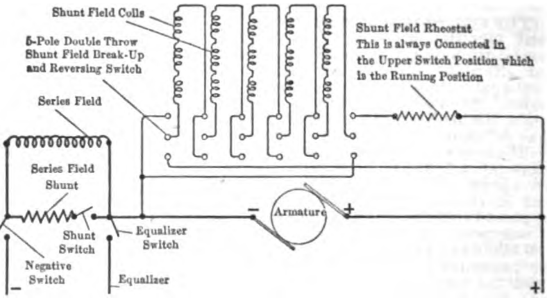

Fig. 16.—Converter connections on direct-current side (alternating-current self-started).

ing. This method is beginning to be employed because it only requires a double-pole double-throw field switch which may be conveniently located on the starting panel adjacent to the main switch.

67. Series-field switch. If a series-field shunt is used, a switch is usually provided for opening the closed circuit formed by the series field and its shunt. If this low-resistance circuit were left closed, the single-phase current induced in it would tend to decrease the starting torque. This effect, however, is small. The detail connections of the direct-current side of the converter are shown in Fig. 16.

68. Reversed polarity with alternating-current self-starting converters. In this method of starting with a self-excited field winding, there is no method of predetermining the polarity of the direct-current terminals. However, if the converter falls into step with the wrong polarity, the machine may be forced to "slip a pole" (if the armature is connected to the low-voltage taps) by reversing the field switch. When the voltmeter indicates that the voltage is reversed, the field switch should be brought back to its original

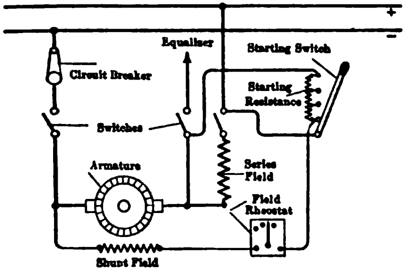

FIG. 17.—Direct-current self-starting connections.

position. In some converters, the field set up by the alternating-current may be so strong even at the lowest starting voltage that the converter cannot be made to "slip a pole" by reversing the field. Under these circumstances it is necessary momentarily to open and close the starting switch, repeating this operation until the correct polarity is obtained.

69. Direct-current self-starting. The converter may be started as a direct-current shunt-wound motor. The current flow at starting is limited by an adjustable resistance controlled by a multi-point starting switch. The connections for this method are shown in Fig. 17.

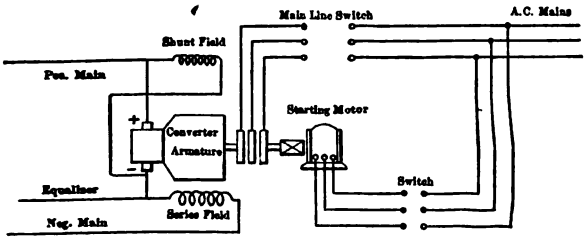

FIG. 18.—Alternating-current motor-starting connections with manual synchronizing.

70. Alternating-current motor starting. A motor usually of the induction type is mounted on the converter shaft. The motor has fewer poles than the converter and, therefore, a higher synchronous speed. In starting, the motor is usually connected directly across the line. The connections for this method are shown in Fig. 18.

A modification of this method has recently been brought out by Dr. Rosenberg of Manchester, England, and by James Burke* in this country, which consists in connecting the starting-motor windings in series with the converter armature. This limits the starting current to a low value, and the

* See U. S. Patent 1073662.

alternating current in the converter armature causes it to lock automatically in synchronism.*

An older modification of the simple motor-starting method, designed to eliminate the necessity for synchronizing, is the addition of reactance in the main circuit as shown in Fig. 19. When the starting motor has brought the converter armature near synchronous speed, the main-line switches are closed with the reactance in circuit. The resulting current in the converter armature causes it to lock in synchronism, after which the reactances should be short-circuited.

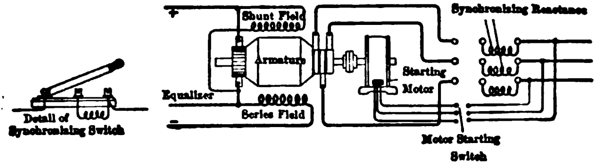

Fig. 19.—Alternating-current motor-starting connections self-synchronizing with reactance.

71. Starting small single-phase converters. A method of starting, adapted to small single-phase converters, has been developed by the Wagner Electric Manufacturing Company, and is used on the small single-phase converters built by that company for charging electrical vehicle batteries, the supply of direct current for moving-picture arc lamps and similar purposes. A special distributed field winding is provided on the stator, so connected that with the double-throw starting switch in the starting position the converter starts as an alternating-current series-wound commutator motor. When the starting switch is thrown to the running position, the alternating-current leads are transferred to the collector-rings, the main-field winding is connected in shunt with the main direct-current armature leads and a part of the field winding is short-circuited to act as a damper winding. See Sec. 17, "Garage Equipment."

72. Methods of synchronizing. With the simple motor-starting method, or with the direct-current self-starting method, the converter must be synchronised with the alternating-current supply circuit before the main-line switches can be closed. The theory and methods involved are the same as employed in synchronizing two alternating-current generators (Sec. 7). Lamps or specially designed instruments (Sec. 3) may be used for indicating synchronism, as with generators.

With the motor method of starting, the running speed of the starting motor should, in general, be higher than the synchronous speed of the converter. The speed may be brought down to synchronous speed by increasing the load on the converter. This can be accomplished by increasing the voltage, thereby increasing the converter losses, or by connecting a resistance across the alternating-current terminals of the converter. Small adjustments in speed may be made by alternately opening and closing the starting-motor switch.

With the direct-current self-starting method, the speed regulation for synchronizing is obtained by varying the converter shunt-field current. The series-field circuit is opened to insure more constant speed under the condition of varying armature current. To prevent a rush of current at the instant of synchronizing, it is usual to leave a small amount of resistance always in the starting-rheostat circuit.

73. Comparison of different starting methods. The alternating-current self-starting method is used in most cases on account of its simplicity and its automatic synchronizing feature. Its principal defects are the uncertainty in polarity and the large starting current required. In most cases wrong polarity can be corrected by means of the reversing field switch (Par. 66), and the amount of starting current is of importance (aside from the momentary line drop) only when the converter rating approaches the rat-

* Report of Com. on "Electrical Apparatus," National Electric Light Asso. Proceedings, 1914.

ing of the alternator supplying it. With commutating-pole synchronous converters, the simplicity of this method is decreased by the necessity of lifting the direct-current brushes. The presence of the steel of the commutating poles greatly increases the armature flux during starting, which causes destructive sparking at the direct-current brushes. To avoid this objectionable feature, commutating-pole converters are provided with a special device for lifting all but two of the brushes (which indicate polarity) during the starting period.

The advantage of the alternating-current motor method of starting is the small current required and the certainty of obtaining correct polarity; the principal disadvantage is the necessity for synchronizing. This disadvantage is overcome by the Rosenberg method or by the use of separate reactance coils (Par. 75). As compared with the alternating-current self-starting method, this method is somewhat more complicated and the necessary apparatus is more expensive. In some cases, however, where small values of starting current are imperative, it is the only method which will meet the requirements.

The direct-current self-starting method can only be used where direct current in sufficient amount is always available. It is very often used in large city lighting and railway substations. It has the advantage of minimum starting current and the absence of disturbances on the alternating-current supply system (which is particularly important on underground distribution systems). As with the simple alternating-current motor method, it has the disadvantage of necessitating manual synchronizing. This disadvantage has been overcome in some cases by combining the direct-current and the alternating-current self-starting methods. The converter is started by means of direct current, and when a speed near synchronous speed has been reached, the alternating-current switches are closed.

74. Parallel operation. When two or more converters are connected to the same low-tension bus on the alternating-current side and to the same bus on the direct-current side, the total direct-current load will divide among the several converters in the inverse ratio of the counter e.m.fs. of the converters and the resistances of the circuits. If two or more converters are so connected, the alternating-current and the direct-current bus bars close the circuit through any pair of converters; hence if the counter e.m.fs. of the two converters vary even slightly, considerable current will circulate between them. The counter e.m.fs. of different converters are seldom exactly the same, and the resistances, made up mainly of the direct-current brushes and brush contacts, are extremely variable—even in the same converter at different times. For these reasons it is not considered good practice to operate converters in parallel on both the alternating-current and the direct-current sides. Separate banks of transformers are usually provided—one for each converter. These not only open the circuit between converters, but also provide means for correcting slight differences in the voltage ratio of different converters.

75. Division of load on the direct-current side is controlled by the same factors as in direct-current generators, and in addition by factors peculiar to the synchronous converter. Division of load is controlled by the voltage, so that all factors affecting voltage affect parallel operation. Parallel operation of shunt-wound converters, with or without auxiliary means for controlling the voltage, is as simple as parallel operation of shunt-wound direct-current generators. With compound-wound converters, equalizer leads are necessary as in direct-current generators. (Sec. 8.)

76. Corrections for improper division of load. With two converters operating in parallel on the direct-current side, one of which takes less than its proportionate share of the load, the load may be equalized by one or a combination of the following adjustments:

(a) **Adjustment of the series-shunt resistance.** The shunts on the series-field windings can be adjusted, decreasing the resistance of the shunt, if possible, on the overloaded converter or increasing the shunt, on the underloaded converter. It should be borne in mind, however, that changing the ampere-turns in the series field by changing the shunt resistance also changes the resistance of the complete series-field circuit. This change in shunt resistance must be compensated for by a corresponding change in the resistance of another part of the series-field circuit, so that the resistance of the total circuit remains unchanged. From another standpoint, a shunt on one converter series field may be considered to be a shunt on both series fields, the effect varying only by reason of the fact that the resistance of the leads and busses is added to one shunt circuit and not to the other (Sec. 8).

(b) **Insertion of resistance in leads between series-field and equalizer bus.** If the relative ampere-turns are correct but the series-field resistances are differently proportioned, the resistance of the leads between the series field and the equalizer bus may be changed to compensate for a difference in the series-field resistances. The resistance in the series circuit of the converter taking more than its share of the load should be increased. This adjustment varies the resistance of one series field without introducing a third parallel circuit between the equalizer and the main bus. Adjustment by this method is less complicated than an adjustment of the series-shunt resistance.

(c) **The transformer ratio can be changed.** This increases the voltage by the same amount throughout the range of load, and will not correct for an unequal division which changes with the total load. An increase in no-load voltage of one converter will cause, at lighter loads, a greater increase in proportionate load on that converter.

(d) **The reactance can be increased in the circuit of the lightly loaded converter,** which will raise its direct-current voltage and cause it to carry more nearly its proper share of the load. This method is similar in effect to an increase in the number of series-field turns, but the effect is obtained at the expense of a greater range in power-factor. It sometimes happens that the reactances of converters in parallel are worked at different saturations, with the result that the reactance voltages of the two converter circuits will have different ratios at light and at heavy loads. Such a relation will cause the converter with the more highly saturated reactance to take less than its share of the load at heavy loads.

(e) **The relative shunt-field currents of the two converters can be changed.** The converter having the smaller ratio of series-field ampere-turns to armature ampere-turns should have its shunt-field current increased. This will increase its no-load voltage (on account of change in power-factor) and cause it to take a greater share of the load at light loads. The voltages will tend to equalize as the load increases, a correct division being obtained at only one value of the load.

77. Load-division study. Since there are so many variables affecting load division, it is important to make a careful and systematic study of the particular case before making any changes. Such a study should be conducted as follows:

(a) Adjust the transformer ratios so that at no-load and with the shunt field adjusted to give equal power-factors, all converters have the same no-load direct-current voltage.

(b) The series fields should be adjusted by shunts so that the ratio of series-field ampere-turns to armature ampere-turns is the same.

(c) The resistances of the series fields (including shunt) plus the resistances of the leads from the series fields to the main bus (positive or negative) should be so adjusted that the resistances are inversely proportional to the rated capacities of the converters.

(d) The reactances should be adjusted, if possible, so that the reactance volts of the various circuits throughout the range of load are equal. If they cannot be made equal, the series ampere-turns should be greater in the converter having the smaller reactance, to afford an approximate compensation.

It is only possible to obtain correct division of load and equal power-factor on all converters when the machines are properly proportioned with respect to all four elements, namely: the transformer ratio, the series-field ampere-turns, the series-field resistance and the reactance.

78. Interruption of alternating-current supply by circuit breaker in substation. Under such conditions, if the converter is connected to another source of direct current, the converter will "motor" unless the direct-current breaker is opened by interlock with the alternating-current breaker (Par. 58) or by a reverse-current relay. A compound-wound converter will run in the same direction when the direct-current power is reversed, the current in the series winding will be reversed (unless there are several converters in the same station connected to an equalizer bus), and the current in the shunt winding will remain the same in direction. With a single converter in a substation which is connected to other converters in other substations on the direct-current side, the converter will increase its speed due to the reversed series field. It may also increase its speed if the shunt field is adjusted for less than 100 per cent. power-factor. The increase in speed from the reversed series field will not be serious unless there is a circuit connected to the alternating-current side which will provide a load. Under these conditions the overspeed device will operate, thereby opening the direct-current breaker.

79. Interruption of alternating-current supply outside substation. In this case an interlock between the substation alternating-current and direct-current breakers will not operate to open the direct-current breaker, and reverse current or overspeed must be depended upon to protect the converter.

In case of interruption of alternating-current supply the converter should be manually disconnected from the direct-current lines (if this is not done automatically) and the switches on the alternating-current side opened for starting.

80. Commutating-pole converters require more complete protection from low alternating voltage because of the excessive sparking at the commutator which is encountered when the converter is not in phase with the supply circuit. If the alternating voltage is lowered momentarily by a short-circuit or other cause, the converter may fall out of synchronism. When the voltage is restored the converter will not be in phase and the sparking may be sufficient to make the converter "buck." The conditions are similar to those which exist when starting the converter with the brushes down.

81. Protection of high-voltage converters. High-voltage converters (1,200 volts and above) should be more completely protected from abnormal conditions than low-voltage converters on account of the more destructive nature of the "bucking" when once started.

82. Sparking at the brushes may be due to any of the following causes: (a) brushes incorrectly set with reference to the neutral point. Correct setting is of particular importance in commutating-pole converters; (b) brushes of improper characteristics; (c) defective electrical design; (d) hunting; (e) severe overloads or extreme variation in load; (f) in non-commutating pole converters, low alternating voltage with large direct-current loads; (g) brush holders insufficiently supported; (h) brushes stuck in holders or inaccurately fitted to commutator; (i) improper brush tension; (j) rough commutator due to high bars, to high mica or to flat spots.

83. Bucking or flashing may be brought about by any condition causing excessive voltage in the coils short-circuited by the brush or between adjacent commutator bars, or may be caused by abnormally low-surface resistance on the commutator between adjacent brush arms. Any condition tending to produce poor commutation increases the likelihood of bucking. Excessive voltage under the brush is usually caused by short-circuits of varying degree. Any direct-current machine will flash if short-circuited at its terminals and the direct-current voltage is maintained. Short-circuits in service usually occur on the line, so that some resistance exists between the "short" and the machine, thereby limiting the current. Excessive voltage between commutator bars is caused directly by increased line voltage, or is indirectly caused by extreme current overloads which distort the field flux. Increased line voltage may be due to disturbances on the high-tension distributing system induced by lightning, switching, short-circuits, etc. A decrease in the insulation strength between brush arms may be due to the presence of conducting gases formed by a relatively small flash or of foreign substance such as dirt or water. Ordinary types of circuit breakers do not act quickly enough to protect machines from abnormal changes in current or voltage. On short circuits, for example, the current increases far beyond the setting of the breakers before the circuit is finally opened.

84. Reactance used as a protection against short circuits. Shunt-wound synchronous converters may be protected from the effects of short circuits by inserting reactance in the alternating-current leads. Twenty-five per cent. reactance, for example, will cause a drop in alternating voltage to approximately zero with four times full-load current, but the drop at full-load current will not be objectionable.

TESTING

85. The tests ordinarily made on synchronous converters are as follows: (a) resistance measurements; (b) polarity determination; (c) ratio of voltages; (d) core-loss and saturation test; (e) alternating-current short circuit or synchronous-impedance test; (f) starting tests; (g) voltage regulation test; (h) temperature tests; (i) commutating-pole saturation test.

86. Measurement of resistance. Resistances may be measured either by the bridge method or by the use of ammeter and voltmeter as in direct-current machines. It is customary in obtaining the armature resistance to measure the resistance both on the direct-current side between the proper commutator bars, and on the alternating-current side between the corresponding slip-rings.

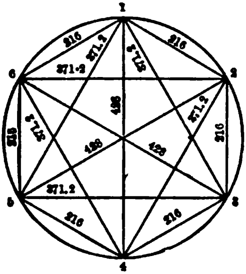

Fig. 20.—Diagram of converter voltages between collecter-rings.

87. Determination of polarity. The correct polarity of the field windings is determined in the same manner as for direct-current generators. The relative polarity of the shunt and the series windings in the compound-wound converter is also determined the first time the converter is under load.

88. Determination of voltage ratio. In order to determine whether the various taps from the armature winding have been brought out correctly and connected to the proper rings, readings of voltages between each ring and every other ring are taken. During the test the direct-current voltage is held constant at some convenient value. The armature winding is usually connected to the collector-rings so that adjacent rings have the minimum voltage possible between them. Under these conditions the voltage between adjacent rings is given by the following formula, N being the number of rings:

$$E_{ac} = \frac{E_{dc}}{1.415} \left(\sin \frac{180 \text{ deg.}}{N}\right) \quad \text{(volts)} \qquad (3)$$

A convenient method of checking the values obtained on test is to construct a diagram such as that in Fig. 20. The numbers outside of the circle represent the collector-rings. The voltages shown were actually obtained from a 600-volt six-ring converter.

89. Determination of core-loss, saturation, friction and windage losses. This test is made either by driving the converter by a small direct-current motor or by driving the converter itself as a direct-current shunt-wound motor. The test is the same as the corresponding test of a direct-current generator except that alternating voltages are obtained as well as the direct-current voltage, in order to obtain the actual voltage ratio. If the converter is self-excited during the test, the measured loss must be decreased by the field-winding and rheostat losses. The **brush friction** is determined by the difference in the measured losses with the brushes down and the brushes up. This reading is of no value unless the commutator has a good polish and the brushes are well seated. The **friction and windage losses** are determined by the difference in measured converter losses with the brushes removed, and with the driving motor running disconnected from the machine under test.

90. Starting tests. With the alternating-current self-starting method, a test is made to check the sufficiency of the starting voltage to bring the converter up to synchronous speed. It is customary to measure the voltage, current and time required to reach synchronous speed. With the induction-motor method of starting, the test is made to ascertain whether the load on the starting motor (provided by the converter) is such as to permit it to operate sufficiently near the converter synchronous speed at the normal converter voltage, so that synchronising will be possible. If the normal losses of the converter are not sufficient to reduce the starting-motor speed to the converter synchronous speed, it is necessary to determine the additional load required.

91. The voltage-regulation test can be made only when the entire equipment of transformers and reactances to be installed with the converter is available. Even under such circumstances the test must be made on the basis of constant alternating voltage on the high-tension side of the transformers. This is rarely, if ever, true in practice, so that the test unless made after installation is of little value and is seldom made. Furthermore, there is no object in adjusting the series winding of a converter except in conjunction with all other converters with which it is to operate in parallel on the direct-current side. With compound-wound converters, the alternating voltage should be adjusted to the desired value, and the shunt field of the converter should be adjusted to give the correct voltage at no load. If the transformer ratio is correct, this will require considerable lagging current, which may be obtained by under-excitation. Load is then placed on the converter and the desired full-load voltage is obtained by adjusting the series-field shunt. This test is never made with shunt-wound converters since a slightly drooping voltage characteristic would always be obtained, and there is no means within the converter of modifying it. With converters designed for wide voltage ranges, it is customary to observe the operation at the maximum and minimum pressures to insure that there is sufficient range in the field windings and rheostats to obtain 100 per cent. power-factor at all voltages, and that satisfactory commutation is obtained throughout the voltage range.

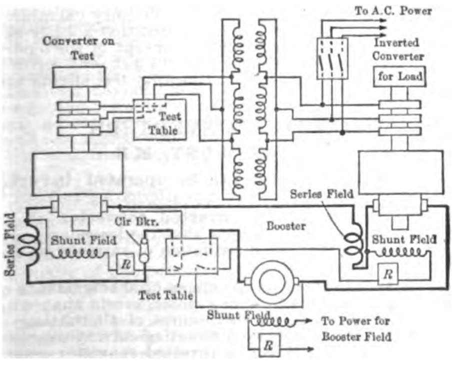

FIG. 21.—Loading-back temperature-test connections.

92. The temperature tests at the factory are performed either by direct loading on resistances or by "**loading back**" on a similar converter or power circuit. In the loading-back method (using a similar converter), the losses can be supplied from either the direct-current or alternating-current sides as is found convenient. The alternating-current sides of the machine under test and of the test machine may be connected together by a complete metallic circuit, or through transformers having a one-to-one ratio. The latter arrangement is preferable, as conditions are thus made more stable and can be more easily controlled. The connections for such a test are shown in Fig. 21. When the machines under test are compound-wound, it is necessary to reverse the series field of the converter running inverted. In Fig. 21 the losses are supplied partly from the alternating-current side and partly by a booster in the direct-current side. Temperature tests are usually made with 100 per cent. power-factor at the converter collector-rings. To obtain this condition, the shunt field should be adjusted for the proper no-load voltage, and the series field shunted to give 100 per cent. power-factor, that is, a minimum value of armature current, at the tested load.

93. Commutating-pole saturation test. On commutating-pole converters this test is made to determine the sensitiveness of the converter to proper adjustment of the commutating-pole ampere-turns. The converter is so connected that it can be loaded with the commutating poles separately excited, in order that the excitation can be adjusted. For various loads and, in variable voltage converters, for various voltages, the minimum and the maximum commutating-pole excitations are determined between which satisfactory commutation is obtained.

94. Determination of efficiency. Efficiencies are usually determined by separate measurements of the various losses. This method does not derive the true efficiency, as the so-called load losses or stray losses cannot be included by direct measurement. Such losses, however, in converters are small and no appreciab e error is introduced by omitting them. They are less in low-frequency converters than in high-frequency converters. If the true efficiency is required, it can be measu ed only by an input-output load test, which may be made with the converter carrying a resistance load or loaded back on another converter. On account of the relatively small losses involved and the large number of instruments to be read, such a test can be made satisfactorily only under laboratory conditions where the power input and output are absolutely steady, and where carefully calibrated instruments are read by skilled observers. Unless the test can be made under such conditions more accurate results will be obtained by calculating the efficiency from the separate measurable losses, and including a reasonable allowance for the load losses.

The reason for the greater accuracy of the efficiency calculated from the separate losses is apparent when it is remembered that a 2 per cent. error in the measurement of the losses results in only 2 per cent. of the 5 per cent. losses (using 95 per cent. as the true efficiency) or 0.1 per cent. error in the efficiency, while 2 per cent. error in the input-output test affects the efficiency by an equal percentage.*

INVERTED CONVERTERS

BY F. D. NEWBURY, M.E.

95. Any synchronous converter can be operated inverted; that is, it can be used to convert direct current into alternating current.

96. The internal action of the inverted converter is the same as that of the synchronous converter except that the losses are supplied from the direct-current side, so that the distribution of currents in the armature is slightly different.

97. The inverted converter has the speed characteristics of a direct-current motor instead of a synchronous motor, except that when the converter operates in parallel with another source of alternating current the speed is controlled by each of the two alternating-current sources in proportion to its share of the load. When an inverted converter operates singly, its speed may be seriously affected by a change in load or power-factor on the alternating-current side. A lagging alternating-current load will demagnetise the main fields and the converter speed will increase, as would that of any direct-current motor with weakened field.

98. Alternating voltage control. There is no means of varying the alternating voltage corresponding to the reactance and series-winding method used with the synchronous converter. The alternating voltage may be controlled by any of the other methods discussed in connection with the synchronous converter.

99. Inverted converters are usually shunt-wound in order to secure as nearly constant speed and frequency as possible.

100. Correction for overspeeding. Where inverted converters are subject to loads of varying power-factor and where constant speed is essential, it is customary to use a separately excited field winding, the excitation being

* See footnote, Par. 32.

supplied by a direct-connected exciter. The exciter is designed with an unsaturated magnetic circuit so that a change in speed will produce a maximum change in exciter voltage. With this arrangement an increase in speed of the inverted converter is at least partially corrected by the increase of its excitation due to increased exciter voltage.

101. Protection against overspeeding. Where the conditions do not require the separate exciter, it is customary to install an overspeed tripping device to protect the converter and its alternating-current load from excessive speed due to unusual conditions.

102. Applications of the inverted converter. The following applications of the inverted converter may be mentioned: (a) to supply a small amount of alternating-current from an existing direct-current supply; (b) to form a connecting link between alternating-current and direct-current systems for the transfer of energy in either direction. Under the latter condition the converter may operate either direct or inverted. An induction regulator or other means of varying the voltage is necessary to control the transfer of energy through the converter or, in the case of operating the load on one system entirely through the converter, to compensate for the voltage drop in the converter and transformers. (c) To enable a storage battery to be used to equalize the energy input in an alternating-current system. Here, also, a means of varying the voltage of the converter is necessary to control the charge and discharge of the battery. A notable installation of this kind is at the Indiana Steel Company, where a 2,000-kw. 250-volt, 25-cycle split-pole converter is used.

MOTOR CONVERTERS

BY F. D. NEWBURY, M.E.

103. Structure. The motor converter, or cascade converter, as it is sometimes called, consists of two elements, or machines, coupled together mechanically and electrically. The primary element, having the structure of an induction motor with a phase-wound rotor, performs the functions of a voltage, frequency and phase converter and of an induction motor. The secondary element, having the structure of a synchronous converter (with taps to the winding but without collector rings), performs the functions of a direct-current generator (driven by the induction motor, the rotors being mounted on the same shaft) and of a synchronous converter (receiving energy of suitable voltage, frequency and phase from the rotor winding of the primary element).*

104. Starting resistance. Three of the inside terminals of the rotor winding of the primary element are attached to collector-rings, to which the starting resistance is also connected. When operating at synchronous speed, all of the inside terminals of the rotor winding of the primary element are connected together to form the neutral.

105. The rotor of the primary element is wound with either 9 or 12 phases, the large number of phases being used to decrease the armature copper loss of the commutating machine. The large number of connections between the two rotors does not lead to any complication as they can be made solidly without collector-rings.

106. Transformers are required only when the line voltage exceeds the highest voltage for which the primary element can be safely and economically wound. In this respect the motor converter is on nearly equal footing with the synchronous motor-generator set. The difference in favor of the latter is due to the fact that the synchronous motor can be satisfactorily wound for higher voltages than the induction-motor element of the motor converter.

107. Applications. The motor converter occupies a position between the motor-generator set and the synchronous converter. Its main advantage over the motor-generator set lies in the fact that a part of the energy is transformed electrically and, therefore, more efficiently than in the motor-gener-

* (a) See German patent 145434 (1902); English patents, 3704 (1903), 7807 (1904); U. S. patent 72400 (1904).

(b) See Arnold u. la Cour, "Der Kaskadenumformer" Enke, Stuttgart, 1904.

(c) Hallo, H. S. "The Theory and Application of Motor Converters," *Journal*, I. E. E. (London), Vol. XLIII, page 197.

ator set in which all of the energy is transformed mechanically. For the same reason it is less efficient than the synchronous converter in which the entire output is transformed electrically. Its main advantage over the synchronous converter lies in the fact that the commutating machine of the motor converter operates at a frequency lower than the line frequency—usually at half the line frequency. This advantage applies only in the case of line frequencies above 40 cycles per sec. and for the higher direct-current voltages, and has been lessened even for these conditions by recent improvements in high-frequency synchronous converters. The motor converter has found its most extensive application in England and Germany. In England approximately 150,000 kw. of capacity has been installed since 1904, and in Germany approximately 65,000 kw. of capacity has been installed, mainly since 1908. These figures were compiled in July, 1913. Practically nothing has been done in the United States toward introducing the motor converter commercially, mainly due to the previous development of the high frequency synchronous converter.

108. Equations of the motor converter.

$$\text{Synchronous speed} = \frac{\text{Line frequency} \times 120}{\text{Sum of poles of both elements}} \quad \text{(r.p.m.)} \qquad (4)$$

$$\text{Rotor frequency} = \text{Line frequency} - \left(\frac{\text{Primary poles}}{120}\right) \text{(r.p.m.)}$$
$$\text{(cycles per sec.)} \qquad (5)$$

$$\text{Power transformed electrically} = \text{Total output} \left(\frac{\text{Secondary poles}}{\text{Total poles}}\right) \qquad (6)$$

$$\text{Power transformed mechanically} = \text{Total output} \left(\frac{\text{Primary poles}}{\text{Total poles}}\right) \qquad (7)$$

When the numbers of poles of both elements are equal, as is usually the case, these relations obviously become very simple.

109. The average armature current and heating in the commutating element is less than in a direct-current generator of equal rating, but more than in the corresponding synchronous converter. Assuming an equal number of poles in the two elements of a motor converter, the commutating element is operating half as a direct-current generator and half as a synchronous converter. Assuming further a twelve-phase rotor circuit and 100 per cent. power-factor at the terminals of the primary element, the average loss will be approximately 0.34 (relatively), the equivalent direct-current generator loss being unity. This is about 30 per cent. greater than the average loss in the ordinary six-phase synchronous converter, also at 100 per cent. power-factor. The maximum loss in one conductor is approximately 10 per cent. less than the maximum loss in the six-phase synchronous converter, at 100 per cent. power-factor.

110. The armature loss increases less rapidly with reduction in power-factor than in the 6-phase synchronous converter, due to the generator current loss, which does not vary with power-factor, and to the higher number of phases employed.

111. Power-factor. The power-factor at the line terminals of the primary element may be varied as in the simple synchronous converter by varying the field excitation of the commutating machine. The magnetizing current for the primary element may be taken from the line or from the secondary element as desired. This is controlled by the excitation of the commutating machine. If the set is operated at 100 per cent. power-factor, it follows that the secondary element is operating at a leading power-factor (with respect to line voltage) in the neighborhood of 93 per cent. at full-load. This has an important bearing on the heating and size of the commutating machine. See Par. 117.

112. Voltage control. A fixed voltage ratio exists between the alternating-current, and the direct-current sides of the commutating element of the motor converter, as in the synchronous converter, and the same means for varying the direct-current voltage must be employed. In a shunt-wound motor converter the direct-current voltage drops with the load assuming constant alternating voltage. In this case the necessarily high reactance of the primary element is a disadvantage. In a certain 500-kw.

motor converter the voltage dropped 5 per cent. between no load and full load. This is less than in a corresponding direct-current generator but more than in a corresponding synchronous converter. The motor converter is well adapted to voltage regulation by reactance and series-field excitation. In general, the primary element will contain inherently sufficient reactance to obtain a 10 per cent. voltage increase (assuming constant primary alternating voltage) with permissible range in power-factor. This range in voltage is ample for the ordinary railway system. Voltage ranges of 20 per cent. to 30 per cent. required by lighting systems using storage batteries cannot be obtained economically by reactance and series-field excitation. For such voltage variation an induction regulator, alternating-current booster or direct-current booster is required. The alternating-current synchronous booster must have the same number of poles as the secondary element and must be connected, electrically, between the primary and secondary rotor windings.

113. Relative size and cost. The cost of the primary or induction element will be approximately the same as that of an induction motor with phase-wound rotor at double the running speed (assuming equal primary and secondary poles). The cost of the secondary or commutating element will be less than that of a direct-current generator of the same rating and more than that of a synchronous converter of the same rating and operating frequency. The cost of the induction element will be somewhat more than that of stationary transformers necessarily used with the synchronous converter. On the basis of a line voltage so low that transformers are unnecessary with the motor converter, the cost without transformers is approximately the same as that of the higher-frequency synchronous converter and the necessary transformers. In case transformers must be used with either form of converter on account of high line voltage, the cost of the motor converter installation will be from 30 per cent. to 40 per cent. greater than the synchronous converter installation.

114. Efficiency. At capacities of 500 kw. and above, the efficiency of a synchronous converter and transformers would be 1.5 per cent. to 2 per cent. better than the motor converter without transformers, assuming American conditions which require the use of open armature slots in the primary element. Including the transformer in the motor converter installation would reduce its efficiency below that of the equivalent synchronous converter installation from 3 per cent. to 4 per cent.

115. The method of starting is the same as in an induction motor with phase-wound rotor, a three-phase resistance controller being used as indicated in the diagram in Fig. 22. It will be noted that, during starting, three phases of the rotor winding of the induction element are in series with the armature winding of the commutating element, the other phases remaining open at the neutral. After the main-line switch is closed, the rotor circuit of the induction element is closed through the starting resistance. As the rotor begins to revolve, two alternating currents are superimposed in the rotor circuits, one at maximum frequency decreasing with the speed, due to the induction element, and one at minimum frequency increasing with the speed, due to the commutating element. The latter current is appreciable only near synchronism or in the case of separate direct-current excitation of the secondary element. As the rotor approaches its normal running speed, these two currents approach the same frequency, which is indicated by a slow oscillation of the needle of the voltmeter connected in the starting circuit. At the moment the voltmeter needle passes through zero, the starting resistance is short-circuited and the set will thereafter operate synchronously. The neutral points of all the rotor phases are connected together and the starting brushes lifted from the rings by a mechanical device. By proper selection of the starting resistance, the starting current may be maintained at a low value throughout the entire starting operation. Due to the small armature current during starting, the direct-current voltage will always build up with the correct polarity. The field reversing switch commonly used with alternating-current self-starting synchronous converters is unnecessary.

116. The motor converter may be used to supply a three-wire direct-current circuit without change except that the brushes are left on the rings after starting. They are connected to the middle terminals of a three-pole double-throw switch, one set of outside terminals being connected to the starting resistance and the other set being short-circuited and connected to the direct-current neutral lead.

117. Commutating poles may be used on the commutating element as in any synchronous converter. Due to the combined generator and converter action the ampere-turns required on the commutating poles more nearly approach the ampere-turns on the equivalent direct-current generator than on the equivalent synchronous converter.

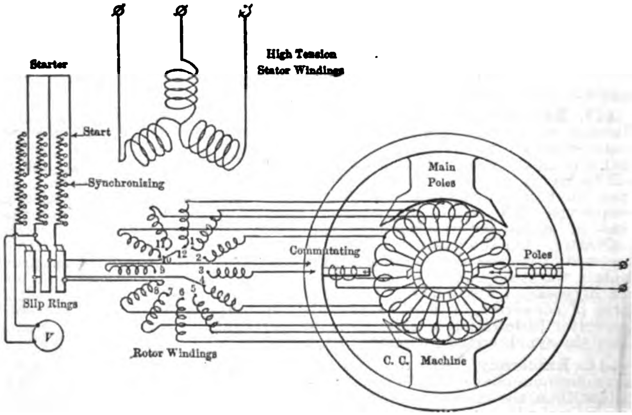

Fig. 22.—Diagram of connections of motor converter.

DIRECT-CURRENT CONVERTERS

BY ALEXANDER GRAY. See p. 2

118. Theory of operation. A three-wire generator, operating with no current in one side of the system, may be used as a direct-current converter with a ratio of two to one. Such conditions of operation are shown diagrammatically in Fig. 23. If the armature be connected across the terminals a and b, it will rotate as a direct-current motor armature and will take a current i_0, at a voltage $2e$, to supply the no-load losses in the machine. If now two diametrically opposite points c and d be connected through a coil C of high reactance and negligible resistance, and if the middle point f of the coil be connected as shown in Fig. 23, the machine will become a three-wire generator (Sec. 8, Par. 193). The point f is then midway in potential between c and d and, since the e.m.f. between c and d is alternating, an alternating current, supplied from the mains, will flow in the reactance coil. This current will be small since the reactance is large.

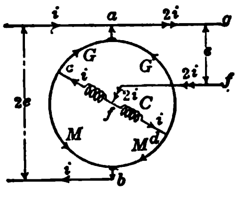

Fig. 23.—Current distribution in a direct-current converter.

A load current at voltage e may now be drawn from terminals f and g, and the current distribution in the system will then be as shown in Fig. 23, the no-load currents being neglected. The currents in sections M flow against the generated e.m.f., so that these sections may be considered to act as motors; the currents in sections G flow in the direction of the generated e.m.f., and so these sections may be considered to act as generators. The driving torque due to the motor sections must overcome the retarding torque due to the generator sections.

119. Armature currents. The current in the armature conductors varies as the armature revolves; this may be seen from Fig. 24 where the armature is shown in four different positions.

In position *A*, the resistance from *c* to *a* is equal to that from *c* to *b*, and the current *i*, entering the armature at *c*, divides into two equal parts. In position *B*, the resistance from *c* to *a* is less than that from *c* to *b*, and the current i_a is greater than the current i_b.

In position *C*, the current in *ca* is practically equal to *i* and that in *cb* practically zero. In position *D*, the currents in all the conductors are zero.

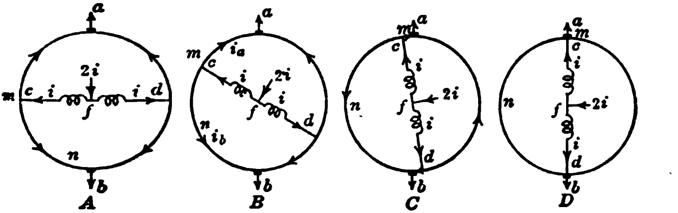

FIG. 24.—Relation between current and position of armature.

Fig. 25 shows approximately how the current varies in two coils *m* and *n* as the armature makes one revolution. In coil *m*, the current varies from zero to *i* while in coil *n* it varies from $-\frac{1}{2}i$ to $+\frac{1}{2}i$; the armature coils are therefore not equally heated. Those next the leads *c* and *d* are the hottest and those midway between the leads are the coolest.

120. The rating of a direct-current converter depends upon the number of phases of the reactance coil. With a 2-phase reactance coil, as shown in Fig. 26, the maximum current in the conductors is less than *i*, and the current in each armature coil is more nearly constant than when only one reactance coil is used. For the same average armature copper loss in each

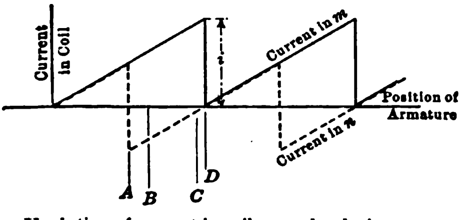

FIG. 25.—Variation of current in coils *m* and *n* during one revolution of armature.

case, a direct-current generator can be given the following ratings when used as a direct-current converter:*

1.00 as a direct-current generator;
1.22 as a direct-current converter with one reactance coil;
1.55 as a direct-current converter with two reactance coils;
1.64 as a direct-current converter with three reactance coils.

The cost and weight of the equivalent direct-current generator may be obtained from Fig. 67 (Par. 178) Sec. 8, an addition of 5 per cent. being made for the slip-rings.

121. The secondary voltage of such a system cannot readily be controlled independently of that of the primary; it decreases with increase of load according to Eq. 38 in Sec 8, Par. 194 and, with a reasonably priced

* Steinmetz, C. P. "Elements of Electrical Engineering," p. 337.

reactance coil, this decrease in voltage can hardly be less than 3 per cent. at full load.

122. The rating of the necessary reactance coil may be found from Sec. 8, Par. 197. The frequency, which equals the number of poles multiplied by the r.p.m. and divided by 120 will generally be between 15 and 40 cycles per sec.

123. The Dettmar and Rothert split-pole machine (Sec. 8, Par. 192) when used as a direct-current converter has the advantage that the secondary voltage can be controlled independently of that of the primary. Each pole of this machine is split so as to form two polar projections of like polarity and these are excited independently of one another. The neutral brush is placed on the commutator midway between the positive and the negative brushes and, by varying the excitation of one polar projection relative to that of the other, the flux entering the armature between the positive and the neutral brushes may be changed relative to that between the neutral and the

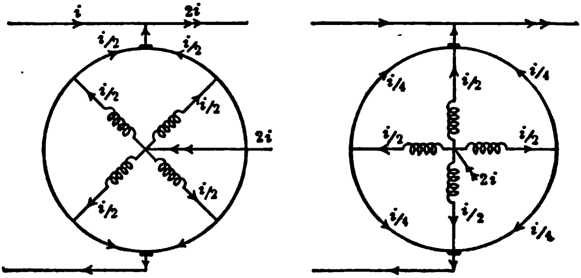

Fig. 26.—Current distribution in a direct-current converter with a two-phase reactance coil.

negative brushes, or the potential of the neutral brush may be varied as desired. By the use of suitable shunt and series coils on the polar projections, any desired degree of compounding may be obtained and, in the extreme case, a constant current may be obtained from the secondary of such a machine while the primary is operating at constant potential.

124. The C. M. B. autoconverter is another type of split-pole machine with the armature tapped by brushes placed between the main positive and negative brushes. A standard line of these machines is on the market and can be supplied with a transformation ratio as high as four to one, and with such a combination of shunt-field and series-field coils that a drooping secondary characteristic may be obtained if desired for constant-current operation. They are supplied with ball bearings and have an efficiency which varies from 75 per cent. for a 1 kw. unit to 86 per cent. for a 10 kw. and 94 per cent. for a 50 kw. unit.

125. Applications.* Direct-current converters of this latter type are used in place of motor-generator sets for many purposes, among others, to obtain 50 volts from a line of higher voltage for the operation of arc lamps at 50 volts in bioscope sets and search lamps. A constant-current characteristic is the most suitable for arc-lamp operation. They are also used for electric welding, the machines being built with such characteristics that, on short-circuit, the current is only 10 per cent. more than full-load current, while the voltage drops practically to zero.

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* For further information on direct-current converters see:
Steinmetz, C. P. "Theoretical Elements of Electrical Engineering," page 337; New York, McGraw-Hill Book Co., Inc.
MacFarlane and Burge. *London Electrician*, July 9, 1909.
Thompson, S. P. Report at Turin Congress; *London Electrician*, Sept. 29, 1911.

DYNAMOTORS

BY ALEXANDER GRAY

126. General description. The dynamotor is similar to the motor-generator set except that the two armature windings are on the same core and revolve in the same magnetic field, each winding being connected either to a commutator or to collector-rings, in accordance with its use for direct or for alternating current respectively. It is rarely necessary to change from direct current to alternating current, so that machines for such purpose are special. A change from alternating to direct current may be realized with less expense by the use of a rotary converter, with a transformer if necessary, than with a dynamotor.

127. Armature reaction. The armature for a direct current to direct-current type of dynamotor is shown diagrammatically in Fig. 27. Here the transformation ratio is four to one, so that there are four times as many effective turns in one winding as in the other. The direction of the generator current is that of the generated e.m.f., but the current in the motor winding is in the opposite direction. If the losses in the machine be neglected, then the

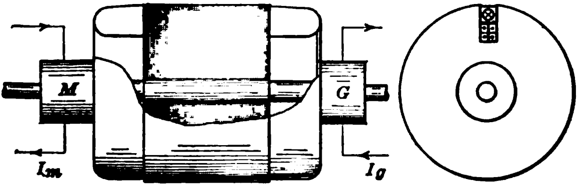

Fig. 27.—Arrangement of dynamotor armature and commutator.

motor input, E_mI_m equals the generator output, E_gI_g, and the value of effective ampere-turns in the motor armature, n_mI_m equals the value of effective ampere-turns in the generator armature, n_gI_g. Therefore the m.m.fs. of the two windings are equal and opposite and there is no resultant armature reaction. For this reason, the dynamotor can be allowed a smaller air gap, a smaller exciting current, and a lighter field coil than a standard machine built upon the same frame.

128. The commutation of these machines is exceedingly good if the brushes on the two commutators are so placed that the short-circuited coils of each of the two windings lie in the same slot. Under such conditions the currents in these coils change at the same time and in opposite directions, so that the reactance voltage is small (Sec. 8, Par. 43). Dynamotors can therefore have deep slots and low-resistance brushes and in consequence are suitable for delivering large currents at low voltages.*

129. Voltage regulation. The principal objection to the standard dynamotor is that the secondary voltage cannot be regulated without changing the excitation of the primary. The ratio of the terminal voltages is fixed by the ratio of effective armature turns and by the voltage drop due to the resistance of both armature windings, so that the terminal-voltage ratio is independent of the excitation and changes with the load. The transformation ratio for a given load can be changed only by inserting a resistance or a booster in the primary or the secondary circuit.

130. Combined dynamotor and booster. A machine which is equivalent to a combined dynamotor and booster can be made by extending one armature winding a longer distance axially along the core than the other, and applying to this extended part of the core a magnetic field from an auxiliary field system. The exciting current for this auxiliary field can be so regulated as to change the voltage of one winding independently of that of the other. If this field system be excited with series-field coils, the secondary voltage can be made to vary with the load, as desired. The chief advantage of this latter machine over the motor-generator set is that it requires less

* Sheldon and Hausmann. "Dynamo-electric Machinery," Vol. I, page 266.

floor space and will have a higher efficiency, but will probably not be cheaper if the machines are of corresponding construction.

131. A special dynamotor is extensively used for telephone ringing. The motor winding is for direct current and the other winding is connected to two slip-rings in order to deliver alternating current at from 16 to 19 cycles per sec., and about 75 volts (effective).

132 Dynamotors can be used in place of motor-generator sets only when the regulation of voltage is not of great importance as, for example, in the ringing of bells and gongs, the operation of signals in connection with fire alarms, telephone systems, annunciators and many other kinds of signaling, and the operation of magnetic contactor switches. For telegraphic work, dynamotors are often used in place of primary batteries, the secondary voltage being 50 to 500 volts direct current, depending on the length of the line (Sec. 21).

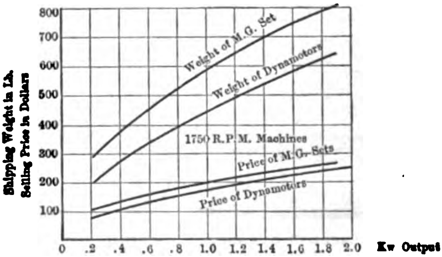

Fig. 28.—Weights and costs of small dynamotors and motor-generator sets.

133. Cost of Dynamotors. Since the two armature windings are upon the same core, that core will be larger for a dynamotor than for a generator of the same output. Fig. 28 shows the shipping weights and selling prices of small dynamotors and motor-generator sets of substantial make on a single bed plate, the motor-generator set consisting of two machines joined by a flexible coupling.

DOUBLE-CURRENT GENERATORS

BY F. D. NEWBURY, M.E.

134. Armature currents in the double-current generator. A machine having the same structure as the synchronous converter may be used to generate both alternating and direct current if driven by a suitable prime mover. Unlike the synchronous converter, the armature currents in the double-current generator are not less than in the corresponding direct-current generator. The alternating and direct-current are not subtractive, as shown in Figs. 1 and 2, but are additive, since both are generator currents. For the same reason, the generation of both alternating and direct current in the same armature winding is not favorable to commutation as in the synchronous converter, but is detrimental.

135. Dependance of direct-current voltage on alternating voltage. A double-current generator has none of the advantages of the synchronous converter and has many disadvantages of its own. One of the most serious disadvantages is the dependence of the direct-current voltage on the alternating voltage and on variations in alternating-current load and power-factor. A change in alternating-current load or power-factor will cause a change in the magnetizing effect of the alternating current in the armature winding and thus change the resultant magnetization on which the direct and alternating voltages depend. To assist in maintaining steady direct-current voltage, it is customary to excite double-current generators separately.

136. Alternating-current parallel operation. If double-current generators are operating in parallel with a relatively large alternating-current system on which the alternating voltage is held constant, the direct-current voltage will also be constant and cannot be varied independently of the constant alternating voltage.

137. Limitations of design. From the design standpoint, the double-current generator is handicapped by the rigid relationship between poles and speed required by the frequency. This, in general, results in the use of many more poles than would be employed in an equivalent direct-current generator, causing an appreciable increase in cost. This is particularly true with slow engine speeds and high frequency. It is also impossible to use commutating poles on account of the effect of variation in alternating-current load and power-factor. No machines larger than 2,500 kw. have ever been built in this type.

138. Abandonment of slow-speed type. During the past 10 years, no slow-speed engine-driven double-current generators of any importance have been installed. The reasons for this have been the disadvantages of the double-current generator already enumerated and the lower cost and greater flexibility of alternating-current generators used in conjunction with synchronous converters.

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SECTION 10

POWER PLANTS

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CONTENTS

(*Numbers refer to Paragraphs*)

SECTION 10

STEAM POWER PLANTS

BY REGINALD J. S. PIGOTT

LAWS OF HEAT TRANSFER

1. No heat can be transmitted from a cold body to a hotter one: flue gases must, therefore, leave the boiler at not less than the steam temperature in an ordinary boiler, or at not less than the incoming feed-water temperature in the counter-current type of boiler.

2. Two kinds of heat transfer take place in a boiler; absorption by radiation from incandescent fuel direct to heating surface, and heat transmission by contact and convection. Stefan and Boltzmann's law states that absorption by radiation is proportional to difference of the fourth powers of the two temperatures involved.

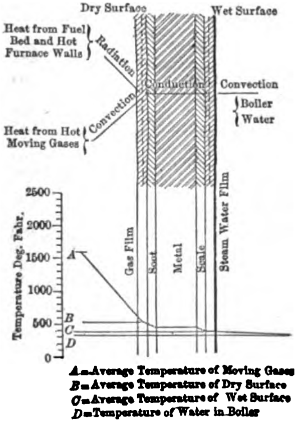

FIG. 1.—Transmission of heat.

B.t.u. radiated per sq. ft. per hour = $16 \times 10^{-10}\ (T_1^4 - T_2^4)$ (1)

where T_1 = absolute temp. in deg. Fahr. of "black" incandescent body, and T_2 = absolute temp. in deg. Fahr. of receiving body.

A "black" body such as carbon, in any form except the crystalline, will absorb all heat transmitted, reflecting none. Metal and other materials will reflect from one-fourth to one-half of that received.

3. Heating by convection from hot gases to water is proportional to some power of each of the velocities of the moving gases and water or steam. The heating is also proportional to the density of the fluids and to the absolute temperatures, since these influence the molecular energy. The formula for heat transfer by convection is,

$$H = AU(T_1 - T_2) \qquad (2)$$

where H = B.t.u. transmitted per hr., A = area, sq. ft., U = transmission coefficient, $T_1 - T_2$ = mean temp. diff.

4. The transmission coefficient for normal rating is somewhere around 5 to 8 B.t.u. deg. of mean temperature difference, per sq. ft., per hour, but may be much larger than this in boilers with much surface exposed to radiant heat and well scrubbed by the gases. The upper limit has probably never been reached, the maximum value for recorded tests being about 20.

5. Effect of dirty surfaces. One important difference noticeable between absorption of heat by conduction and by radiation is that the relative cleanness of the surface affects the rate of conduction very readily, but absorption of heat by radiation is practically unaffected. Soot increases the thickness of the film of motionless gas, besides adding its own resistance to heat flow.

6. The resistance of the film of inert gas entangled in the rough surface of the tube (or soot) is from 20,000 to 35,000 times as great as that of the metal tube alone, so that the thickness of the dead gas film is the controlling

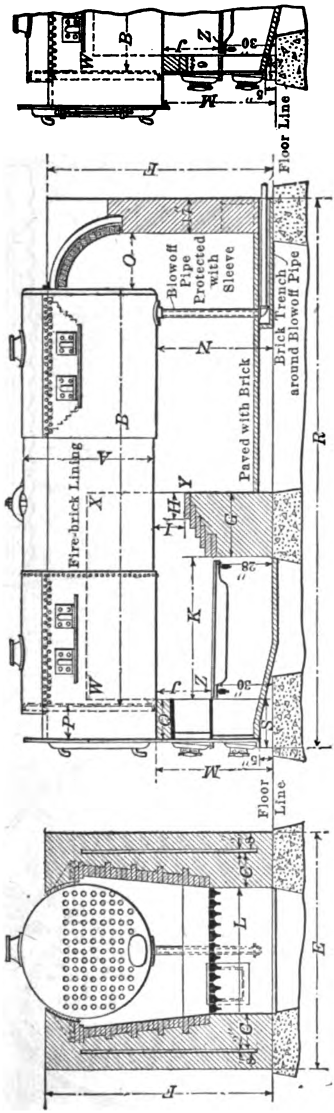

Fig. 2.—Horisontal return tubular boiler.

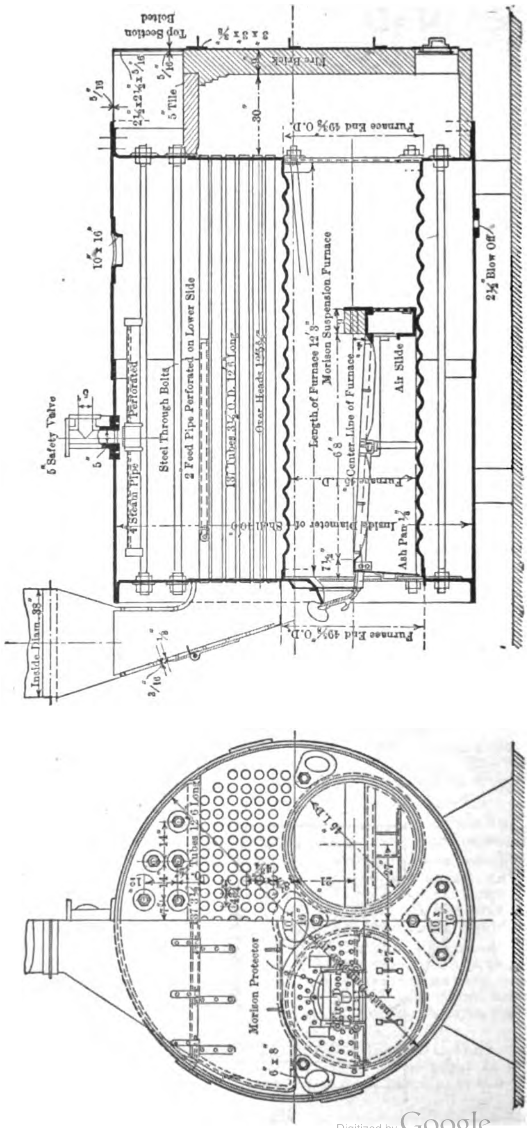

Fig. 3.—Scotch marine boiler.

factor. In absorption of heat by radiation, however, the interposition of a gas film or layer of soot has practically no effect, since conduction does not bear a part in the action.

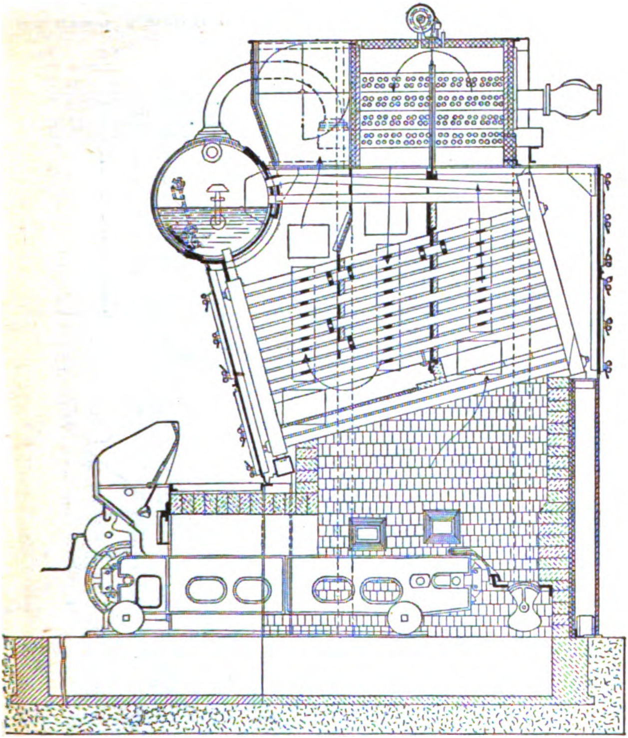

FIG. 4.—B. & W. marine boiler with superheater.

BOILERS

7. Boiler types: in the following classification modern types only are considered.

Fire Tube... { Horizontal return tubular (Fig. 2).
Scotch (Fig. 3).
Continental and other internally fired types (Fig. 3).

Water Tube. {
Definite circulation path. {
B. & W....... { Stationary (Fig. 5). Marine (Fig. 4).
Rust
Stirling (Fig. 6).
Heine, etc., etc., and 7
Yarrow
Thorneycroft.
Field Tubes............Niclausse

All types give efficiencies not differing widely when subjected to the same kind of furnace and flame conditions, the structure having almost no inherent influence upon efficiency. But inasmuch as the structure may influence very materially the conditions of combustion, by restricting combustion spaces, by altering the length and the hydraulic mean depth of

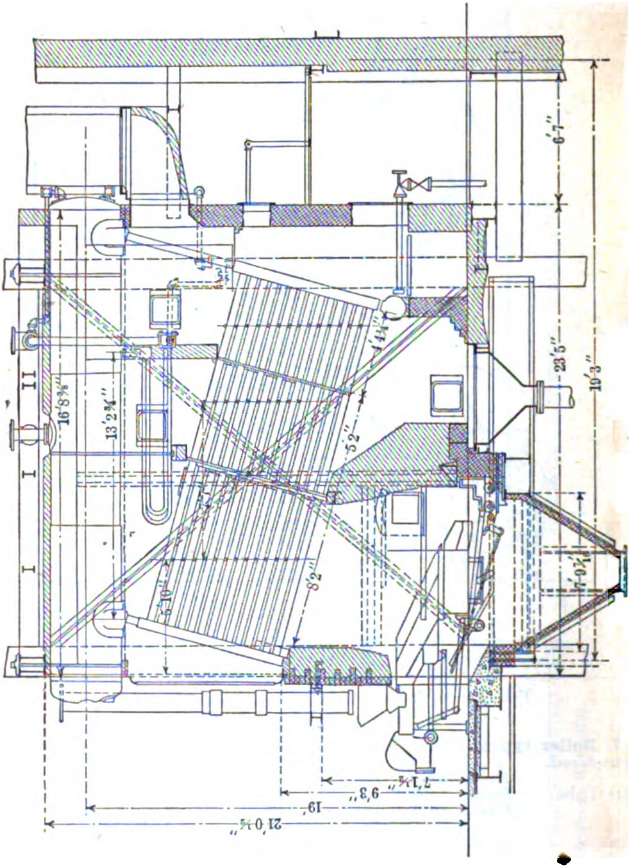

Fig. 5.—B. & W. stationary type with superheater.

gas passages, and by extinction of flame and accumulation of dirt, it may alter the efficiencies somewhat. If combustion could be entirely complete, so that the flame would be extinct before reaching any heating surface, it would make no difference what type of boiler were employed so far as efficiency is concerned.

8. Fire-tube boilers are cheapest in first cost, but lowest in capacity for space occupied; in general they are the most difficult to keep in good operating condition, especially with dirty water, since the water space is not accessible. The internally fired boilers such as the Scotch and the Continental (or similar) types are somewhat superior in capacity, but not up to the water-tube type. As a class, fire-tube boilers, from the standpoint of safety, are least desirable, as they carry a large body of hot water, storing considerable energy to be liberated at the instant of rupture.

9. Water-tube boilers are much lighter and smaller per unit of capacity, and higher in first cost than tubular boilers, but easier to maintain inasmuch as the water surface is all practically accessible, either for hand cleaning or for turbine tube cleaners. They are very safe, having very small water storage (subdivided into many smaller bodies by the tubes), and are made up almost entirely of the strongest natural shapes—cylindrical—with little or no stayed surface. There are practically no records of serious accidents resulting from the explosion of water-tube boilers.

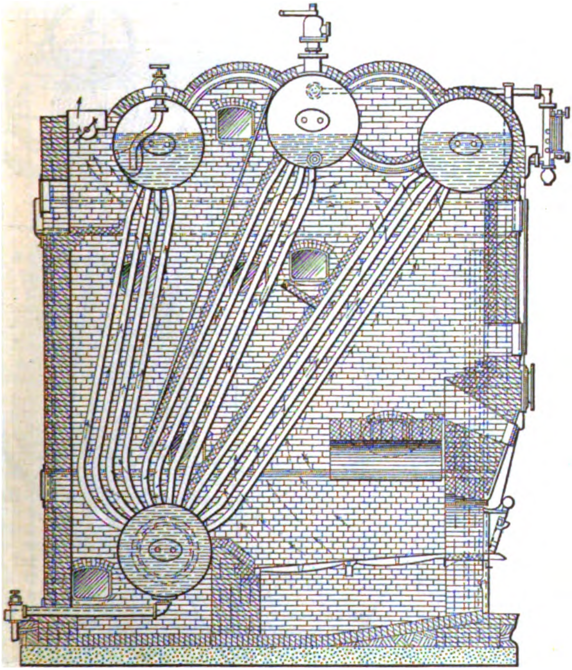

FIG. 6.—Stirling boiler.

10. Field-tube boilers are almost unused except for the French marine boiler known as the Niclausse. The principal objection to their use is the uncertain and spasmodic nature of the circulation which may partake of the nature of flash generation, alternating with periods of flooding with water, causing strains due to rapid and unequal expansion and contraction.

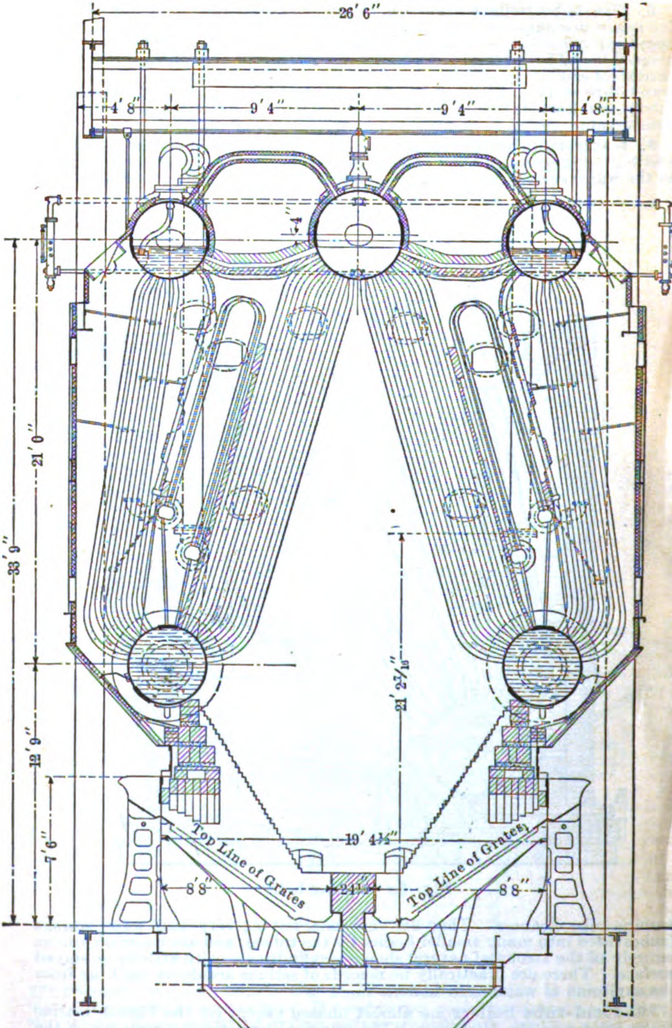

FIG. 7.—Stirling double-end boiler. Delray type.

11. Flash generators are at present unused except for steam automobile boilers and some torpedo boats. In American power stations they are unknown. However, if any standard boiler, such as the B. & W. or Stirling, be forced much above its normal rated capacity, the generation, in the lower rows of tubes at least, becomes of the flash type by reason of the extreme conditions.

12. Superheaters are of two general types: self-contained, and separately fired. The separately fired superheater is unpopular in America, chiefly because it has not shown such pronounced economies as the self-contained type. The two types of self-contained superheater are the plain tube and the protected tube types. To the former class belong the Heine, the B. & W. (Fig. 5) and the Stirling; to the latter class belong the Foster (Fig. 8) and the Schwörer.

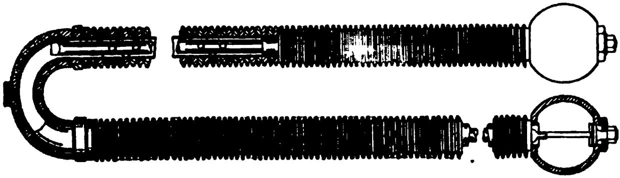

FIG. 8.—Foster superheater.

13. Superheaters may be located (usually) between the first and the second passes, or in the breeching. With later boilers of the ordinary stationary types the first position is popular. With the marine types now sometimes used in power stations, the latter position is satisfactory, as the gases leave the boiler at a higher temperature (see Marine B. & W. boiler, Fig. 4).

14. Heating surface is defined as any surface in a boiler or superheater which is exposed to hot gases on one side and water or steam on the other. In water-tube boilers the heating surface is defined as

$$\frac{\pi dln}{12} + \frac{\pi DLN}{24} \qquad \text{(sq. ft.)} \qquad (3)$$

where d = outside diameter of tubes in in. l = length of tubes in ft., n = number of tubes, D = outside diameter of drums in in. L = length of drums in ft. and N = number of drums, headers not included.

15. Rating of superheaters. Superheaters are not usually rated by sq. ft. of surface, but are figured for each case. A good average rule is 15 sq. ft. of heating surface per boiler h.p., for unprotected tubes; 18 sq. ft. of heating surface per boiler h.p., for protected tubes. The reason for using larger figures for superheaters than for steam-making surface is that heat transmission is much more difficult between gas, iron and gas, than between gas, iron and water, or between gas, iron and vapor, the latter two conditions obtaining in the boiler proper. The protected tubes interpose an additional resistance to heat transfer because of the cast-iron protection rings, the roughness of which also materially increases the thickness of the dead gas film.

16. Grate surface is any surface upon which coal is being burned. In hand-fired furnaces this amounts to the horizontal dimensions of the furnace, side wall to side wall, and front wall to bridge. With the automatic stoker, the term becomes more or less anomalous, since part of the surface may be used exclusively for coking, and the grates may not be horizontal; and part of the grates may be used only for accumulating clinker and ash. With underfeed stokers, coal is not burned upon the grates to any appreciable extent. The term is useful for comparison, if the projected area of the furnace is used in each case.

17. The ratio of heating surface to grate surface was once considered important and was generally made 60 to 1 when good coals were used, but now not much attention is given it. This ratio shows a tendency to decrease to 30 to 1 or 40 to 1 recent installations, particularly with stokers intended for forcing to high capacities, or where low-grade fuel such as culm, or No. 3 buckwheat is burned.

18. The value of the boiler h.p. is at present 34.5 lb. of water evaporated from and at 212 deg. Fahr., per hour; this is equivalent to 33,479 B.t.u. per hour. A new unit recently proposed to eliminate this somewhat illogical unit, is the **myriawatt,*** a multiple of the watt, having a value of 34,150 B.t.u. per hour, about 2 per cent. larger than the boiler h.p.

19. Evaporation. Taking dry coal, the actual evaporation per lb. is,

$$E = \frac{W}{w} \tag{4}$$

$$E' = EF \tag{5}$$

$$F = \frac{H - h}{970.4} \tag{6}$$

E = actual evaporation
E' = equivalent evaporation
F = factor of evaporation
H = total heat of steam at boiler pressure and quality.
h = heat in the feed water = feed temperature − 32.
W = lb. steam per hr.
w = lb. dry coal per hr.

970.4 = latent heat at atmospheric pressure = heat to convert 1 lb. of water to steam, from and at 212 deg. Fahr.

Or the above evaporation may be used "per lb. of combustible," substituting lb. of combustible per hour in place of lb. of dry coal per hour. All temperatures are expressed in deg. Fahr., and all pressures in lb. per sq. in., and all heat in B.t.u.

20. Losses in boilers comprise: (a) sensible heat escaping in flue gases; (b) sensible heat lost in hot ashes; (c) radiation of heat to external air from boiler setting; (d) incomplete combustion; (e) excess air. Theoretically some of these losses are avoidable. Actually, about the following proportions hold good in recent practice.

Heat in coal	100 per cent.
Heat absorbed in steam (overall efficiency)	70 to 76 per cent.
Stack loss, sensible heat only	10 to 15 per cent.
Incomplete combustion	5 to 10 per cent.
Hot ashes	Negligible
Radiation and leakage	6 to 8 per cent.

21. The combustion efficiency of automatic stokers runs as high as 96 to 97 per cent. and is maintained up to a very high rating in some cases. That of a hand fire is seldom over 90 to 92 per cent. and generally much less due to inevitable carelessness in operation.

22. Radiation is kept down by thorough lagging of exposed parts and by the usual double-walled construction of boiler settings (Figs. 5 and 6). It does not vary greatly for any type of boiler, but is reduced somewhat by setting in batteries instead of singly.

23. Excess air is caused by the slight vacuum in the setting due to draft; it can be reduced by painting or white-washing the setting and stopping up all cracks between metal and brick with plastic asbestos. In some cases enamel brick or sheet-iron settings are used, but the expense is not generally justified from this point of view alone. Another method of reducing **setting infiltration** is by the use of balanced-draft systems; in these the methods of forced draft, and natural or induced draft are so employed as to give practically zero pressure in the fire-box, by this means reducing the average difference of pressure from atmosphere, over the whole setting.

24. Furnace efficiency is expressed by the formula

$$\text{Furnace efficiency} = \frac{\text{Combustible burned}}{\text{Combustible fired}}$$

Combustible burned = (Combustible fired) − (Combustible in ash) − (Combustible in unburned gas) − (Combustible in soot).

* Stott and O'Neill. p. 411, *Trans.* A. I. E. E., Vol. 32, 1913.

Combustible fired = (lbs. dry coal) × (B.t.u. per lb. [by calorimeter]) (9)

Combustible burned = (combustible fired) − (B.t.u. per lb. of ash) × (lbs. ash) − (B.t.u. per lb. of soot) × (lb. of soot) − (B.t.u. in unburned gases). (10)

The last item is derived from the flue-gas analysis and as it always involves several assumptions, its accuracy is not very certain.

25. Boiler efficiencies. Fig. 9 gives a series of efficiency curves for various sizes and makes of standard boilers in central station service. The actual results in operation usually fall from 3 to 5 per cent. below test figures, the smallest falling off being noticed in those stokers which require the least hand manipulation during operation.

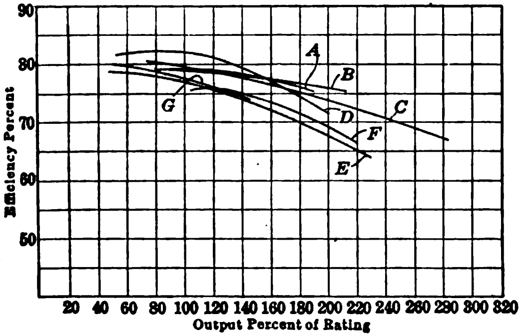

FIG. 9.—Boiler efficiency.

Combined efficiency, boiler and furnace: *A*, 2,365 h.p. boiler, Taylor stoker D. E. Stirling; *B*, 2,365 h.p. boiler, Roney stoker D. E. Stirling; *C*, 520 h.p. boiler, Taylor stoker B. & W.; *D*, 750 h.p. boiler, Taylor stoker B. & W. (part 2-in. tubes); *E*, 600 h.p. boiler, Green chain grate, B. & W.; *F*, 520 h.p. boiler, Westinghouse-Roney stoker B. & W.; *G*, 1,000 h.p. boiler, Taylor stoker B. & W.

26. Combined furnace and boiler efficiencies. The table below gives the pounds of water evaporated per pound of coal, and the pounds of coal required per boiler h.p. hr. with coals of various heat content and with boiler installations having varying combined boiler and furnace efficiencies.

	50 %		60 %		70 %		80 %	
B.t.u. per lb. dry coal	Evaporation per lb. coal	Lb. Coal per boiler h.p. hr.	Evaporation per lb. Coal	Lb. coal per boiler h.p. hr.	Evaporation per lb. coal	Lb. coal per boiler h.p. gr.	Evaporation per lb. coal	Lb. coal per boiler h.p. hr.
8,000	4.142	8.33	4.971	6.94	5.799	5.96	6.627	5.20
9,000	4.660	7.41	5.592	6.18	6.524	5.28	7.456	4.63
10,000	5.224	6.60	6.269	5.50	7.314	4.72	8.359	4.13
11,000	5.695	6.06	6.834	5.05	7.973	4.33	9.113	3.79
12,000	6.213	5.56	7.456	4.63	8.698	3.97	9.941	3.47
13,000	6.731	5.12	8.077	4.27	9.423	3.66	10.769	3.20
14,000	7.249	4.76	8.698	3.97	10.148	3.40	11.598	2.98
14,500	7.508	4.60	9.009	3.83	10.511	3.28	12.012	2.87

Efficiencies at head of columns are combined boiler and furnace efficiencies. Evaporation is given in pounds of water "from and at" 212 deg. Fahr. per lb. of dry coal. The heating value can also be taken for coal "as fired" whence the "evaporation per lb. of coal" and the "pounds coal per boiler h.p. hr." will also be referred to coal "as fired." This latter use of the table will contain a slight error due to the absorption of a portion of the heat by the moisture in the coal.

27. The failure of a furnace to burn all of the combustible is due to two principal causes: (a) molecules of oxygen are not brought into contact with all the particles of combustible material; (b) the temperature may be too low for ignition when they are in contact. The first condition is found where some of the fixed carbon in the lumps of coal becomes surrounded by a coating of fused ash, so that the air never reaches it during the time that the lump is upon the grate. Another cause, in the case of bituminous coal, is the lack of proper mixture of the volatile matter with air. The second condition is found as a result of the first, if streams of stratified hot combustible gas and air leaving the furnace are brought into contact with the comparatively cold heating surface, they will quickly be chilled below the ignition point, and will sweep through the boiler without further combustion taking place.

28. Water-tube boilers are generally rated on one boiler h.p. for each 10 sq. ft. of heat surface; **Scotch marine types** on 8 sq. ft., and **horizontal return-tubulars** on 12 sq. ft. **Superheater surface** is usually based on a transmission coefficient of 5 to 8 B.t.u. per deg. of mean temp. difference per sq. ft., per hour.

An empirical formula given by Bell (Trans. A. S. M. E., May, 1907) is, Sq. ft. superheating surf. per boiler h.p. =

$$S_s = \frac{10T_s}{2(T_g - T_o) - T_s} \qquad (11)$$

The temperature of gases at the superheater may be found from the following relations:

S_s = superheater surface per b.h.p., sq. ft.
S_a = per cent. of total surface passed over by gases before reaching superheater.
T_s = superheat, deg. Fahr.
T_o = saturated steam temp., deg. Fahr.
T_g = temp. of gases at superheater, deg. Fahr.

$$(0.172S_a + 0.294)(T_g - T_o)^{0.16} = 1 \qquad (12)$$

These two formulæ are based on the following assumptions: constant coefficient of heat transmission; furnace temperature 2,500 deg. Fahr.; flue temperature 500 deg Fahr.; steam pressure 175 lb. gage; one boiler h.p. equivalent to 10 sq. ft. of heating surface.

29. Boiler design. Since the efficiency of boilers is so little influenced by the disposition of heating surface, comparatively little original designing can or should be done outside of standard forms. For central-station work, the water-tube boiler has practically the whole field, the specifications for a boiler therefore look more to the safety and reliability, by rigorous attention to materials, than to the actual detailed design. The management of the furnace and combustion have much more to do with the efficiency of a boiler, than the arrangement of heating surface.

30. Boiler settings have become more or less uniform in general type. For the water-tube boilers, a steel structure or skeleton for supporting the boiler proper, the brick walls being merely self supporting, is now usual practice. Common red brick is used for the outer walls, a double-wall construction being employed to allow for the differential expansion of inner and outer surfaces (on account of the great temperature difference), to minimize radiation by interposing dead air space, and to reduce air filtration. Wherever the temperature exceeds 1,000 deg. Fahr., fire-brick is employed for this inner lining.

31. The baffles are always of fire-brick, of various special shapes, sometimes backed or supported on the cooler side by cast-iron bars or plates. Figs. 5 and 6 show these constructions.

32. The setting for tubular boilers, generally supports the boiler; for internally fired boilers, no setting is required (see Figs. 2 and 3).

33. The computation of superheater surface is much complicated by the change of temperature of the flue gases at the superheater with load on the boiler, and the uncertainty of the transmission coefficient. The amount of superheater surface installed for superheats of 100 deg. to 175 deg. Fahr. varies from 13 to 20 per cent. of the boiler heating surface. Fig. 10 gives results of actual tests.

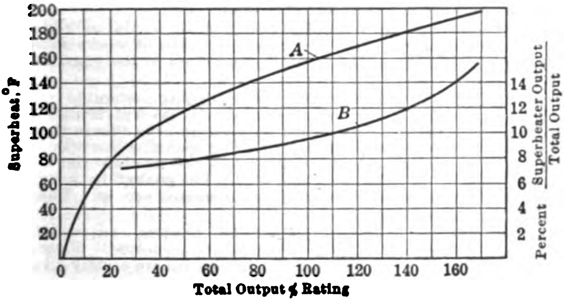

FIG. 10.—Superheater variation with output.

34. Uptakes are usually allowed 0.03 to 0.04 sq. ft. of cross-section (flue area) per rated h.p. of boilers attached. Where the uptakes are very long this allowance should be increased, or the loss of draft will be excessive. Where economisers are employed, the flues are best made of brick and combined with the economizer setting. Otherwise sheet-steel ducts, lagged with asbestos or other insulating material, are cheaper and more convenient. In nearly all cases the uptakes proper are made of steel. It is not necessary to line these with fire-brick unless the flue temperatures exceed 700 deg. a large part of the time; with properly operated boilers this condition need not occur. Bends in uptakes should be avoided, if possible, but where necessary should be of large radius; sudden changes of section should also be avoided.

35. Flue areas are based on a normal velocity of 25 to 40 ft. per second; maximum velocity, 60 to 70 ft. per second. The breeching area of water-tube boilers is about 0.03 to 0.045 sq. ft. per rated boiler h.p. It is best to be generous with areas wherever possible so as to keep the draft loss low.

36. Safety valves of the **pop type** are now always used, the weighted-lever type being prohibited by law in most cases. There are two principal classes: **low lift**, in which the rise of the valve is from 0.04 in. to 0.08 in.; and **high lift**, in which the rise is 0.12 in. to 0.16 in. The high-lift valves have been much more widely used in the last few years. Their principal advantage is greater relieving capacity; their principal disadvantage is possible slamming of the valves and destruction of the seat thereby; and, with dirty or hard boiler water, violent priming and throwing of water from the valve.

37. The rule of the U. S. Board of Supervising Inspectors of Steam Vessels in regard to safety valves is expressed as follows:

$$A = 0.2074 \left(\frac{W}{P}\right) \qquad (13)$$

where A = safety-valve disc area, in sq. in., per sq. ft. of grate area under boiler,

W = evaporation, in lb. of steam per hr. per sq. ft. of grate surface,

and P = absolute pressure, in lb. per sq. in. at boiler.

This is based on an assumed ratio of lift to diameter of valve of $\frac{1}{32}$ and a 45 deg. bevel seat.

38. Connection of safety valves. There must be **no valves between the safety valve and the boiler connection**; seats and valve discs must be of such material as will not rust together; no valves are allowed in the discharge from safety valves; in fact it is preferable to have only a muffler on the valve, and no discharge pipe at all.

39. Gage glasses of the ordinary type should be connected, preferably, directly to the steam drum and protected by wire gauze if near the level where firemen or others are working. The Klinger type of **gage glass** with heavy corrugated plate glass and brass casing is much safer, but more costly; the water level is much more clearly distinguished.

40. Quick-closing gage cocks operated by chain or rod are now almost universally used. The gage glass and blow-off cocks should never be so arranged that the fireman must stand close to the gage glass when "blowing down."

41. Manholes provided for entry to boiler drums, preferably in the heads where they least affect the strength, are made of pressed plate steel and fitted from the inside of the drum against a bumped lip or saddle in the drum by means of one or two bolts made fast to a dog spanning the opening on the outside. The pressure inside the boiler keeps the manhole tight, the bolts being used only to pull the cover to a seat. The **gasket** between manhole cover and seat is of asbestos, lead alloy or corrugated copper. The standard dimensions are 11 in.×15 in.

42. Handholes are placed in mud-drums, headers, etc., which are too small to admit the body, but must be cleaned and inspected. They are made in the same manner as manholes, but the dimensions are usually 4 in. by 6 in. or 6 in. by 8 in.

43. The blow-off should be connected to the lowest and quietest place in the boiler, where the mud and scale settle, or from specially designed chambers in which the sediment is induced to collect. The blow-off pipe must be protected from the fire, as it has normally no circulation of water to protect it. Many installations have been made with a plug cock next the boiler, followed by a gate valve to prevent leakage. There are now, however, one or two successful valves on the market which do not require the additional gate valve.

44. The feed pipe should enter the boiler so that the flow is in the direction of natural circulation in the boiler. Outside the drums the feed pipes are generally of brass to eliminate the chance of a break at this point from corrosion. A **check valve** is fitted at the entrance to each drum, to prevent water flowing back.

45. The steam gage is connected to the steam space of the boiler, to prevent blocking of the pipe by scale or mud. A **condensing coil** should be applied to prevent hot water or steam from getting into the Bourdon tube of the gage. **Thermometers** are practically never used as a measurement of steam pressure, except on tests, but are much more reliable.

46. Pyrometers are used for measurement of flue gas temperature, leaving the boiler, and are very valuable aids in checking the operation and efficiency.

47. Safety plugs are made of pure Banca tin, and are so placed that the active fire will play upon them, or at least in the first pass through the tubes. They are placed about 10 or 12 in. above the danger limit of low water; they are ordinarily protected by the water, but melt in case the level falls below them. The fire side of the plug must be kept clean of soot, or it may become so protected as to be inoperative.

48. Boiler corrosion is caused either by direct oxidation of the iron by **oxygen** dissolved in the water or by reaction with some **acids** present in the feed-water, having their source either in national acidity or from the products of decomposition of impurities introduced into the feed. Corrosion by oxidation is the more important, as the other is always avoidable by proper purification of feed water. Oxidation goes on continuously wherever dissolved air is present, and is much increased by the vibration or flexure of any particular point. The constant bending breaks off the film of iron oxides formed by the process, and exposes new surface to be attacked; for this reason pitting is commonest near joints where the flexure of some one portion of a plate is apt to be severe.

49. Incrustation is caused by the deposit of solid matter during the heating and boiling of the water. It may be merely a mechanically entrained impurity, such as mud and sand, or it may be the result of precipitation of various salts insoluble in hot water, or by super-saturation. The **salts** of magnesia, lime and iron are those giving most trouble in boiler water. Some of these salts are soluble and cause the formation of scale by super-saturation; others are insoluble in hot water and precipitate as the water is heated.

50. Treatment of feed water. The principal salts are iron, calcium and magnesium carbonate, bicarbonates, and sulphates. The bicarbonates are usually decomposed by boiling. The general method of treatment is by adding lime (CaO), and sodium carbonate (Na_2CO_3) called in the impure commercial form, soda ash.

51. Removing the precipitation. Where the character of the water or the plant layout does not allow the treatment in a separate purifying system, these reagents are added in the boiler feed, and the precipitation takes place in the boiler, assisted by the heat. The main object in this case is to precipitate the salts as soft scale, or mud, in order that it may be readily blown out. Periodic cleaning with some kind of mechanical cleaner is necessary, however, even with feed-water treatment, as some of the hard salts are bound to stick, especially in the hardest worked tubes over the hottest fires.

52. Periodic inspection of boilers is in itself a good preventive of accident. The straight tube, water-tube boilers lend themselves most readily to thorough inspection, as every part can be seen, and the whole of the shells can be hammer tested.

53. Boiler insurance covers the possible damage done by boiler explosion. The boiler insurance companies exercise a vigorous and valuable control over the manner of operation of boilers, and by their frequent enforced inspection, prevent little flaws from becoming disastrous weaknesses.

54. Cleaning. Those operations which make for safety in the boiler generally aid efficiency. A good rule is never to allow more than $\frac{1}{16}$ in. thickness of scale to collect; and to overhaul thoroughly every part of the boiler twice a year. In a well-operated plant, with moderately good water, this generally means cleaning the two rows of tubes nearest the fire about once a month, and the remainder of the boiler, twice annually. It generally pays, both in safety and efficiency, not to use water requiring more frequent cleaning of the boiler than last stated, but instead to purify the water in separate apparatus.

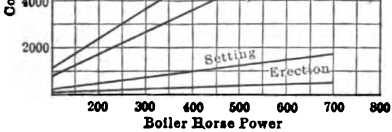

FIG. 11.—Cost of water-tube boilers.

55. The removal of soot from the outside of the tubes is usually required once or twice a week in well-operated plants; but for high rates of forcing, and especialy for low-grade fuels requiring heavy blast, the interval may be shortened to once every alternate day.

56. As far as possible, all conditions about a boiler should be kept uniform—water level constant, feed supply steady, draft well regulated, and firing (either by hand or stoker) uniform. The use of draft, pressure, steam-flow indicators or feed meters, is always valuable in this connection. Changes of load should be anticipated by gradual changes in the running of the boiler, since sudden alterations of draft or feed not only cause strains in the boiler, but loss of efficiency, thus disturbing the normal operation of the fire and flow of steam.

57. Boiler costs. Fig. 11 shows the variation in total cost of **water-tube boilers** of the B. & W. or Stirling types. The cost remains practically constant at $12.00 to $12.40 per h.p. This is partly due to the fact that most of the smaller boilers are built for lower pressures than the larger units. If all were built for high pressures, say 200 lb. gage, the cost would follow approximately the rule given by C. H. Benjamin in 1902, which is.

$$\text{Cost in dollars} = 500 + 9.2 \text{ (rated h.p.), for boiler alone.} \qquad (14)$$

58. The average setting cost for 300-h.p. to 600-h.p. units is $2.50 per h.p., and varies little. The delivered price is approximately 71 per cent. the erection cost 9 per cent., and the setting 20 per cent. of the total cost, which remains very nearly constant at about $12.40 per h.p. for horizontal water-tube boilers between 300 h.p. and 750 h.p. Gebhardt gives $1.00 per sq. ft. of heat surface as the price (delivered only), on all boilers over 100 h.p.

59. The cost of vertical water-tube boilers averages 10 per cent. less than horizontal water-tube boilers. Benjamin gives the cost in dollars = 500 + 8.5 × (rated h.p.), for vertical water-tube boilers (delivered only).

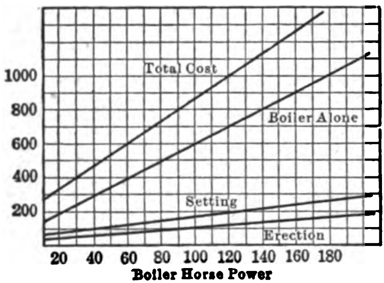

Fig. 12.—Cost of fire-tube boilers.

60. The corresponding costs of fire-tube boilers are given in Fig. 12.

FURNACES AND STOKERS

61. Principles of combustion: Referring to Fig. 13, a stream of oxygen is shown ascending past a piece of white-hot carbon—say a piece of **coke**, or a piece of **anthracite** having practically no volatile matter. Provided the temperature of the coke is high enough, combustion takes place to CO_2 and CO, the former predominating. Now suppose this stream of CO and CO_2 flows past more incandescent coke with little or no oxygen in the immediate neighborhood. Some of the CO_2 will combine with the incandescent C and reduce to CO. This combustible gas now flows on till it finds more oxygen, and is then burned to CO_2. This oxidation and reduction may go on reversing many times during the travel of the stream through the bed of coal to the top of the fire, and the burning of CO to CO_2 by contact with the needed oxygen is evidenced by the familiar blue flame of anthracite coal fires.

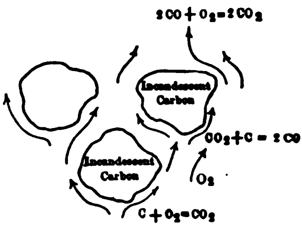

Fig. 13.—Elementary combustion of fixed carbon.

62. With bituminous or semi-bituminous coals, there are two distinct phases in the combustion process: first, on heating, the distillation and burning of the volatile hydrocarbons, leaves behind a mass of porous coke; second, the burning of this coke takes place exactly as the anthracite is burned. The distillation of the volatile matter introduces, therefore, a period during which the coal absorbs heat instead of giving it out. The extra volume of gas given off requires a freer supply of air than the hard-coal fire.

63. The two great requirements for efficient combustion are: (a) thorough "scrubbing" of the coal (or coke and volatile gases) with air, so that each particle of combustible receives its necessary oxygen within the smallest possible space of time; (b) the maintenance of both air gases and coke at a temperature above the ignition point.

64. Types of furnace and stoker: Hand firing always necessitates a horizontal or slightly inclined grate, so that coal may be fired through open doors all over the surface of the grate; most of the air is fed through the fire from below the grate. In the case of anthracite practically no air is admitted over the fire, because the compact nature of the small sizes of anthracite makes the use of air blast generally a necessity, and more than enough air can be supplied from below the grates. With bituminous coal, not enough air can be supplied from below, and some must be admitted by way of the fire doors or other openings for the purpose above the fire. The required reverberatory action for soft coals must be obtained chiefly by methods of firing. Regenerative action can be improved by the use of Dutch oven furnaces, in which the whole furnace is roofed over with fire-brick, which reflects heat instead of absorbing it, raising the temperature of the furnace. The soft-coal furnaces should always have as high a combustion chamber as possible, but with anthracite coals 18 in. is sufficient. Fig. 14 shows one type.

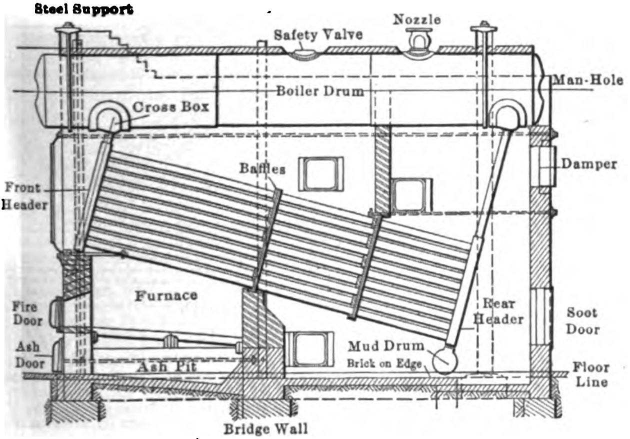

FIG. 14.—Hand-fired grate.

65. The overfeed stokers are those in which coal is fed somewhat in the manner of hand firing; green coal is pushed in at one end, or side of the combustion chamber, coked under a combustion arch, and finally burned to ash in a continuous progress across the furnace, the combustion of fixed carbon taking place upon the grates. The best known inclined types are the Roney, Wilkinson, Murphy, Model, Detroit and Wetsel. Fig. 15, shows the Roney type; coal is fed in at the top and worked down by gravity and the continual rocking of the grate bars.

66. The chain grate types are the B. & W., Green, Laclede, Illinois, etc. Fig. 16 shows a typical chain grate.

67. The underfeed stokers supply coal from below the fire, coke it as it approaches the incandescent top bed, and drive the gases, along with the blast air, through the white-hot coke on top. No combustion arches are required and there are no grate bars, strictly speaking, as little or no combustion takes place on iron—only upon a bed of coal.

68. Types of underfeed stokers. The Jones was the original of this type, followed by modifications utilizing gravity as well; the principal one of the latter type is the Taylor (Fig. 5), followed very recently by the Riley and the Westinghouse underfeed. Lately, extension grates of the overfeed type and continuous dumping devices have been incorporated in this type of stoker, lowering the combustible content in the ash, and reducing the operating labor.

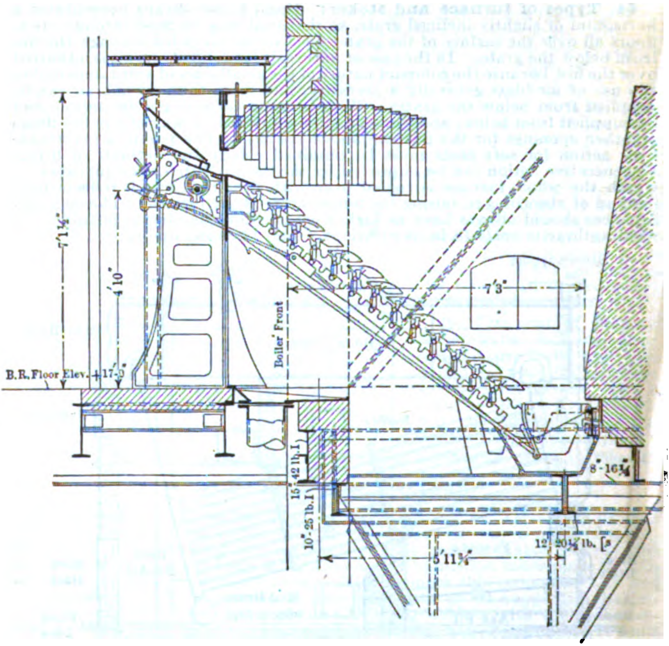

Fig. 15.—Roney stoker.

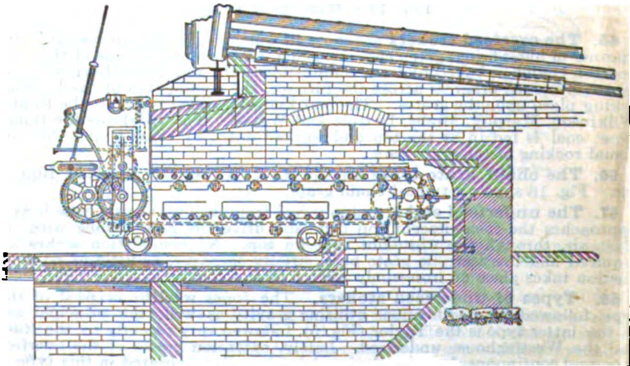

Fig. 16.—Chain-grate stoker.

69. Grates for hand fires are of three types, stationary, shaking and dumping. Stationary bars are of three principal forms: (a) plain girder-shaped straight bars, spaced from each other ½ in. or ⅜ in. by lugs, for air supply; (b) herringbone bars—two straight girder bars about 4 in. to 6 in. apart, cast with herringbone-shaped tie ribs; (c) pinhole bars, for burning sawdust, fine dust and culm, tan bark and similar materials. Rocking and shaking grates are made in a multitude of variations of these simpler forms; and are so arranged that the bars may be rocked in groups, to aid in cleaning the fire, or overturned to dump entirely.

70. Hand stoking of hard coals is done in the following manner. Coal, generally of small size (No. 2 or No. 3 buckwheat), is thrown well over the fire, and maintained about 6 in. to 8 in. thick and under considerable blast (1.5 in. to 2.5 in. of water). As fast as a hole blows through any portion, it is covered with fresh coal. This implies frequent firing, and in order to minimize the inrush of cold air at open fire doors some form of balanced draft is very desirable. Portions of the fire are allowed to burn out and are then dumped bodily and fresh fire raked over the bare grate. **With shaking grates** the dumping periods may be farther apart—4 to 8 hr., depending on the coal and rate of firing, as part of the ashes are removed at more frequent intervals by shaking the grate without opening the fire doors.

71. Bituminous coal can be hand fired in two ways: the alternate and the coking methods. In the first method, one side of the fire is at the period of hottest combustion while firing green coal on the other, to provide the necessary heat to volatilise and ignite the large volume of gas given off. When this green coal has finished giving off gas and becomes well coked and white hot, the other side, now burned out, is fired. In the coking method, the front part of the grate near the fire doors is made solid and is called the dead plate; green coal is fired upon this, under a coking arch, and receives enough heat from the main body of the fire and from this arch, to become coked. The gas thus given off passes out from the coking arch over the hot part of the fire, is mixed with air admitted over the fire, and thus ignited. The green coal, now coked, is pushed back over the hot part of the fire. As portions burn out, they are dumped and fresh coke raked over the bare grates. There are many variations in the manner in which these operations are performed, depending on the kind of coal. One man can ordinarily take care of one boiler up to 600 h.p., or two boilers at the utmost.

72. Automatic stoking in the overfeed type occurs almost in the same order as the hand firing of bituminous coal, except that all the processes, feeding, coking, segregation of ash, and sometimes dumping, are done by power and are continuous, instead of intermittent. The advantage in avoiding irregularity in the processes is obvious.

73. Automatic stoking in the underfeed type requires no regenerative devices in the furnace (such as the coking arch), since the gases and the air are mixed by passing through the bed of coal together and are finally heated by direct contact with the incandescent coke, before issuing into the furnace. The underfeed stokers are capable of almost unlimited forcing without serious loss of furnace efficiency, and are much lower in maintenance costs than the overfeed types, as no hot fire is carried on cast-iron parts.

74. Maintenance costs of stokers. The maintenance of Roney stokers with good coal, varies from about $0.10 to $0.12 per ton fired; the Murphy, Model, Detroit, Wetzel and Wilkinson vary from $0.11 to $0.14, the higher cost being due to the use of long bars in the fire, which are injured only in about the lower third, necessitating the scrapping of about two-thirds of the bars practically uninjured. With the Roney finger grate, the parts actually in the fire are separately removed, and consequently the efficiency of use of the metal is higher. Chain-grate stokers are comparable in maintenance with the Murphy type. Jones stokers require about $0.04 to $0.06 per ton fired for maintenance, and the Taylor stoker from $0.025 to $0.04 depending on the coal. Highly volatile coals, which must be fired thinner on account of clinkering, use up more iron, as the heat is nearer to the fingers and retorts.

75. Stoker labor. One stoker operator to each four stokers, and one coal passer to rake up siftings for each five stokers is good practice for the Roney type. The size of the stoker makes comparatively little difference, and hence the larger the stoker the better. One stoker operator for 6 stokers, and one coal passer for raking siftings to 6 stokers, is good practice for the Green or B. & W. types. One stoker operator to 15 stokers is needed for the Taylor, but no coal passers, as there are no siftings. The Jones type requires about the same labor as the Green, as the ashes must be raked out by hand.

76. The rate of combustion for hand fires is normally 10 lb. to 12 lb. of coal per sq. ft. of grate for anthracite, and 15 lb. to 20 lb. for bituminous coals. Under forcing the rate may go as high as 80 lb. per sq. ft. of grate, with forced draft. For power plants the usual maximum is 40 lb. to 50 lb. of soft coal.

77. Natural or chimney draft is common for bituminous coals. On hand fires 0.3 in. to 0.6 in. water draft at the breeching will generally produce rated capacity from the boiler; 0.3 in. draft at the breeching will produce rated capacity on the overfeed slope-grate types with high percentage of air space (35 per cent. to 45 per cent.). With the restricted types (Wilkinson) and the chain-grate stokers, where the air space is only 8 per cent. to 15 per cent., the required draft to produce rating is usually 0.4 in. to 0.5 in.

78. Forced draft with underfeed stokers and anthracite hand fires is practically a necessity, as the resistance through the fires is very much greater (Par. 80). The small sizes of anthracite pack very closely, and in 6 in. or 8 in. thickness may offer as much as 1 in. to 2 in. difference of pressure above and below the fire. In the underfeed stokers the fire is much thicker than in the overfeed type (the latter is about the same as hand-fired bituminous grates or 10 in. to 14 in.), or usually about 2 ft. 6 in. or 3 ft. thickness of fuel bed.

79. The amount of air required varies with the volatile content of the coal. The combustible constituents are carbon, hydrogen and sulphur. As far as heat and air supply are concerned, the carbon and hydrogen alone are important, the sulphur seldom exceeding 3 per cent. being low in heat value.

$$C + O_2 = CO_2 \qquad (15)$$

$$\underbrace{2H_2}_{\text{2 vol.}} + \underbrace{O_2}_{\text{1 vol.}} = \underbrace{2H_2O}_{\text{2 vol.}} \qquad (16)$$

The combining weights are in the proportions of the molecular weights, so that

$$12 \text{ lb. } C + 32 \text{ lb. } O_2 = 44 \text{ lb. } CO_2 \qquad (17)$$

$$1 \text{ lb. } C + \tfrac{32}{12} \text{ lb. } O_2 = \tfrac{44}{12} \text{ lb. } CO_2 = 3.67 \text{ lb. } CO_2 \qquad (18)$$

Air is 20.9 per cent O_2 and 79.1 per cent. N by volume, and 23.6 per cent. O_2 and 76.4 per cent. N by weight, so that, as 1 lb. C requires 2.67 lb. O_2, it will require $\frac{100}{23.6} \times 2.67 = 11.30$ lb. of air per lb. of carbon. Similarly, hydrogen requires 34 lb. of air per lb. Then the air required per lb. of any coal will be given by

$$(\text{fraction C per lb.}) \times 11.3 + (\text{fraction H per lb.}) \times 34 = \text{lb.} \qquad (19)$$

air required per lb. of coal.

The theoretical amount cannot be used because mixing is imperfect. Usually 18 lb. of air per lb. of coal are supplied for underfeed stokers and 20 lb. to 24 lb. for overfeed and hand fires.

80. Automatic damper regulators are used to maintain substantially constant boiler pressure under variable load. A diaphragm operated by steam pressure controls a pilot valve admitting water or oil under suitable pressure to a cylinder which in turn operates the damper lever. If increase in load causes drop in pressure, the diaphragm and pilot cause the pressure cylinder to open the damper wider, increasing the draft and the rate of combustion, thus making more steam to recover the proper steam pressure; and *vice versa*. This device may be employed in the stack or breeching for natural draft; or it may control the fan-engine throttle for forced or induced draft, producing the same results.

81. In the balanced-draft systems, a steam pressure regulator controls the forced-draft fan, and a combustion-chamber pressure regulator controls the stack damper or induced-draft fan, so as to maintain zero pressure difference over the fire. This is specially advantageous for hand firing, as the fire doors may be opened and shut without a rush or cold air over the fire. It is also a convenience with any forced-draft stoker.

32. The accessories of the automatic stoker consist of the forced-draft fan (if required), the stoker engine, and usually, for overfeed stokers—a slice bar and a poker, needed occasionally for obstinate clinkers. In the later types of underfeed stokers, automatic dumping devices are attached, which eliminate the need of hand manipulation of the fire altogether (Fig. 5).

33. The stoker engines required with all stokers except the Jones and the Wilkinson, may be of any standard type. The slope-grate overfeed stokers require about 1.5 to 2 h.p. per stoker, the highest being for the largest sizes—say 150 in. in width. Chain grates require 2 to 3 h.p.; underfeed stokers, 3.5 to 4 h.p. per stoker. The Jones type has a steam cylinder attached individually to each plunger and requires no other drive. The Wilkinson type generally has a hydraulic cylinder operating each stoker.

34. Furnace efficiency is defined in Par. 27. Its value for hand fires may be brought up to 94 or 95 per cent. but seldom runs higher than 90 per cent. in regular operation. Automatic stokers can be made to operate at efficiencies as high as 96 to 97 per cent. It is a question chiefly of adequate air supply, intimate mixture of gases, and high temperature.

35. Flue-gas analysis. The Orsat apparatus is the simplest and commonest means of analyzing flue gases. It appears in several forms, all of which employ some form of graduated glass gas-measuring chamber, usually waterjacketed, and has means for exposing the sample of gas successively to solutions of potassium hydroxide, potassium pyrogallate, and cuprous chloride (generally the acid solution), for removing CO_2, O_2 and CO, respectively. The gas is returned to the measuring chamber after each absorption, to measure the reduction of volume. Several automatic machines have been devised for measuring and recording CO_2 content in flue gases continuously; but it is now well known that CO_2 measurement alone is an insufficient indication of boiler efficiency. Flue temperature and sometimes the full gas analysis are desirable. The absorption of CO is particularly troublesome, as a rule, because the cuprous chloride must be used fresh, and is apt to throw off the absorbed CO if diluted; this also may happen in the Elliott apparatus. **The Elliott apparatus** differs from the Orsat in using long burettes and pipettes for greater accuracy, and the pouring of the absorbents through the absorbing chamber by hand; also, an explosion pipette for measuring the unburned hydrocarbons is added. **The Hempel apparatus** is still more accurate and refined, but is strictly a piece of laboratory apparatus. The Orsat type is made in easily portable form for use at the boiler.

36. Smoke consists chiefly of unburned carbon suspended in the flue gases; it may be in the form of particles of unburned coke blown up from the fire by heavy driving or high blast, or in the finely divided lamp-black form, developed by the breaking up of hydrocarbon gases, deficient in air, and exposed to high temperature. The latter form is chiefly indicative of bad combustion; the cure consists of thorough mixing of volatile matter and air in the furnace, and the maintenance of a high temperature of this mixture until combustion is complete, or in other words, until there is no more flame. In so far as any furnace or method of firing accomplishes these two things, in that degree it will be smokeless.

37. Specifications for stokers should cover the following: (a) general, and terms of delivery and erection; (b) drawings of stokers and dimensions of boilers to which they are to be attached; (c) operating conditions of boilers and rating; (d) general description of stokers; (e) dampers, doors, drive, and labor used; (f) fan requirements, foundations, air ducts and brickwork; (g) tests and operating conditions for tests, including full description and proximate analysis of coal to be used; (h) guarantees, capacity, efficiency, labor to operate, gas analysis, smoke, maintenance; (i) time of shipment, price and terms of payment; (j) detailed description of stoker and all parts.

38. The cost of automatic stokers per rated h.p. of boiler varies but little with size, as most of the stokers are made up of parts such that increase in size means merely increase in unit structure. The price is given delivered but not erected, although superintendence of erection is included; common labor for erection is furnished by the purchaser. The cost of Roney and other step-grate stokers is from $3.17 to $3.91 per rated boiler h.p., average $3.60; chain grates, $6.20 to $7.00, average $6.60; underfeed (Jones type), $3.70 to $4.76, average $4.44; underfeed (gravity plunger).

$5.45 to $6.10, average $5.65. The last type can also be listed at $495.00 per retort, a retort yielding about 86 rated boiler h.p.

89. The forcing capacity of these different types is extremely variable; the overfeed step-grate types usually cannot exceed 200 per cent. of rating; the chain grates are about the same. The underfeed types are readily reaching 300 per cent. and over. The cost per rated h.p. is therefore not entirely fair as the sole criterion.

90. Cost figures from a very large stoker installation using three types are as follows:

	Rating	Cost per h.p.	Rating	Cost per h.p.
Step grate..............	100 %	$3.17	200 %	$1.59
Chain grate with blast...	100 %	$6.55	266 %	$2.46
Gravity underfeed......	100 %	$5.77	325 %	$1.78

The weight of the step-grate stokers is about 500 to 550 lb. per rated boiler h.p.; chain grates, 1,300 to 1,400 lb.; underfeed types (gravity), 550 to 630 lb.

CHIMNEYS

91. Chimney draft is based upon the difference of specific gravity of cold air and heated air. The column of warm air in the chimney exerts a pressure per sq. ft. at the base of $h\gamma$, where h is the height in feet and γ is the density of hot gases in lb. per cu. ft. The pressure of the outside air for the same height is $h\gamma_2$, where γ_2 is the density of cold air in lb. per cu. ft. The motive force is therefore the difference of these two, or $h(\gamma_2-\gamma_1)$, in lb. per sq. ft.

92. Formula for chimney draft. For ordinary use,

$$D_1 = H\left(\frac{7.64}{T_2}-\frac{7.95}{T_1}\right) \tag{20}$$

Where H = height of chimney in ft., D_1 = intensity of draft, inches of water, T_1 = absolute Fahr. temp. of chimney gases, T_2 = absolute Fahr. temp. of outside air, and P_2 = observed atmospheric pressure, lb. per sq. in. For high altitudes above sea level:

$$D_1 = 0.52\ HP_2\left(\frac{1}{T_2}-\frac{1}{T_1}\right) \tag{21}$$

This gives the maximum theoretical draft with no flow taking place. The actual draft obtained is about 20 per cent. less, due to chimney friction, and head required to create velocity of gases.

93. Kent's draught formula is

$$H = \left(\frac{0.3\ \text{h.p.}}{E}\right)^2 \tag{22}$$

$$E = A - 0.6\sqrt{A} \tag{23}$$

Where E = effective area of chimney, A = actual area, (cross-section) of chimney, H = height at top in ft. above grates and h.p. = total connected boiler h.p.

Based on a maximum combustion of 5 lb. coal per rated B.H.P. per hr., this formula may be modified to

$$H = \left(\frac{0.06\ W}{E}\right)^2 \tag{24}$$

where W = total lb. coal fired per hour under connected boilers. This form is more suitable for high rating conditions.

94. Meyer on chimneys. Meyer* assumes a combustion rate of 4 lb. of coal per hour per boiler h.p. and 500 cu. ft. of flue gas per lb. of coal. In his table on chimneys referred to in the footnote he gives the friction loss for square steel flues; for brick it is 33 per cent. greater; for rectangular steel flues with sides as 1 to 2, it is 7 per cent. greater; for circular steel flues, 13 per cent. less.

* Meyer, H. C., Jr. "Steam Power Plants;" McGraw-Hill Book Company, Inc., 1912; Chap. XIII. Table XXXIII.

95. Table of sizes and h.p. of chimneys.
Table gives h.p. of chimneys computed by Kent method (Eq. 24, Par. 96).

Diam., ins.	Height								Effect. Area sq. ft.	Actual Area sq. ft.
	60 ft.	80 ft.	100 ft.	125 ft.	150 ft.	200 ft.	250 ft.	300 ft.		
18	25	29	3	36	40	46	51	56	0.97	1.77
24	54	62	69	78	85	98	110	120	2.08	3.14
30	92	107	119	133	146	169	189	206	3.58	4.91
36	141	163	182	204	223	258	288	315	5.47	7.07
42	200	231	258	289	316	365	408	447	7.76	9.62
48	269	311	348	389	426	492	549	602	10.44	12.57
60	437	505	565	632	692	800	894	979	16.98	19.64
72	646	747	835	934	1,023	1,181	1,320	1,447	25.08	28.27
84	896	1,035	1,157	1,294	1,418	1,637	1,830	2,005	34.76	38.48
96	1,186	1,370	1,532	1,713	1,876	2,167	2,423	2,654	46.01	50.27
108	1,517	1,751	1,959	2,054	2,392	2,770	3,098	3,393	58.83	63.62
120	.....	2,180	2,438	2,557	2,986	3,448	3,855	4,223	73.22	78.54
132	.....	2,656	2,970	3,114	3,637	4,200	4,696	5,144	89.18	95.03
144	.....	.....	3,554	3,726	4,352	5,027	5,618	6,155	106.72	113.10
168	.....	.....	4,878	5,115	5,974	6,899	7,713	8,449	146.50	153.94
192	.....	.....	.....	6,724	7,852	9,068	10,138	11,105	192.56	201.06
216	.....	.....	.....	.....	9,987	11,532	12,894	14,123	244.90	254.47
240	.....	.....	.....	.....	12,378	14,293	15,980	17,505	303.53	314.16

For pounds coal burned per hour for any given size of chimney, multiply figures in table by five.

Chimneys 25 per cent. larger are recommended for low-grade bituminous coal in middle and western states.

96. Chimney design must be based upon kind of coal required. For overfeed stokers and hand fires, Fig. 17 (from B. & W. 1913 issue of "Steam") gives the usual draft required for various coals.

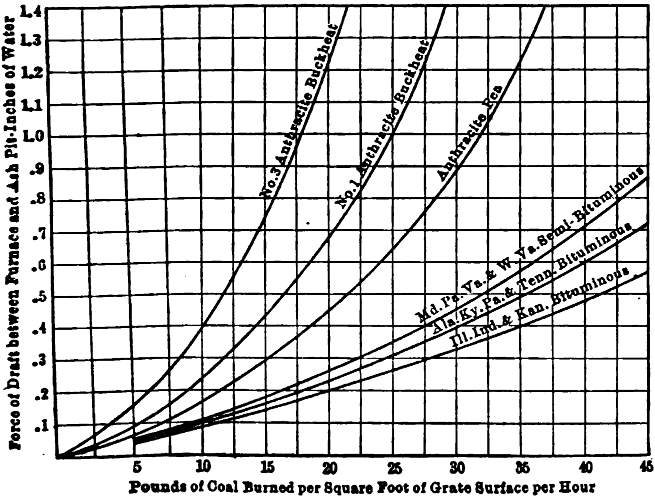

FIG. 17.—Draft for various coals.

The draft loss through a B. & W. boiler with standard baffling, clean, varies from 0.10 in. or 0.15 in. at rating, to 0.29 in. to 0.45 in. at 200 per cent. rating and 0.54 in. to 0.65 in. at 300 per cent. rating. The loss in flues of fairly uniform cross-section is given as 0.1 in. per 100 ft. straight flue, and 0.05 in. for 90 deg. bends. But in the irregular flue shapes often necessary, double these values are not infrequent (Meyer). The draught loss through economizers varies from 0.25 in. to 0.70 in. The sum of all these losses gives the required chimney draft. The diameter is computed (Par. 96 and 97) from the weight of coal burned. **With stokers using blast** it is necessary only to allow 0.1 in. **draft** over the fire at maximum capacity, as the only function of the stack is to draw off the gases without pressure in the furnace, the resistance of fire bed and stoker being overcome by the blast pressure.

97. Chimneys are built of the following materials: (a) red brick, fire-brick lined; (b) radial buff brick, fire-brick lined; (c) reinforced concrete, lined; (d) steel plate, lined; (e) steel plate, unlined. For natural draft, the radial brick, the lined steel plate and the concrete types of chimney are in general use.

98. Brick chimneys. The red-brick chimney cannot be less than 0.7 ft. thick at the thinnest portion; in other respects it is designed for stability against a wind pressure of 50 lb. per sq. ft. and against crushing. The walls, therefore, are always thicker at the bottom, and the stack is tapered. This type is not often used for power stations. Radial-brick chimneys may be 0.58 ft. thick at the thinnest part, as the brick is specially moulded; the cross-section is always circular, and tapers in the same manner as red-brick chimneys. Brick chimneys are the most durable of all the types. The fire-brick portions of lining need be carried up only 30 ft. above the grates.

99. Steel chimneys have the advantages of lightness and strength, but since they are better conductors of heat, must be lined with brick for heights over 75 ft. except in forced-draft installations. They must be carefully inspected and painted from time to time, as they are subject to deterioration by corrosion.

100. Reinforced concrete is much stronger than brick and will stand high tensile strains like the steel chimney. The stack is therefore often built straight like the steel chimney, and is always considerably lighter than brick, as it may safely be much thinner. It is usually poured in 5-ft. or 6-ft. sections. which may be carried up a section a day, making erection rapid. No lining is required other than the short section of fire-brick above the grates (30 ft.). It is one of the cheapest and most durable forms if well designed and built, but like all reinforced concrete, is dependent upon care and watchfulness during construction.

101. Foundations for brick chimneys are now made almost exclusively of concrete, and are designed on the basis of proper bearing values, like any other foundation. They are usually spread or stepped out at the foot, in order to provide sufficient resistance to overturning from wind pressure (Par. 590).

102. Cost of Brick Stacks

Approx. boiler h.p.	Height	Diameter	Diam. square base outside	Price
85	80	2 ft. 1 in.	7 ft. 5 in.	598.00
135	90	2 6	8 3	786.00
200	100	2 11	9 10	1226.00
300	110	3 7	10 2	1492.00
450	120	4 3	11 2	1785.00

Brick stacks may be figured on a basis of $12.00 per thousand for laying with masons at $0.55 per hour.*

103. The cost of concrete stacks is about 5 to 10 per cent. less than brick (Par. 106).

* Further cost data may be found in Gebhardt's "Power Plants," Wiley, 1912.

104. The cost of steel stacks may be figured on a basis of \$0.045 per lb. of steel erected.

MECHANICAL DRAFT

105. Limitations of natural draft. From the figures in Par. 91 to 96, it is evident that for high rates of combustion the stack becomes impracticably high, or the sensible heat loss due to high flue temperature becomes too large for economy. To mitigate this, mechanical or artificial draft of some form may be employed.

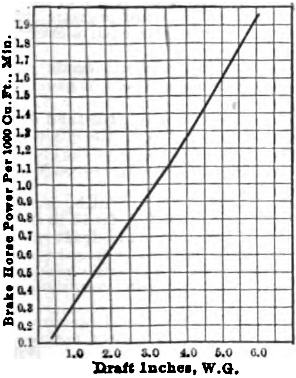

FIG. 18.—Required horse-power for forced-draft fans.

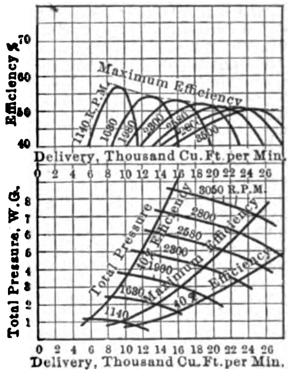

FIG. 19.—Characteristics of 24 by 30 in. forced-draft blower.

106. The theoretical pressure produced by a revolving fan wheel is given by Murgue as

$$H = \frac{U^2}{g} \tag{25}$$

where H = maximum pressure difference, between fan suction and discharge, in feet of air; U = velocity of fan blade tips, feet per second; and $g = 32.2$, acceleration due to gravity. Air pressure in inches of water column is generally referred to in blast and draft.

$$h = \frac{SH}{144p} \tag{26}$$

where h = inches of water pressure; S = weight of 1 cu. ft. air at 75 deg. fahr. (usual room temperature), or 0.074495 lb.; and p = pressure of 1 in. water column in lb. per sq. in., or 0.0361 lb.

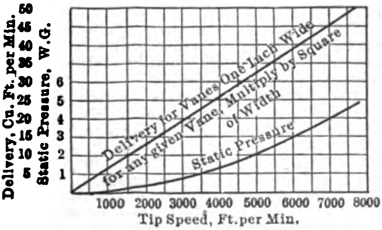

FIG. 20.—Power and volume of forced-draft fans.

$$U = \frac{2\pi rn}{60} \tag{27}$$

where r = radius to tip of blade in inches and n = r.p.m. Hence

$$h = \left(\frac{2\pi rn}{60}\right)^2 S = C(rn)^2 S \tag{28}$$

Fig. 18 gives the h.p. required at any pressure, for average fans. The characteristics of a forced draft fan for underfeed stokers are given in Fig. 19. The static pressure and volume of any size fan, at any speed, can be found from Fig. 20.

107. Forced draft. If the fan is placed so as to blow under the fire, the pressure is greater than atmospheric; this system is termed forced draft.

108. Induced draft. If the fan suction is connected to the boiler flue, and delivers to the stack, the pressure in the furnace and ashpit is less than atmospheric; this system is termed induced draft. The two systems may be used together, one fan forcing air through the fire, and the other drawing from the flue, maintaining a more or less balanced pressure over the fire. A forced draft fan also may be used, in connection with a chimney to draw off the gases.

109. Induced draft for hand fires with bituminous coals may be substituted for natural draft since the required maximum is not usually over 2 in. of water.

110. Forced draft combined with either natural or induced draft is always used with the underfeed stokers and frequently with the chain grates. Forced draft cannot be used alone, as without some suction at the breeching, there would be pressure above atmosphere in the fire-box, causing flame to issue from all openings.

111. Cost data on blowers and fans are difficult to furnish; about the only factor remaining nearly constant is the price per lb. at $0.15 to $0.17.

112. The comparative advantages of mechanical draft are: (a) greater forcing capacity than with natural draft, since it is easy to produce much greater differences of pressure than are at all practicable with stacks; (b) entire flexibility of control; (c) better combustion conditions with balanced draft arrangement; (d) low cost of apparatus.

113. The objections to mechanical draft are increased operating cost due to energy consumption by driving apparatus, and increased maintenance cost, which are balanced against the low maintenance of stacks. But the energy consumption (of steam, for turbine drive, say) is not a net loss, as it may be profitable to use the steam exhaust in feed heating, and the stack requires a certain loss of fuel due to flue gas temperature, in order to operate. This temperature can be lowered when using induced draft. **Forced-draft fans** have low maintenance costs, as they handle cool air; **induced-draft fans**, however, are likely to have high maintenance, as they deteriorate from handling hot flue gases.

PROPERTIES OF FUEL

114. Anthracite, or hard coal, contains very little volatile matter; is mainly fixed carbon and ash; is difficult to ignite; hard and bright fracture, not soiling the fingers in rubbing; oldest coal formation, being next to graphite.

115. Semi-anthracite contains a little less fixed carbon, more volatile matter; is easier to ignite and softer. **Semi-bituminous** is the next in order, having enough volatile matter to coke, with moderately long flame, and soft crumbly fracture.

116. Bituminous coals are rich in volatile matter, which may be as high as 40 per cent.; usually fairly low in ash—5 to 9 per cent.; and may be divided into many different classes with regard to flame, caking and coking qualities. They are very easy to ignite, brittle and dull fracture, crumbly, and soil the fingers in handling, due to softness.

117. Coke is the resulting fixed carbon and ash which remains a porous mass after driving off the volatile matter from a bituminous or semi-bituminous coal. It is largely a product of the coal gas industry; but as a power station fuel, its price is practically prohibitory. Oven coke, which is very hard, is used for blast furnace and crucible furnace work.

118. Lignite is a more recent formation than the bituminous coals and is hardly distinguishable from the lower grades of these; it is non-fibrous, and often brownish in appearance, whereas the coals are all black; absorbs oxygen and gives off CO_2 at ordinary temperatures. It contains quantities of oxygen and the volatile matter given off is mainly CO_2, which distinguishes the lignites still further from the coals, whose volatiles are chiefly hydrocarbons.

119. Properties of Various Coals

Sample	Bed	Proximate analysis: Moisture	Proximate analysis: Volatile matter	Proximate analysis: Fixed carbon	Proximate analysis: Ash	Ultimate analysis: Sulphur	Ultimate analysis: Hydrogen	Ultimate analysis: Carbon	Ultimate analysis: Nitrogen	Ultimate analysis: Oxygen	Air drying loss per cent.	Calorific value B.t.u.	
Alabama	Warrior field	2.58	33.15	51.74	12.53	1.02	4.79	69.24	1.55	10.87	0.8	12,449	Lump, Nut & Pea Coal
Arkansas	Huntington bed	0.80	19.75	67.65	11.8	1.3	4.07	76.37	1.55	4.91	0.8	13,655	Lump & Slack.
Colorado	Boulder field	13.49	37.11	43.03	6.37	0.58	5.75	61.13	1.22	24.95	6.0	10,791	Run of Mine, Lignite.
California	Alameda Co.	18.51	35.33	30.67	15.49	3.05	5.93	47.34	0.66	27.53	10.4	8,500	Run of Mine, Lignite.
Illinois	Belleville field	5.31	34.29	36.24	24.10	4.3	4.57	54.06	0.78	12.13	7.1	9,848	Slack.
	Marion Co.	5.96	30.29	52.16	11.59	1.77	4.92	67.30	1.43	12.99	2.7	12,103	Run of Mine.
	Montgomery Co.	13.2	34.33	39.94	12.53	4.47	5.51	57.25	1.02	19.22	4.4	10,514	Nut Coal.
	Franklin Co.	8.31	31.65	49.56	10.43	1.55	5.18	65.83	1.48	15.48	4.6	11,727	Egg Coal.
Indiana	Warrick Co.	6.24	37.49	42.76	13.51	4.6	5.11	62.97	1.25	12.56	3.6	11,538	Run of Mine.
	Sullivan Co.	13.99	29.4	42.29	14.32	2.31	5.36	57.18	1.11	19.72	10.8	10,318	Run of Mine.
	Vigo Co.	9.55	36.19	43.65	10.61	3.72	5.49	64.08	1.08	15.02	4.6	11,759	Lump Coal.
Indian Territory.	Hartshorne bed	1.7	37.19	49.79	11.32	1.56	5.00	71.9	1.72	8.91	2.8	12,969	Run of Mine.
	McAlester bed	4.91	37.79	43.9	13.4	4.02	4.84	63.21	1.38	13.15	1.4	11,389	Lump Coal.
Iowa	Polk Co.	4.52	40.96	38.99	15.53	6.83	4.93	60.62	0.93	11.16	9.8	11,356	Lump Coal.
	Lucas Co.	9.22	32.71	44.52	13.55	3.42	5.35	59.89	1.22	16.57	6.8	10,989	Run of Mine.
Kentucky	Western field	5.85	36.9	46.96	10.29	....	5.27	66.75	1.43	12.66	2.2	12,292	Run of Mine.
	High Splint bed	4.36	35.02	56.92	3.7	0.67	5.16	77.44	1.57	11.46	2.8	13,923	Run of Mine.
Maryland	Garrett Co.	2.33	16.11	68.43	13.13	1.49	3.99	75.21	1.29	4.89	1.4	13,255	Run of Mine.
Missouri	Rich Hill field	3.5	35.35	40.77	20.38	5.35	4.64	60.00	0.99	8.46	5.0	11,144	Run of Mine.
	Bevier field	9.14	34.53	39.02	17.31	5.3	4.96	56.25	0.99	15.19	2.6	10,451	Run of Mine.
Montana	Red Lodge	9.05	36.7	43.03	11.22	1.76	5.25	60.41	1.36	20.0	2.2	10,777	Black lig., washed nut
New Mexico	Gallup field	10.86	35.14	46.9	7.10	0.64	5.73	64.34	1.05	21.14	1.6	11,435	Lump and Slack.
North Dakota	McLean Co.	35.96	31.92	24.37	7.75	1.15	6.54	41.43	1.21	41.92	12.7	7,069	Lump, Brown lig.
Ohio	Jefferson Co.	3.53	37.45	49.9	9.12	3.47	5.15	71.66	1.31	9.29	1.4	13,072	Lump, over ¾" screen.
	Guernsey Co.	6.65	33.94	48.86	10.55	3.13	5.3	67.38	1.2	12.44	2.6	12,179	Lump, over 1¼" screen.
Texas	Houston Co.	13.4	42.75	29.00	14.58	1.04	5.57	52.06	0.95	25.53	24.6	9,385	Brown Lignite.

120. Properties of Mineral Oils

No.	Name and source	Density			Ultimate analysis				Prox. H_2O	B.t.u. per pound		
		Sp. gr.	F	Bé	C	O+N	H	S		By calorimeter	High value	Low value
1	Ogaio, crude	0.985	32	12.135	87.1	10.4	2.5	.....	......	18,146	18,983	18,065
2	California, fuel	0.966	60	14.93	81.52	11.61	6.92	0.55	......	18,667	18,926	17,903
3	California, Whittier	0.9637	60	15.28	......	......	......	0.845	8.71	18,518	....	....
4	California and Bakersfield fuel	0.962	60	15.53	84.43	10.99	3.99	0.59	......	....	18,976	18,005
5	California crude	0.9572	60	16.24	86.3	16.7	......	0.8	......	18,646	12,723	21,254
6	Hanover	0.955	32	16.505	86.2	11.4	2.4	.....	......	....	19,488	18,493
7	California crude	0.9533	60	16.85	85.75	11.3	......	0.67	......	18,797	19,356	18,363
8	California, Whittier and Los Angeles	0.953	60	16.9	......	......	......	0.98	4.93	18,714	....	....
9	Texas fuel	0.945	....	18.155	......	......	......	.....	......	19,242	....	....
10	California	0.943	60	18.47	......	......	......	0.735	1.06	18,677	....	....
11	California, Whittier	0.9417	60	18.67	......	......	......	0.975	1.06	18,626	....	....
12	Baku Russia heavy	0.938	60	19.26	86.6	12.3	1.1	.....	......	19,440	20,052	18,978
13	Petroleum residue, Baku	0.928	....	20.95	87.1	11.7	1.2	.....	......	19,260	19,761	18,739
14	Texas, Beaumont fuel	0.926	60	21.25	83.26	12.41	3.83	0.5	......	....	19,654	18,570
15	California	0.920	60	22.17	84.0	12.7	1.2	.....	......	....	19,917	18,807
16	Pennsylvania	0.914	70	23.18	86.1	13.9	......	0.06	......	....	20,949	19,735
17	Shale oil, Ardeche	0.911	....	23.682	80.3	11.5	8.2	.....	......	16,283	18,452	17,647
18	Ohio distillate	0.887	60	27.84	84.2	13.1	2.7	.....	......	18,718	20,188	19,044
19	Pennsylvania, crude, heavy	0.886	32	28.01	84.9	13.7	1.4	.....	......	19,210	20,654	19,457
20	Russian, crude, light	0.884	32	28.38	86.3	13.6	0.1	.....	......	22,628	20,796	19,608
21	Shale oil	0.875	....	30.005	......	......	......	.....	......	18,217	....	....
22	West Virginia, heavy	0.873	60	30.37	83.5	13.3	3.2	.....	......	....	20,207	19,046
23	East Galicia	0.870	32	30.92	82.2	12.7	5.7	.....	......	18,153	19,675	18,545
24	Kansas, crude	0.866	60	31.67	85.4	13.07	......	.....	......	....	20,345	19,203
25	West Virginia, light	0.8412	....	36.435	84.3	14.1	1.6	.....	......	18,502	20,809	19,578
26	Ohio distillate	0.838	60	37.07	......	......	......	.....	......	19,880	....	....
27	Ohio, Mabery Noble	0.829	70	38.89	85.0	13.8	0.6	0.6	......	....	20,752	19,547
28	Pennsylvania, crude	0.826	60	39.50	82.0	14.8	3.2	.....	......	17,930	20,699	19,606
29	American petroleum	0.82	....	40.73	83.4	14.7	1.9	.....	......	17,588	20,042	19,758
30	Pennsylvania, light	0.816	....	41.57	82.0	14.8	3.2	.....	......	17,533	19,899	19,606
31	American, crude	......	....	....	83.0	14.4	3.0	.....	......	19,980	20,801	19,544
32	Caucasus, Russia	......	60	....	84.94	13.96	1.25	.....	......	18,610	20,817	19,649

121. Composition of Natural Gases

No.	Source	Authority	Volumetric Analysis							
			O_2	CH_4	C_2H_6	H	CO	C_2H_4	N_2	CO_2
1	West Virginia	Report Gas Eng. Com. N.E L.A.	0.4	99.5	0.1	......	......	......	......	......
2	Kansas	Report Gas Eng. Com. N.E.L.A.	0.25	98.3	......	......	0.25	......	1.2	......
3	Caucasus	Bunsen	......	97.57	......	......	2.69	......	......	......
4	Kokomo, Ind.	Levin	0.3	94.16	......	1.7	0.55	0.3	2.8	0.29
5	St. Mary's, Ohio	Levin	0.35	93.85	......	2.74	0.44	0.2	2.98	......
6	Marion, Ind.	*Eng. & M. J.*	0.55	93.57	......	1.2	0.6	0.15	3.42	0.3
7	Findlay, Ohio	*Eng. & M. J.*	0.39	93.35	......	1.64	0.41	0.35	3.41	0.25
8	English	Lewes	......	93.16	2.94	......	1.0	......	2.9	......
9	Russian	Lewes	......	93.1	3.26	0.98	......	......	1.9	2.18
10	Anderson, Ind.	*Eng. & M. J.*	0.42	93.07	......	1.86	0.73	0.47	3.02	0.26
11	Ohio	Lewes	0.35	92.84	0.35	1.89	......	......	3.82	0.75
12	......	Lucke	0.34	92.6	......	2.18	0.5	0.31	3.61	2.6
13	Leechburg, Pa.	Hoyle	......	89.65	......	4.79	0.26	4.39	......	0.35
14	Penna. & W. Va.	Allen & Burrell	......	83.0	16.4	......	......	......	0.6	......
15	West Virginia	Report Gas Eng. Com. N.E.L.A	0.15	81.5	17.6	0.2	......	......	0.55	......
16	Butler County, Pa.	Hoyle	......	80.11	......	13.5	......	5.72	......	0.66
17	Pittsburgh, Pa.	Levin	0.8	72.18	......	20.0	1.0	3.0	......	0.8
18	Penna.	Jüptner	......	67.0	5.0	22.0	0.6	1.0	3.0	0.6
19	Pittsburgh, Pa.	Hoyle	0.8	67.0	......	22.0	0.6	5.0	3.0	0.6

122. Composition of Coke Oven and Retort Coal Gas

No.	Description	Volumetric analysis								
		H_2	CH_4	CO	C_2H_4	C_6H_6	Heavy hydro-carbons	CO_2	O_2	Remainder and N_2
1	Solvay coke oven	56.9	22.6	8.7	....	....	3.0	3.0	....	5.8
2	Retort coal gas, Lewes, 5–6.5 O in coal	54.21	34.37	6.68	2.48	.79	....	1.47	....	....
3	Aachen retort gas	54.0	34.2	5.2	....	....	3.3	1.1	....	2.2
4	†Norwich retort gas, bit. coal	53.79	36.11	3.40	....	....	3.26	.27	.14	3.03
5	Coke-oven gas	53.0	35.0	6.00	2.0	....	....	2.0	....	2.0
6	Retort coal gas, Lewes, 6.5–7.5 O in coal	52.79	34.43	7.19	3.02	.99	....	1.58	....	....
7	Retort coal gas, Sexton	51.88	31.8	9.1	....	....	5.2	....	....	2.02
8	London coal retort gas, Pryce	50.7	37.8	4.1	....	....	4.4	....	....	3.0
9	Retort coal gas, Newton, Mass.	50.59	34.80	6.16	....	....	5.23	1.16	....	2.06
10	Common coal gas	50.1	38.0	6.0	4.0	....	....	....	....	1.9
11	Laclede Gas Co., bit. coal	49.8	32.3	6.7	....	....	8.0	2.40	.60	0.2
12	†Gloucester retort gas, bit. coal	48.88	38.25	4.64	....	....	4.95	.03	.51	2.74
13	Retort coal gas, average	48.49	35.9	6.61	....	....	3.83	.12	....	5.05
14	‡Good Solvay average coke-oven gas	48.0	35.5	5.1	4.2	1.2	....	1.3	.5	4.2
15	Common coal gas	47.73	35.6	6.15	4.88	....	....	1.41	.31	3.92
16	Coke oven, Milwaukee	47.1	34.7	6.2	3.8	....	....	3.1	.3	4.8
17	Heidelberg retort coal gas	46.2	34.02	8.88	....	....	5.09	3.01	.65	2.15
18	Coal retort gas—Bunsen & Roscoe	45.58	34.9	6.64	....	....	6.46	3.67	....	2.75
19	Common coal gas	44.4	37.1	5.2	2.3	....	....	1.3	1.1	8.6
20	†Sheffield retort gas, cannel	43.05	43.05	4.72	....	....	6.28	.24	.10	2.56
21	Average coke oven, Klumpp	42.0	34.3	6.0	....	....	4.0	2.5	1.1	10.1
22	Otto coke oven, poor part of gas	41.6	29.6	6.3	....	....	2.8	3.2	.4	16.1
23	†Leeds retort gas, cannel	40.23	42.74	5.02	....	....	7.28	.34	.07	4.32
24	Birmingham, Eng., retort coal gas	40.23	39.0	1.50	....	....	4.76	1.50	....	13.01
25	Glasgow, Scot., retort coal gas	39.18	40.26	.29	....	....	10.0	.29	....	9.98
26	Otto coke oven, good part of gas	37.6	40.8	5.6	....	....	5.8	3.7	.4	6.1
27	Rich coke oven, Klumpp	37.4	40.4	7.1	....	....	5.8	2.1	1.6	5.6
28	Retort gas cannel coal, Sexton	36.1	37.8	6.8	....	....	16.4	....	....	2.9
29	Cleveland, Ohio, retort coal gas	34.8	28.8	.20	....	....	11.2	.20	....	24.8
30	Cannel-coal gas	27.7	50.0	6.8	13.0	....	....	.10	....	2.4
31	Newcastle coal, 10 minutes	20.1	57.38	6.19	....	....	10.62	2.21	....	3.50
	High volatile coal:									
32	Solvay oven, Blauvelt, 1st hr.	41.4	41.5	5.8	3.2	.90	....	.90	.50	5.8
33	Solvay oven, Blauvelt, 6th hr.	49.8	31.4	4.6	1.6	.90	....	1.1	1.1	9.5
[illegible]	[illegible] Blauvelt, 10th hr.	60.4	13.6	6.2	0	0	....	.2	.4	10.2

123. Composition of Blast-furnace Gas and Air Gas

No.	Description	Volumetric analysis						
		CO	H_2	CH_4	CO_2	N_2	$\frac{CO}{CO_2}$	$\frac{CO}{CO+CO_2}$
1	Coke in small Dowson producer, Dowson and Larter	32.6	1.0	....	1.4	65.0	23.2	.96
2	Blast-furnace, splint coal, Sexton No. 3	30.1	6.2	3.2	5.4	55.1	5.58	.85
3	Blast furnace, Upper Silesia, Germany	29.7	6.3	....	7.8	56.2	3.81	.79
4	Metallurgical air gas, Lewes	29.0	2.5	....	4.0	64.5	7.25	.88
5	Coke, Lackawanna Steel Co.	28.4	1.7	....	11.8	....	2.40	.71
6	Blast furnace, unwashed, Sexton	28.19	10.24	1.78	6.23	53.56	4.53	.82
7	Blast furnace, splint coal, Sexton No. 2	28.06	5.45	4.39	8.61	53.38	3.26	.76
8	Blast furnace, English	27.71	1.34	....	8.62	62.33	3.21	.76
						+5.0		
9	Blast-furnace gas	27.5	3.0	....	10.0	59.4	2.75	.73
10	Bituminous coke air gas, Loomis Pettibone	27.3	5.1	.8	2.7	....	10.1	.91
11	Blast furnace, Frodingham coke, Allen	26.9	2.4	....	6.3	64.4	4.27	.80
12	Coke Lackawanna Steel Co.	26.8	1.4	....	8.6	....	3.12	.76
13	Scotch blast furnace, Wishan	25.83	4.55	3.45	7.21	58.96	3.58	.78
14	Isabella Furnace, U. S. Steel Co., Gayley	25.8	....	....	12.6	4.25	2.04	.67
15	Producer gas, little steam	25.3	9.2	3.1	3.4	58.2	7.44	.88
16	Dowson gas, average	25.0	18.0	3.0	7.0	47	3.57	.78
17	Producer gas, little steam	24.8	8.5	5.2	5.6	55.1	4.44	.82
18	Producer gas, little steam	24.0	9.8	3.4	6.0	55.6	4.0	.80
19	Blast-furnace coke	24.0	2.0	2.0	12.0	60.0	2.0	.67
20	Durham coke, Allen	23.84	2.34	....	10.94	5.55		
						57.3	21.8	.69
21	Blast furnace, Ledebur, Germany, coke, of 10 per cent. H_2O	21.6	1.8	1.8	10.8	54.0 +10.0	2.0	.67 -
22	Producer gas, little steam	20.8	6.9	2.2	4.6	64.9	4.53	.82
23	Producer gas, little steam	20.0	5.3	3.0	3.6	67.5	5.56	.85
24	Loomis Pettibone coal	20.0	14.0	2.0	8.2	55.5	2.44	.71
25	Loomis Pettibone wood	20.0	14.0	2.0	16.0	47.7	1.25	.55
26	Taylor gas, average	12.0	21.0	2.0	5	57.0	2.4	.71
27	Mond gas	12.0	29.0	2.0	14.5	42.5	.83	.45
28	Mond gas	11.5	28.5	2.1	15.0	42.9 water	.77	.43

124. Peat is the most recent of the formations. High-bog peat is formed from swamp moss, etc.; low-bog peat is formed from grasses around low bodies of water. They show the fibrous structure of vegetable origin, and range in color from ochre to brown and black; are very soft in texture, with no fracture; carry large moisture, oxygen and nitrogen content; the volatile matter is poorly combustible, containing largely CO_2.

125. Wood is still higher in oxygen and nitrogen, up to 40 to 45 per cent., with carbon from 45 to 49 per cent. Its scarcity and cost make its use as a power station fuel impossible except for saw mills and logging camps where the unmarketable waste may be profitably used.

126. Briquettes* are small artificial lumps of solid fuel made up by pressing peat, bituminous slack or anthracite culm, with a suitable tarry binder, so as to recombine the soft peat or unmanageable coal dust into a convenient lump form. Briquettes behave somewhat like lumps of soft coal, but usually are very troublesome in giving smoke. The cost of briquetting presses, and the need of suitable inexpensive binder, have prevented the wide use of briquettes in America. With peat briquetting is practically a necessity.

127. Mineral oils have their source in crude petroleum. The heavy oil engines, such as the Diesel and the Junkers run on raw petroleum; many of the smaller engines, however, are designed for kerosene and gasolene.

128. Gas for power production may be natural gas,† producer gas, coke-oven gas,‡ or blast-furnace gas.§ Illuminating gas is too expensive to use for anything but very small isolated plants. See Par. 26, 27 and 28.

129. The main feature in the use of gas is the engine compression pressure which is practicable; blast-furnace gas, being lean and much diluted with neutral matter, will stand very high compression; producer gas, natural and coke-oven gas, being richer (especially in hydrogen), cannot be compressed as much.

130. The cost of anthracite No. 1, No. 2, or No. 3 buckwheat is about $1.10 to $2.50 per ton at the plant in quantity. The mine cost is not over $1.00 to $1.40. **Bituminous coal** costs from $2.00 to $4.50 at the plant. The cost averages $0.085 to $0.095 per million B.t.u.

131. Fuel oil costs from $0.01 to $0.03 per gal. The cost averages about $0.090 to $0.094 per million B.t.u., in the oil-burning districts. While its cost per million B.t.u. is about the same as coal, or somewhat better, in the districts where it is available, it has a further advantage in the better boiler efficiency obtained, and in the elimination of some of the power-station auxiliary apparatus.

132. Natural gas costs $0.07 to $0.085 per million B.t.u. All of these figures apply chiefly to large consumers; the prices will go up considerably for small plants.

WATER SUPPLY AND PURIFICATION

133. Boiler feed. Boilers must be fed with fresh water of reasonable quality; in general, if a water is not potable, it is not fit, as it stands, for boiler feed. Wells, fresh-water lakes, rivers and ponds are the prime sources.

134. Water analysis to determine the value of a water as boiler feed should be performed by a chemist; but the ordinary tests for hardness, with standard soap solution, hydrochloric acid and methylorange, may readily be carried out in the plant in conjunction with water-softening apparatus.

135. The dangerous impurities are sulphuric acid (or other acids if the water has been contaminated by factories), grease and oils in quantity,

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* Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913; Table CIV.

† Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CIX.

‡ Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CX.

§ Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CXIV.

and the natural scale-forming salts such as magnesium, iron and calcium carbonates and sulphates.

136. The treatment of feed water has been outlined in Par. 49 to 51.

137. The use of condensate returned from surface condensers is usually a valuable way of eliminating most of the boiler incrustation. The only drawback lies in the presence of oil and grease in the condensate, if the condenser serves a reciprocating engine. Quantities of oil in excess of 0.4 to 0.5 g. per gal. are objectionable, as they collect whatever soft scale may be present in the boiler and form a brown mass which bakes on the tubes and has the same effect as hard scale.

138. Oil and grease extractors, designed on the same general lines as steam separators are employed between the engine and condenser, in order to keep down the amount of oil passing into the condensate. As a matter of fact, the baffles placed in these devices are really of very little use; it is the reservoir effect of the extractor in slowing down the current of steam which really does the work. Where turbines are the prime movers, no grease or oil separators are required. Fig. 20a shows a typical separator.

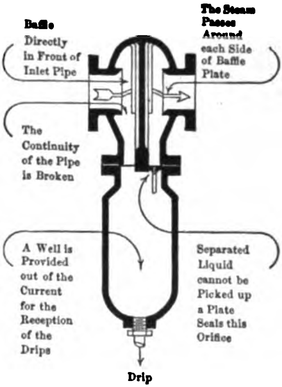


FIG. 20a.—Horizontal steam separator.

COAL AND ASH HANDLING

139. Coal is delivered to the power plant of any size, either by barge, schooner or railroad car. Handling coal by truck is practically too expensive for use in any but small isolated plants.

140. Unloading may be done by a grab-bucket digger, or if delivered by car, an elevated trestle may be employed, dumping from the car bottoms. For most of the large plants, a coal tower with a 1-ton or 1.5-ton clam-shell digger is employed to unload and hoist the coal high enough to pass by gravity through crushers and weighing scales, and finally to conveyors or coal cars. In smaller plants, a locomotive crane, or mono-rail telpher, may perform the same work and also serve the storage yard. Towers may be either steam or electric driven; the former is generally the cheaper and more rugged construction.

141. Crushers are heavy rolls of cast iron, studded with teeth, geared together in such fashion as to crush the coal to small size; some spring or relief device must be fitted to allow harder materials to pass through, such as link chains, sprags and occasionally a car coupler. Crushers are not needed for anthracite.

142. Conveyors are of five principal types; scraper, reciprocating, belt, bucket and suction. **The scraper conveyor** consists of flights or paddles rigidly fastened upon a special bar-link chain, and dragged along in a trough shaped to the flights. The **reciprocating conveyor** is very similar, but only moves a few feet forward and backward. The flights are so hinged that on the backward stroke they lift out of the coal and trail over the top, digging in again when the chain reverses.

143. Belt conveyors consist of wide rubber or textile belts travelling continuously over idlers spaced from 2 ft. to 4 ft. apart, and with the outer pulleys tilted up to trough the belt. The belt conveyor is not suitable for ashes.

144. The bucket conveyor has separate buckets from 24 in. to 48 in. square, either fixed rigidly to long-pitch side links, or pivoted in the center, so as to remain vertical. In the latter case, all of the conveyor is malleable iron except the rails and framing. It is exceptionally suited to handling ashes.

145. The suction conveyors are used only for **ashes; coal is too heavy** and packs too readily to be handled in this manner. The suction is usually provided by a high-speed centrifugal blower, attached to the outlet. The rest of the equipment consists merely of 10-in. and 12-in. cast-iron pipe lines with swing-door openings at which the ashes are admitted. The drawback to this system is the deterioration of the fan from grit, and all turns and elbows from abrasion. If the ashes are too wet, the blocking of the pipes is practically certain to give trouble.

146. Comparisons of conveyors. The belt conveyor is very satisfactory on "carry" of coal, but not so good on "lift;" the bucket conveyor is probably the most satisfactory all-around conveyor, handling coal or hot ashes equally well in lift or carry; it is, however, the most expensive.

147. Another method of conveying is by cable cars; where possible this gives the cheapest and most satisfactory means of carry.

148. Storage of coal outdoors for power-plant purposes requires less care and handling than for coal companies, as the material is turned over fast enough to avoid much loss by weathering. The storage yard may be served by: (*a*) a locomotive crane, (*b*) a gantry crane, (*c*) a Dodge girder unloader, (*d*) a telpher grab bucket operating on an overhead structure, (*e*) or if the storage is in a pit, by a conveyor in a tunnel. Usually the capacity should equal at least two weeks supply, or better, one month. One company having trouble from spontaneous combustion of bituminous coal, uses a concrete pit flooded with water; but this is generally unnecessary, the excessive wetting of the coal being a drawback.

149. Bunkers placed under the roof of the boiler house are almost always provided, to feed coal by gravity to the fires. Where external storage is available, two to four days supply in the building is all that is necessary; but in city plants where external storage is impossible, ten days to two weeks supply must be provided.

150. Bunker construction. Steel framing with concrete or cinder-concrete lining, faced with granolithic or other hard finish, is the best construction for large work; for smaller work, the suspended type, catenary shape, of plate steel with concrete lining, or simply of reinforced concrete, has been much used.

151. Hoppers. Ash hoppers of structural material with brick lining are the standard practice, but reinforced concrete is also being used to some extent. The coal hoppers should always be of sheet steel, $\frac{3}{16}$ in. being the usual thickness; it is good practice to reinforce the hoppers with renewable wearing plates where the abrasion is severest.

152. Weighing is done at the hoisting tower (just after crushing) in hoppers carried in knife-edge supports which operate standard beam scales; two sets are required, one hopper receiving the continuous flow of coal from the crusher while the other is being weighed. Reversing gates for the supply, and trip gates for the weighing hoppers are under the control of the weighmaster.

153. Automatic scales of the hopper type are in use for anthracite, and are fairly accurate, as the angle of repose and slip of anthracite in the small sizes is very little affected by moisture, and the small size allows ready control of the flow; with bituminous coals they are somewhat unsatisfactory, as the highly variable angle of repose affects the spillage when closing the feeder gates, making the "dribble" a variable quantity. Conveyor scales of several makes are on the market, but not widely used.

154. There is also a coal meter for use in pipe downtakes, acting on the principle of a propeller driven by the moving coal, which is very simple and quite accurate for small sizes of coal. It is not yet fully satisfactory for lump coal and run of mine.

155. Spouting of coal in closed pipes must always be done at an angle of 45 deg. or steeper to be satisfactory, if the spout is a closed pipe; 8-in. to 10-in. pipes may be used with anthracite; but nothing less than 12 in. should be used for bituminous crushed coal. In designing hoppers and spouts it should be remembered that the intersection of two sides each at 45 deg. from the horizontal, is much less than 45 deg., so that the coal will always hang at such a junction.

156. The power required by belt conveyors is given by the following formula:

$$H.P. = \frac{CTL}{1,000} + \frac{TH}{1,000} \qquad (29)$$

where C = power constant, T = load in tons per hour, L = length of conveyor in feet, H = lift of conveyor in feet, and B = width in inches.

Values of C for material weighing 25 lb. to 75 lb. per cu. ft.

B (in.)	C	H.P. on account of trippers in belt	B (in.)	C	H.P. on account of trippers in belt
12	0.234	0.5	26	0.187	2.0
14	0.226	0.5	28	0.175	2.25
16	0.220	0.75	30	0.167	2.5
18	0.209	1.0	32	0.163	2.75
20	0.205	1.25			
22	0.199	1.5	34	0.161	3.0
24	0.195	1.75	36	0.157	3.25

Add 20 per cent. for conveyors under 50 ft. long.

Add 10 per cent. for conveyors between 50 and 100 ft. long.

The formula does not include friction of gear drive. Add about 10 per cent. for the drive and 10 per cent. for each 180 deg. turn idler, exclusive of the head and tail pulleys. Speeds run from 300 to 450 ft. per min.

157. The power required by flight or scraper conveyors is as follows:

$$H.P. = \frac{ATL - BWS}{1,000} \qquad (30)$$

where A and B are constants in the table below, W = weight of chain and flights in both runs, L = length of feet, S = speed in feet per minute, and T = load in tons per hour.

Values of A and B

Inclination	0 deg. for horizontal	5 deg.	10 deg.	15 deg.	20 deg.	25 deg.	30 deg.	35 deg.	40 deg.	45 deg.
A.......	0.343	0.42	0.50	0.585	0.66	0.73	0.79	0.85	0.90	0.945
B.......	0.01	0.01	0.01	0.01	0.009	0.009	0.009	0.008	0.008	0.007

Speeds 100 to 200 ft. per min.

158. Bucket Elevators and Conveyors

Size, buckets,	12″×12″			24″×15″			36″×20″			48″×24″		
Spacing..........	18″	24″	36″	18″	24″	36″	18″	24″	36″	48″		
H.p. for 100′ vertical lift..........	0.46	0.35	0.23	1.35	1.0	0.67	3.8	1.9	3.5	2.7		
H.p. for 100′ horizontal run empty	1.2	1.1	0.9	1.7	1.5	1.3	2.4	1.6				
H.p. for 100′ horizontal run full, anthracite.......	2.5	2.1	1.5	5.3	4.3	3.1	12.4	6.6				
H.p. for 100′ horizontal run full, bituminous coal.	3.2	2.6	1.9	7.4	5.8	4.2	18.0	9.4				

Add 5 per cent. for each turn.

159. Ash handling is very frequently done by trolley locomotive and side dump cars, in large plants; these allow for thorough quenching before delivering to conveyors for elevation. Of the conveyors, the malleable-bucket type lasts the best in ash service. A skip hoist may be substituted for conveyors, for elevation; and where it can be used, is a most satisfactory means of disposal. Ash bunkers are almost always provided for storage purposes, as in many plants the ash removal from the individual boiler ash hoppers is done on night shift, when cars or boats are not readily available.

160. Helical or screw conveyors. The power required is

$$H.P. = \frac{W'LC}{33{,}000} \tag{31}$$

where W' = capacity in lb. per min., L = length in feet and C = 0.67 for coal, 1.00 for ashes.

161. Typical combinations are: low-hoist grab-bucket tower, containing crusher and scales; belt conveyors, horizontal, to power station; V-bucket or pivoted-bucket elevator, belt distribution at top of building to bunkers. Inclined belts may be used for "lift," but are not too satisfactory. Belts are very good on "carry," however. If the tower is close to the building, bucket elevators may be used both for lift and carry. A very good arrangement is: high towers, performing the whole lift at once, delivery through crusher and scales to cable car for distribution over bunkers. For small or moderate size plants telpher grab buckets offer a satisfactory solution, serving storage yard, cars or boats, and bunkers on overhead monorail structure. The usual system for ash disposal consists of collection from ash hoppers by industrial railway and trolley locomotive, and delivery to skip hoist or bucket elevator for lifting to ash storage pockets, for which the ashes are spouted to cars or barges. The vacuum system is useful for small and moderate size plants; or a single hand car may be enough. Belt conveyors should never be employed for ash handling.

162. The cost of conveyors is exceedingly variable and is dictated chiefly by structural conditions. It is almost impossible, therefore, to give unit costs. Belt conveyors of the lengths usual in power station work cost from $1.10 to $1.40 per inch of belt width, per foot of conveyor; bucket elevators and conveyors, roughly $0.18 to $0.25 per ton capacity per hour, per foot of conveyor.

STEAM ENGINES

163. Source of energy. The steam engine must obtain its energy from the heat drop available by adiabatic expansion between any two pressures. For adiabatic expansion, there must be no heat interchange with the surroundings while the mass of steam in the cylinder undergoes the expansion; therefore a non-conducting cylinder is required. This is commercially unattainable, and consequently the expansion is never truly adiabatic. The heat drop obtainable is always less, if the expansion is not adiabatic.

164. The thermal efficiency of a perfect engine working on the Rankine cycle (Par. 166) is given as

$$E_r = \frac{H_1 - H_2}{H_1 - h_2} \tag{32}$$

where H_1 = total heat of steam at initial condition (pressure and quality or superheat), H_2 = total heat of steam at final pressure after an adiabatic expansion (constant entropy), and h_2 = heat of the liquid, at final pressure. For modern steam pressures, superheats and vacua, this possible efficiency does not exceed 35 per cent. for turbines. The usual steam pressures and vacuum for reciprocating engines would not give a higher efficiency than 30 per cent.

165. The efficiency ratio for good compound engines seldom reaches 60 per cent., giving an actual thermal efficiency of 18 per cent., 13 per cent. and 14 per cent. are more commonly reached in large size reciprocating engines.

166. The Rankine cycle upon which these comparisons are based pre-supposes a non-conducting cylinder, no leakage and no clearance; admission at constant pressure, instantaneous cut-off; expansion adiabatically to the back pressure; exhaust at constant pressure; and since there is no clearance, no compression is required. In the real engine, conduction of heat, leakage, wire-drawing, friction, incomplete expansion, and clearance all tend to reduce the efficiency ratio by adding losses.

167. A single-expansion engine is one in which the complete expansion from initial to back pressure takes place in one cylinder; a **compound engine** is one in which the expansion is from the initial pressure to an intermediate pressure in one cylinder, and from this intermediate pressure to the back pressure in a second cylinder. A **triple or quadruple expansion engine** performs the expansion similarly in three or four stages, respectively. All engines using more than one cylinder to complete the expansion are termed **multiple expansion**, in general.

168. Cut-off usually takes place at $\frac{1}{3}$ to $\frac{1}{4}$ stroke in simple non-condensing engines, $\frac{1}{4}$ to $\frac{1}{8}$ in condensing. **The number of expansions** is the ratio of final cylinder volume to volume contained at cut-off; for simple non-condensing engines the ratio is 3 to 4; simple condensing, 5 to 8; compound and triple, etc., 8 to about 50. For power station purposes 16 to 20 is common, with compound condensing units.

169. Non-condensing engines exhaust freely to atmosphere, or to a system in which the pressure is atmospheric or a few lb. per sq. in. above; condensing engines exhaust to a condenser in which a partial vacuum is maintained, below atmospheric pressure.

170. High-speed engines operate at 350 to 250 rev. per. min., in sizes from 5 h.p. to 500 h.p. **Medium-speed** engines operate at 250 to 150 rev. per min. in sizes from 250 h.p. to 1,000 h.p. **Low speed** engines (generally Corliss types) operate from 100 to 70 rev. per min., in sizes from 400 h.p. to 8,000 h.p.

171. Single-acting engines take steam on one side of the piston only; they may be simple, compound or triple expansion; and are always high-speed engines, usually with vertical cylinders.

172. The slide valve in the original D-valve form is unbalanced, moving on flat faces; it is unsuitable for large sizes and heavy pressure. Balanced forms of the slide valve, such as the Ball, Skinner, Mackintosh & Seymour grid, etc., overcome some of these objections. **The piston valve,** shaped like a piston, is inherently balanced; it can be made tight, but requires large clearance percentage, on account of length of the ports.

173. The Corliss valve is of general cylindrical shape, oscillating over ports parallel to the axis of the valve and crosswise of the cylinder; it can take care of but one function, therefore four are required per cylinder, two for admission and two for exhaust. The preceding types, except the grid, take care of all four functions with one valve. The Corliss valve is always used with a trip or releasing gear to vary the cut-off without changing any other event in the steam admission or exhaust. In all fixed valve gears, it is usually impossible to vary the cut-off without varying other functions at the same time.

174. Poppet valves are those in familiar use on automobile engines; but for steam use are generally made double-seated so as to be balanced. They have met with great success in Germany, and are undoubtedly the best type for superheat. They may be used with releasing gears, and require four valves per cylinder, as with the Corliss type.

175. Jackets for keeping the cylinder hot with live steam, to reduce condensation in the cylinder, have been used with some success for pumping engines; but have not been successful in many other applications.

176. Receivers are used to eliminate variations of pressure between high-pressure and low-pressure cylinders in multiple-expansion engines, due to intermittent exhaust and admission: they must be of large capacity to be effective. **Reheating coils** are sometimes employed to dry the steam passing through these receivers, to improve conditions in the succeeding cylinders. They are of practically no value in engines for power-station service.

177. Governors for steam engines are of two principal types: flyball and shaft governors. The flyball type consists of two or more weights or balls supported by movable arms, the whole rotated around a shaft so that centrifugal force tends to throw the balls outward; this tendency is resisted by weights or springs, and the relative movement of the arms made to operate the engine valve gear. In the **shaft governor** the weights are arranged to rotate vertically around the main crank shaft, and attached direct to the eccentrics without the intervention of other mechanism. It cannot be used with slow-speed engines, nor with any form of trip or releasing gear. Inertia effects are introduced in the Rites type of shaft governor.

178. Either centrifugal or inertia types of governor can be made isochronous, but are generally only approximately so; isochronism, or complete instability of the governor at all speeds except the correct speed, is undesirable.

179. Engine frames are usually made entirely of cast iron, for stationary, work; the vertical engines are of the A-frame type in large and small sizes and of the enclosed type, with automatic oiling, for small and moderate size, only. Horizontal engines of small and moderate sizes, may be enclosed, with automatic or splash oiling.

180. Girder frames. The large horizontal Corliss type engines are made with girder frames connecting the cylinders and the main bearings, for the **standard type**; in the **heavy-duty type**, the girders are completely surrounded by the frame, which is carried down to the sole plate all the way from cylinder to main bearing.

181. Mean effective pressure is the average pressure which if exerted during the full stroke would equal the work done by the varying pressures really existing during the course of the stroke. The mean effective pressure (m.e.p.) is obtained from the indicator card as follows:

$$\text{M.e.p. in lb. per sq. in.} = \frac{\text{card area in sq. in.} \times \text{scale of spring}}{\text{card length in inches}} \qquad (33)$$

The shorter the cut-off, the lower the m.e.p. for any given steam pressure and back pressure; consequently the larger the cylinder dimensions become for a given horse-power, other things being constant.

182. Cylinders are usually so proportioned as to divide the total work equally between high- and low-pressure cylinders; roughly, for compound engines, the cylinder ratio is given by

$$Rc = \left(\frac{P_1}{P_3}\right)^{\frac{1}{2}} \text{ and } P_2 = (P_1P_3)^{\frac{1}{2}} \qquad (34)$$

where Rc = cylinder ratio, or ratio of low-pressure displacement to high-pressure displacement, P_1 = initial pressure in lb. per sq. in. absolute, P_2 = receiver pressure in lb. per sq. in. absolute, and P_3 = back pressure in lb. per sq. in. absolute.

This is based on no clearance, no compression, equal cut-off in both cylinders, logarithmic expansion, and receivers of infinite capacity. It is varied in practice by the clearance of both cylinders; by finite receivers and by the effects of wire-drawing.

183. The speeds usually employed in America are given in Par. **170**. Snell gives a table of usual English practice, which is slightly higher than American usage.*

For sizes above 1,750 k.w., the speed is from 75 to 60 rev. per min., for Corliss engines. **Piston speeds** range from 350 to 600 ft. per min. in the high-speed engines, and from 600 to 750 ft. per min. in the low-speed, long-stroke Corliss types.

184. Indicated horse-power is given by the indicator, and is the amount of power actually developed in the cylinder by the steam. **Brake horse-power** is the actual output at the shaft.

$$\text{I h.p.} = \frac{PLAN}{33{,}000} \qquad (34a)$$

where

P = mean effective pressure, lb. per sq. in.;
L = length of stroke, ft.;
A = piston area, sq. in.;
N = number of strokes per min.

* Snell, "Power House Design," p. 146, Table XLVII.

185. The mechanical efficiency is given by the formula

$$E_m = \frac{\text{b.h.p.}}{\text{i.h.p.}} \tag{35}$$

where E_m = mechanical efficiency, b.h.p. = brake horse-power, and i.h.p. = indicated horse-power.

$$\text{Friction h.p.} = \text{i.h.p.} - \text{b.h.p.} \tag{36}$$

Lucke gives the formula

$$E_m = 1 - \frac{K_1 - K_2}{(\text{m.e.p.})} \tag{37}$$

where $K_1 = 0.02$ to 0.05, average 0.04; and $K_2 = 1.3$ to 2.0, average 1.6.

186. Mechanical design of the steam engine is limited by first cost, efficiency and reliability: these three factors exert influences in varying directions. Low cost per h.p. capacity indicates high rotative speed and simplicity of mechanism. High economy indicates lower speeds, complicated valve gear, multiple cylinders, reheaters and large receivers. Reliability dictates heavily built parts, elimination of small parts, and especially the elimination of small bearings. **The outcome** is that for small powers, moderate speeds and low steam pressures, the simple non-condensing slide-valve engine, throttle governed, is used. Under steady load and speed it has fair economy, and is very reliable. For small electric isolated plant service, the high-speed automatic engine, with shaft governors and piston-valves or balanced slide valves, is used. For higher powers the low-speed condensing engine, either simple or compound, is adopted. The higher economy demanded justifies the increased cost due to low speed and Corliss valve gears; reliability is also provided, since the complex gear is now large enough not to be fragile.

187. Friction loss, which causes the difference between brake and indicated power, is made up of bearing friction; piston, valve and rod friction; and windage. The principal bearing friction occurs in the main bearings, crank pins and crosshead slippers, the remainder occurs in the valve gear. **Suitable lubrication** greatly reduces this kind of friction. Piston, valve and rod friction occur in a steam atmosphere where lubrication is at best uncertain. The latter depends upon the type of valve, whether balanced or not; upon the kind and number of piston rings; and upon the condition of the rod packing.

188. Lubrication of all bearings is accomplished with engine or machine oil; or prepared grease. In small engines, sight-feed oil cups are commonly used; for large units, a central gravity oiling system piped to all bearings is considered the best practice. In the latter case, the oil is caught after use and returned to filters, whence it is again pumped to the elevated supply tank. In this way copious supplies of oil may be given without great expense and the friction is very much reduced. **Splash oiling** in closed crank-case engines is employed for high speeds and small or moderate sizes. Grease can only be fed by individual compression cups at each bearing.

189. Cylinders are oiled with heavier lubricants, whose lubricating qualities in the steam become the same as ordinary engine oil at room temperatures. Cylinder oil is fed into the steam pipe just above the throttle, or into the steam chest: a hydrostatic sight-feed lubricator, or a force pump may be employed. The latter is considered the better method. **Graphite** has been used with much success in assisting cylinder lubrication; the chief difficulty lies in getting it into the cylinder.

190. The total losses occurring in a steam engine can be classified as follows: cylinder condensation; leakage; clearance; incomplete expansion; wire-drawing; radiation; mechanical friction.

191. Cylinder condensation is caused by the conduction of heat away from the steam through the cylinder walls; the cylinder assumes an average temperature about half-way between steam admission and exhaust temperatures. Consequently the hot in-coming steam gives up heat to the cooler walls; some of this is returned, too late to be of use, during the exhaust stroke. **Moisture in the entering steam** makes this effect worse; but **superheat** much improves it, by increasing the surface resistance to heat transmission.

192. Leakage occurs past all sliding joints—the joint behaves like an elongated capillary orifice for steam flow; such joints occur at the piston, the piston rod, the valve seat and the valve rod. The means of reducing leakage are generally snap and spring-rings for pistons and piston valves, pressure plates insuring a close fit for flat balanced valves, and sectional metallic or soft packing compressed by a gland, for all rods.

193. Clearance is any space left between the valve and the piston, when the latter is at the end of the stroke. It varies from 3 to 4 per cent. of the displacement in well-designed Corliss engines; from 8 to 14 per cent. on high-speed and medium-speed engines; from 15 to 30 per cent. in badly designed or low-price slide-valve and piston-valve engines.

194. Zero clearance is not possible in any commercial construction, since piston must have some clearance from the cylinder head, and the steam and the exhaust passages must always have some volume. Clearance necessitates compression, in order to bring the volume of steam trapped in the clearance space to approximately the initial pressure; this has the double effect of cushioning the engine and avoiding loss due to filling the clearance space with fresh steam at each stroke.

195. Incomplete expansion is due to the limitations in size of cylinders, which commercially cannot be made large enough to handle the high volumes at low pressure.

196. Wire drawing is the term applied to pressure drop between steam chest and cylinder due to insufficient area in the valves and ports, or slow opening of the valve; it reduces the effective pressure and therefore causes a loss.

197. Radiation is the heat loss which occurs when the cylinder temperature is higher than that of the surrounding air. Not only the cylinder, but also those parts of the engine which become hot by conduction, radiate heat. The cylinder is heavily lagged (or even jacketed in a few cases) to reduce the loss. This loss amounts to 1 or 2 per cent. of the total heat of steam used by the engine.

198. Indicated horse-power is obtained from the indicator card (Par. 184) and was the basis of most guarantees up to a few years ago. Brake horse-power, which is the useful power delivered at the shaft, is now more common.

199. Non-condensing single-cylinder engines are usually rated at $\frac{1}{4}$ or $\frac{1}{3}$ cut-off and 100 lb. gage steam pressure; compound non-condensing engines at $\frac{1}{4}$ to $\frac{1}{3}$ cut-off in the high-pressure cylinder and 150 lb. gage pressure; simple condensing engines at $\frac{1}{4}$ or $\frac{1}{5}$ cut-off and 125 to 150 lb. gage pressure. The guarantees should always state steam pressures, back pressures and actual cut-off, instead of the above figures.

200. The locomobile type of engine developed abroad and lately introduced in this country is a combination consisting of a tandem compound engine mounted directly on an internally fired boiler. The high-pressure cylinder is in the smoke flue, and the low-pressure cylinder is jacketed by the steam dome. A superheater is also fitted in the smoke box. The advantage of maximum jacketing effect, high superheat, and practically no piping losses, make the fuel economy high. This type of unit is now manufactured in this country, but the advantages of the turbine, coupled with the comparative inflexibility of a single boiler-engine unit, will prevent extensive use of the locomobile in America.

201. Exhaust steam heating makes use of the heat wasted by the engine; it may amount to 80 or 90 per cent. of the heat originally in the steam. Consequently, the power is obtained at very low cost for fuel, since most of the ordinary inherent losses are recovered as heat in the heating system. Hence in most industrial plants serving buildings with lighting and power service, non-condensing engines are used. Generally the expense of a condenser to be used during the summer months will not be justified, as the small gain in economy for the year will not offset the fixed charges on the condenser equipment.

202. Average steam-engine performance. The brief summary which follows, with a few omissions and additions, is taken from the more extensive tables given in Gebhardt's "Steam Power Plant Engineering."

Expansions	Number	Type of engine and operating conditions		Horse power	Initial pressure lb. gage	Back pressure lb. abs.	Temperature of feed water	Superheat at admission, deg. fahr.
Simple (1×)	1	Single-valve	Range	33–257	80–124	Atm.	....	....
		Non-cond.	Avg.	137	104.9	Atm.	....	....
	2	Single-valve	Range	33–204	69.3–114	1–3.2	....	....
		Condensing	Avg.	116	83.3	2.4	....	....
	3	Four-valve	Range	120–506	99.6–125.4	Atm.	....	....
		Non-cond.	Avg.	264	106.9	Atm.	....	....
	4	Four-valve	Range	145–613	67–96	1.0–2.9	....	....
		Condensing	Avg.	381	78.2	1.9	....	....
Comp. (2×)	5	Non-condensing	Range	33–1125	114–210	Atm.	212*	....
		Sat. steam	Avg.	359	151	Atm.	212*	....
	6	Condensing	Range	340–7365	100–185	.8–2.2	100–130	....
		Sat. steam	Avg.	2770	152	1.47	119.3	....
	7	Condensing	Range	145–2202	114–163	.84–2.15	97–130	40–343
		Superheated	Avg.	673	132	1.39	112*	218
(3×)	8	Condensing	Range	464–1823	134–185	.85–1.8	122–158	....
		Sat. steam	Avg.	988	152	1.22	145	....
	9	Condensing	Range	549–2940	147–173	.79–1.28	95–111	87–264
		Superheated	Avg.	1517	165	1.00	102*	195
(4×)	10	Condensing	Range	712–990	200–243	.9–1.25	310–334	....
		Sat. steam						
1×	11	Locomotives, sat. steam		399 & 975	110 & 196	Atm.	....	....
2×	12	Locomotive, sat. steam		495	210	Atm.	212*	....
1×	13	Corliss N. C. sat.		237	103.5	Atm.	....	....
1×	14	Corliss Cond. sat. } jacketed		155	103.8	1.2	....	....
1×	15	Poppet Cond. sat. } jacketed		262	79	1.36	....	....
3×	16	Binary, superheated		211	143	2.2	....	221
2×	17	White automobile, sup.		40	426	Atm.	212	316

1× = simple engine; 2× = compound; 3× = triple; 4× = quadruple expansion.
* Ideal feed-water temperature (temperature of hot well).

Expansions	Number	Type of engine and operating conditions		Pounds of dry steam per i.h.p. hour	B.t.u. per i.h.p. minute	Thermal efficiency of engine 42.42 ÷ B.t.u.	‡ Cylinder efficiency or eff. ratio	M.e.p. referred to L.P. cyl.	Remarks
Simple (1×)	1	Single-valve	Range	26.0–30.6	436–510	8.33–9.75	57.5–65.7	35.0–58.5	
		Non-cond.	Avg.	27.63	463	9.20	61.3	44.5	Avg. 7 engines.
	2	Single-valve	Range	22.2–27.5	410–490	8.67–10.35	39.7–41.3	38.1–41	
		Condensing	Avg.	25.7	450	9.47	40.5	39.9	Avg. 4 eingines.
	3	Four-valve	Range	22.24–25.9	374–434	9.80–11.30	66.2–73.5	25.7–48.4	
		Non-cond.	Avg.	24.06	404	10.54	70.2	38.6	Avg. 5 engines.
	4	Four-valve	Range	18.5–22.0	342–397	10.7–12.4	48.0–60.2	30.9–38.2	
		Condensing	Avg.	19.84	359	11.85	51.3	35.0	Avg. 4 engines.
Comp. (2×)	5	Non-condensing	Range	17.17–22.3	291–376	14.5–11.2	65.5–83.0	31–56	
		Sat. steam	Avg.	20.3	342.3†	12.4	72.3	37.1	Avg. 10 engines.
	6	Condensing	Range	11.20–12.70	220–234	18.1–19.2	63.5–76.5	13.0–27.9	
		Sat. steam	Avg.	12.14	223.6	18.8	69.0	21–2	Avg. 8 engines.
	7	Condensing	Range	8.58–11.80	176.1–223	24.0–19.0	78.5–54	....	
		Superheated		10.0	202.2†	20.98	69.0	....	Avg. 8 engines.
(3×)	8	Condensing	Range	10.33–11.33	196–208	20.4–21.63	70.0–76.0	19.5–23.4	3 pumping, 1 mill engine.
		Sat. steam	Avg.	10.81	202.2	20.98	72.8	21.05	
	9	Condensing	Range	8.97–10.00	188.7–207.3	20.4–22.6	66.7–73.5	....	
		Superheated	Avg.	9.65	198.4†	21.4	70.1	....	Avg. 5 engines.
(4×)	10	Condensing	Range	12.26–11.25	186–169.3	22.8–25.05	74.2–88.2	35.5	Trans. A. S. M. E. 1900
		Sat. steam		2 Engines with Regeneative Cycle					and 1907.
1×	11	Locomotives, sat. steam		24.97–23.4	420–398	10.1–10.65	65.0–55.9	54–75.6	A. S. M. E., XIV
2×	12	Locomotive, sat. steam		18.6	316†	13.4	68.5	55	St. Louis Expo. 1904.
1×	13	Corliss N. C. sat. } jacketed		21.5	358	11.85	78.0	42.1 }	Peabody's "Thermody-
1×	14	Corliss Cond. sat. } jacketed		16.5	302	14.05	53.3	32.0 }	namics."
1×	15	Poppet Cond. sat. } jacketed		15.0	275	1.54	63.8	30.2	*Zeit. v. D. I.*, Aug., 1905.
3×	16	Binary, superheated		8.6	158.3†	2.68	....	....	Franklin Inst., 1902.
2×	17	White automobile, sup.		11.96	244	17.4	68	....	A.S.M.E., 1907.

‡ Cylinder Efficiency = (Theor. B.t.u. per min. with Clausius or Rankine cycle with complete expansion) ÷ actual B.t.u. per i.h.p. min.

† Above ideal feed-water temperature.

203. Water rates vary greatly with steam pressure, superheat or moisture, and back-pressure. No comparison of water rate alone can be fair, unless the steam conditions are known. Fig. 21 shows typical curves for engines of small and moderate size, and Fig. 22 for large engines. The Rankine-cycle efficiency ratio is the best means of comparison for varying steam conditions. For small non-condensing engines, the efficiency ratio varies from 0.50 to 0.65; condensing lowers the ratio about 0.05 to 0.10.

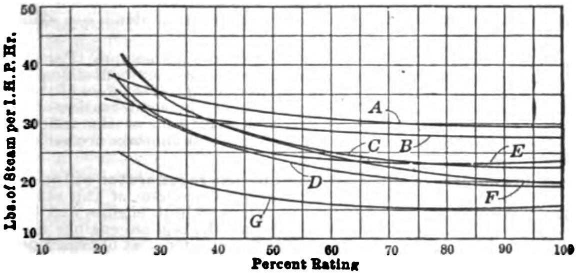


FIG. 21.—Water rates of small engines.

A, Automatic single cylinder, non-condensing, pressure = 125 lb., 80 i.h.p.; *B*, automatic single cylinder, non-condensing, pressure = 125 lb., 100 i.h.p.; *C*, automatic tandem compound, non-condensing, pressure = 140 lb., 200 i.h.p.; *D*, automatic tandem compound, condensing, pressure = 140 lb., 300 i.h.p.; *E*, Corliss or medium speed four-valve simple, non-condensing, pressure = 130 lb., 200 i.h.p.; *F*, Corliss or medium speed four-valve tandem compound, non-condensing, pressure = 150 lb., 300 i.h.p.; *G*, Corliss or medium speed four-valve tandem compound, condensing, pressure = 160 lb., 300 i.h.p.

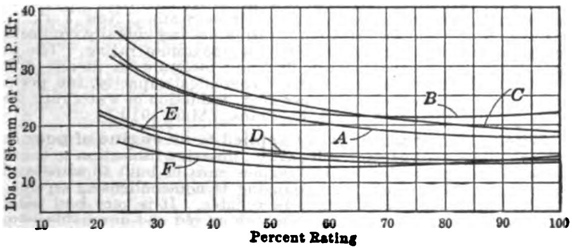


FIG. 22.—Water rates of large engines.

A, Automatic tandem compound, condensing, 700 i.h.p., pressure = 150 lb.; *B*, Corliss or medium speed four-valve simple, non-condensing engine, 900 i.h.p., pressure = 130 lb.; *C*, Corliss or medium speed four-valve tandem compound, non-condensing engine, 950 i.h.p., pressure = 150 lb.; *D*, Corliss or medium speed four-valve tandem compound, condensing engine, 900 i.h.p., pressure = 160 lb.; *E*, Corliss or medium speed four-valve tandem compound, condensing engine, 1,500 i.h.p., pressure = 160 lb.; *F*, Manhattan type, double compound Corliss condensing engine, 10,000 i.h.p., pressure = 175 lb.

204. The thermal equivalent of a horse-power hour is 2547 B.t.u. Large high-grade engines actually develop a horse-power on 15,600 to 17,000 B.t.u.; small engines, 25,000 to 34,000 B.t.u. Par. **202**, gives these values in terms of B.t.u. per indicated h.p. per min.

205. The effect of raising the back-pressure upon an engine can readily be seen from the Mollier diagram; the available adiabatic heat drop is re uced and consequently, although the efficiency ratio may not change, the thermal efficiency of the Rankine cycle is reduced, and therefore the thermal efficiency of the actual engine. In other words, the water rate increases. Since the heat drop is less, there will be somewhat more heat per lb. in the exhaust.

206. Exhaust steam turbines are of valuable use in connection with non-condensing engines used intermittently. The economy of such engines (say, for rolling mill service) is low, and large quantities of steam are exhausted to the air one moment, and almost none the next.

207. Regenerators. The exhaust of several such engines (Par. **206**) is piped to regenerators, which are simply heat reservoirs containing a large body of hot water in contact with the exhaust steam. The effect of the regenerator is to absorb heat, when delivered in excess, by condensation of steam; and to release it upon shortage, by evaporation of some of the water. The slight pressure variations between full delivery and shortage are sufficient to accomplish this.

208. A low-pressure turbine served by the regenerator will operate on about double the water rate of high-pressure machine of the same size. The resulting overall water rate for the output of both engines and turbines may be from 20 to 50 per cent. less than with the original engines alone; or the energy delivered by the turbine may be considered as obtained practically for nothing except the fixed charges and maintenance on the regenerator, piping and turbine.

209. Low-pressure turbines may sometimes be used in connection with high-grade engines as a convenient means of increasing capacity. The efficiency ratio of non-condensing engines is always much higher than that of condensing engines of the same size (Par. **201**); this is due mainly to the low-pressure cylinder, which has a very low efficiency. The low-pressure turbine has a better efficiency ratio than the high-pressure machine, because the friction of the steam is always less at the lower densities, and the friction is again reduced by the removal of the moisture in the steam before reaching the turbine.

210. The largest installation of low-pressure turbines is at the Interborough Rapid Transit Company's 59th-Street Station, New York. Five Curtis turbines of 7,500 kw. maximum rating are individually connected to five compound Corliss engines of 7,500 kw. maximum rating. The steam pressure is 190 lb. gage; vacuum, 28.5 in.; moisture in steam, 1.5 per cent. The net results are: increase of economical capacity, 146 per cent., increase of maximum capacity, 100 per cent. reduction of water rate, 25 per cent. (Stott and Pigott; A. S. M. E. Trans.; Mar. 1910.)

211. When exhaust turbines are applied to an engine of poor economy, the saving is even greater. However, there is a limitation to the use of the low-pressure turbine, in that the engines must be built to withstand the extra pressures which result from changing to non-condensing service, and must be in good enough condition to be reliable. It is very bad policy to make such an installation in connection with an old and unreliable engine.

212. Engine specifications should cover the following points; (a) Number and location; character of building. (b) Type, service, and manner of connection to load. (c) Principal dimensions. (d) Steam and back pressures, normal and overload capacity. (e) Speed regulation under all kinds of load variation; variation of angular velocity. (f) Satisfactory operation, noise, vibration, etc. (g) Tests and inspection. (h) Construction details—cylinder, piston-rods, crosshead, connecting-rod, pins and bearings, shaft and flywheel, governor, valves, frame, foundation, lubricators, and receivers, piping, engine-stop, erection. (i) General: arrangements for delivery into plant.

213. The only large-size engines in use in electric power plants are of the Corliss type, and the grid-valve type. The moderate-size, medium-speed or high-speed engine may be of the following types: Corliss, automatic piston valve, or Lentz type poppet valve. The high-speed small engine for exciter service or small direct-current generation is practically always a shaft-governor automatic slide-valve or piston-valve engine, generally simple.

214. The medium-power and high-power engines are practically always compound. Wherever possible, the vertical compound, or at least the angle compound (horizontal-vertical) should be used on account of the saving in floor space, and the more satisfactory wear of the parts. The horizontal engine is used only where the headroom is restricted.

215. Automatic stops consist of some form of flyball governor, belt or chain driven from the engine shaft: the governor is so set as to release a trigger or close an electric circuit when the predetermined speed is exceeded. This trigger, or a magnet in the electric circuit, releases a weight arranged to close the throttle. The usual connection consists of a steel wire rope around a drum on the throttle valve stem. In another form of automatic stop the operation of the magnet or trigger releases the pressure of steam on a pilot pipe line; this in turn releasing the pressure behind a piston in the specially designed throttle valve, which then closes. Both the systems are arranged for additional operation by hand.

216. The operation of steam engines, after correct adjustment of moving parts has been made, is chiefly a matter of lubrication. In **starting**, the usual procedure is to "crack" the throttle in order to admit a little steam to warm up the engine all over without allowing it to turn. After the preliminary warm-up, standing, the engine is allowed to turn over slowly for a few minutes to warm all parts thoroughly; it is then ready for full speed and load. Five minutes may be long enough for "**warming up**" an engine of 300 h.p. or less; 15 or 20 min. are required for large machines. Just before starting, a few strokes of the hand oil pump (usually attached) should be given, to insure thorough lubrication. All automatic oiling rigs should be started a few minutes before turning over. Drips should be wide open while warming up, and while turning slowly, but closed when the engine is brought up to speed. **Shutting down** only requires the closing of the throttle, shutting off automatic feeds, and the opening of drips. All bolts and nuts should be gone over periodically, say once a month, and a thorough overhauling given the piston, cylinder, bearings, etc., once a year.

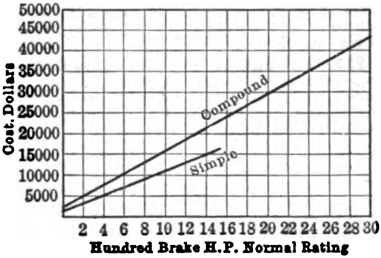


Fig. 23.—Cost of large reciprocating engines.

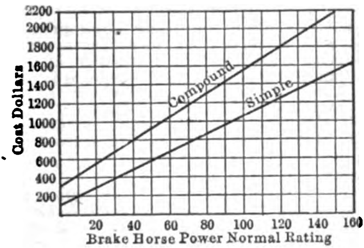


Fig. 24.—Cost of small reciprocating engines.

217. Engine costs. Figs. 23 and 24 give the usual costs of large and small engines. The cost per lb. of engine varies from $0.10 to $0.15.

218. The present status of the reciprocating engine is revealed by a progressively diminishing percentage of the total h.p. of prime movers sold. The large steam turbine has totally displaced it in central stations; and recently the development of fairly economical small turbines is cutting down the field in all directions. The immense advantages of the turbine are great enough to overcome a slight inferiority in water rate in the small sizes. Ultra-conservatism and ignorance of the real cost of power, of which coal and water are only fractional parts, account for the purchase of reciprocating engines where turbines ought to be installed. The oil engine and the gas engine, for small and moderate sized plants, are also giving the steam engine vigorous competition.

STEAM TURBINES

219. The thermodynamics of the steam turbine is a simpler matter in theory than the steam engine. The energy of the adiabatic expansion in the turbine is converted into kinetic energy by producing motion of the steam particles, which issue from the nozzles as jets.

220. Resisted and free expansion. The expansion in the engine is termed "perfectly resisted;" in the turbine it is "free." Therefore all the work is done upon the steam itself during the expansion, producing high velocity of the steam particles; these particles in turn impinge upon curved vanes or buckets, which change the direction of flow of the jets in such a manner as to produce a force in the direction of rotation of the wheel.

221. The losses are wholly different from those in the engine; there is no initial condensation, because the parts assume the temperatures of the moving steam, instead of being alternately heated and cooled, and radiation is so slight as to be negligible (0.1 per cent. or less).

222. Friction. The only true mechanical friction is in the bearings, and is usually under 2.5 per cent. in small turbines, and under 1 per cent. for larger sizes. The principal loss is steam friction, which is made up of (a) nozzle friction, (b) blade friction, (c) eddies in the flow and (d) windage of the discs or drums revolving in steam. There is some **leakage**, but generally less than in the engine. The presence of any velocity in the exhaust steam is also a source of direct loss.

223. The flow of gas through a nozzle is a phenomenon divisible into two classes—(a) above, and (b) below, the critical pressure. When difference of pressure is maintained across an orifice, steam will flow with increasing velocity and in increasing quantity as the pressure difference increases up to that point at which

$$\frac{P_2}{P_1} = 0.58, \text{ for steam,} \qquad (38)$$

where P_1 = initial pressure in lb. per sq. absolute and P_2 = back pressure in lb. per sq. absolute.

224. The critical pressure is,

$$P_2 = 0.58P_1. \qquad (39)$$

This is true for all initial pressures. The corresponding velocity varies from 1,300 to 1,500 ft. per sec., and is found practically to coincide with the velocity of sound in steam at the pressure $P_2 = 0.58P_1$.

225. Effect of reducing back-pressure. Up to this point (Par. **223**) the stream issues from the orifice in parallel lines; but if the value of P_2 is reduced below $0.58P_1$, no further increase in velocity or quantity can be obtained, at the orifice, but there is further acceleration beyond the orifice, and the stream flows out laterally as well as forward. Heavy accoustic vibrations occur, and the efficiency of conversion decreases. To correct this, a conical or conoidal section is added to the orifice, diverging in the direction of flow, and the further pressure drop is permitted to take place in this flaring or trumpet-like exit.

226. The exit area should be that suited to the velocity and volume resulting from the total heat drop from the pressure P_1 to P_2; but the throat always remains of that size required for a pressure of $0.58P_1$, and a velocity of about 1,300 to 1,500 ft. per sec. The theoretical velocities are not realized, due to friction of the steam in the nozzle.

227. The velocity efficiency of a convergent nozzle (orifices with rounded entrance) varies from 98 per cent. at low velocities down to 95 per cent. at 1,300 to 1,400 ft. per sec. The **velocity efficiency of a divergent nozzle**, for expansion beyond the critical pressure, ranges from 94 per cent. at 1,500 ft. per sec. to 90 per cent. or 85 per cent. at 3,000 ft. per sec.

228. The velocity efficiency of the buckets varies from about 95 per cent. to 98 per cent., for the low velocities used in reaction turbines (less than 1,000 ft. per sec.), to 84 per cent. or 86 per cent. in impulse turbines at velocities of about 2,500 ft. per sec. The second and succeeding rows of buckets or guides in velocity-compounded turbines have even lower efficiencies, reaching 84 per cent. at about 1,500 ft. per sec.

229. The velocity obtainable by expansion is expressible by

$$V = 223.7\sqrt{H_1 - H_2} \qquad (40)$$

where V = velocity at exit of nozzle in ft. per sec., H_1 = total heat contents of steam at initial condition, and H_2 = total heat contents of steam at final condition. If H_2 denotes the heat contents after an adiabatic expansion, it follows that V is the theoretical value; but H_2 is always higher than this, because internal friction reduces the quantity of heat removed from the steam by the work done.

230. Pressure drop. In the impulse turbine, all pressure drop occurs in stationary nozzles, and there is no difference of pressure across the moving blades. In the reaction type, about half the pressure drop takes place in the stationary blades, and the remainder in the running blades; and the latter, therefore, act also as nozzles. There is an unbalanced force due to this difference of pressure across the moving blades that must be cared for by balancing devices.

231. There are two basic types of turbines: impulse and reaction. Neither of the two is really pure impulse or pure reaction, but the work done by impulse predominates in the impulse type, and the work by reaction in the reaction type. The simple impulse wheel is only employed in the single-stage de Laval type; velocity compounding and pressure compounding are employed in all other impulse types. Compounding becomes a necessity, to secure reasonable rotative speeds.

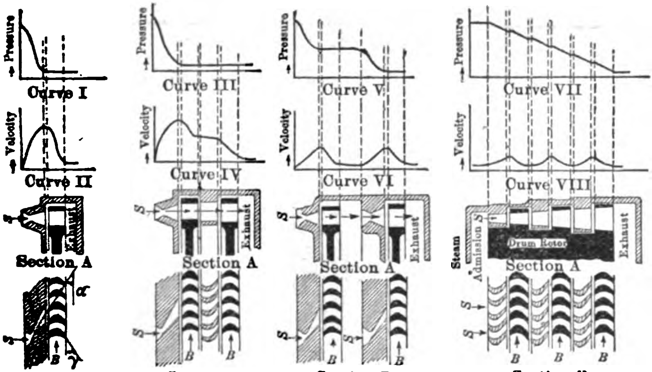


Fig. 25.—Elemental turbine types.*

232. The steam velocity in a single expansion from 150 lb. gage to a 28-in. vacuum would be about 3,100 ft. per sec. For best efficiency the blade velocity should be a little less than half the steam velocity, or in this case 1,500 ft. per sec., which results in centrifugal stresses in the disc much in excess of suitable stresses for commercial materials. If the wheel is run slower, the exit velocity of the issuing steam is increased, reducing the efficiency.

233. In velocity compounding the exit velocity from the first wheel is received in a series of guide blades and redirected to a second wheel, so that more of the energy is removed, without unreasonable wheel velocities (300 to 600 ft. per sec.).

234. Pressure compounding is the division of the pressure drop into two or more stages, which are essentially de Laval single-stage nozzles and wheels in series. Fig. 25 shows these types with characteristic figures.

* From "The Steam Turbine" by J. A. Moyer.

235. The reaction turbine for best efficiency runs at $\sqrt{2}$ or 1.414 times the peripheral speed of the impulse turbine for the same pressure drop. It is never built single-stage, but always pressure-stage compound.

236. Principal types. The de Laval is the original single-stage impulse type; the velocity-compounded type (generally also combined with few-stage pressure compounding as well) is usually known as the Curtis; the pressure-stage type (pure), as the Rateau; and the reaction type, as the Parsons.

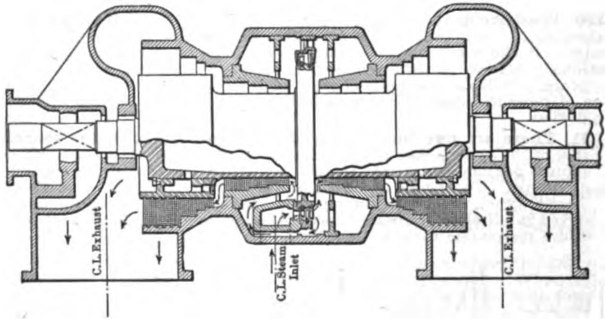


Fig. 26.—Curtis-Parsons double-flow turbines.

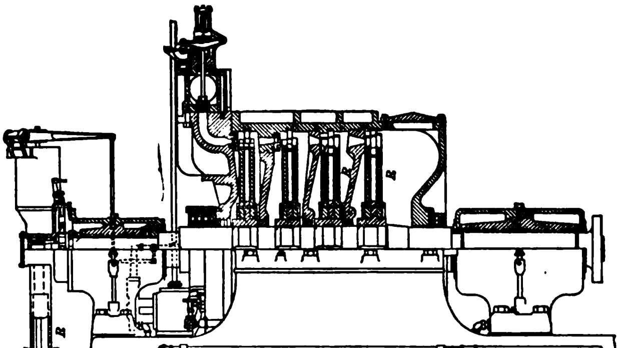


Fig. 27.—Curtis turbine.

237. The blading of the three principal types, Parsons, Curtis and Rateau, is shown in Figs. 26, 27, and 28.

238. Hybrid types have lately proved the most efficient, or cheaper to build. In moderate sizes the Parsons turbine is built with a Curtis 2-wheel velocity stage for the high-pressure stage; the advantage is a large pressure drop in a small nozzle chamber, avoiding high pressure in the casing, shorten-

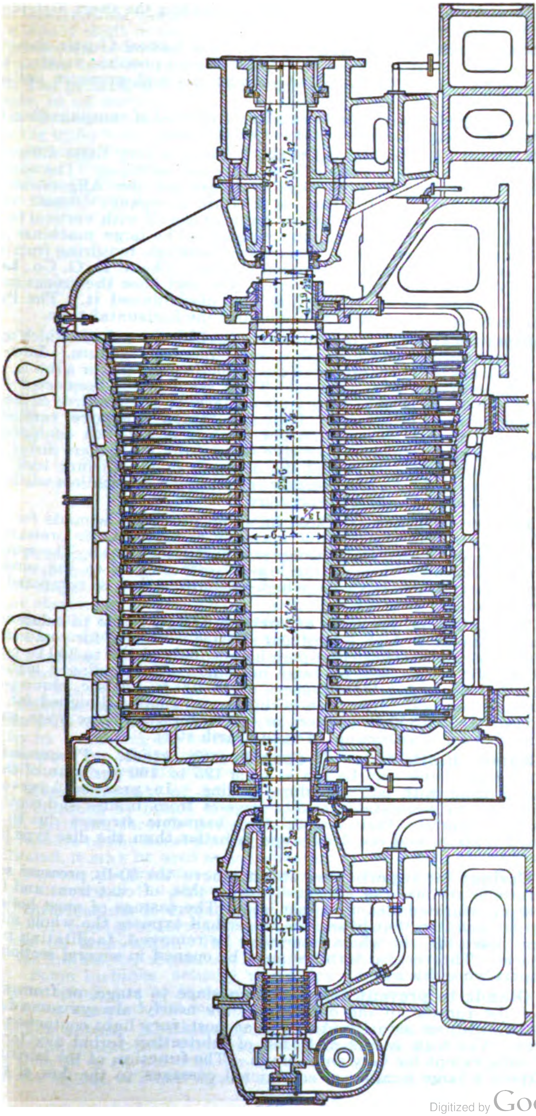


FIG. 28.—Rateau turbine.

ing and cheapening the construction, and eliminating the short high-pressure reaction blading, which is the least efficient.

239. The Curtis-Rateau type consists of a 2-wheel Curtis element for the high-pressure stage, followed by 6 to 12 Rateau pressure stages. It has the same advantage with regard to keeping the high-pressure out of the casing.

240. Velocity staging is the least efficient method of compounding, but is chiefly used for small turbines, as it lowers the cost.

241. Vertical and horizontal types. There is very little difference in principal features between vertical and horizontal turbines. The only companies that have built large vertical machines are the Allgemeine Elektricitäts Gesellschaft and the General Electric Company. Small vertical turbines, in small sizes, are sometimes built for use all with vertical fans and pumps, using a ball step bearing for support. The large machines are all provided with oil or water high-pressure step bearings, requiring from 650 to 1,000 lb. per sq. in. pressure, and special pumps. The A. E. G. Co., has discontinued building this type for several years, and since the recent increase in rotative speeds, the G. E. Co. has also discontinued it. The Parsons turbine has never been built in anything but the horizontal type.

242. Pressure types. High-pressure turbines are those which operate on full boiler pressure and exhaust to atmosphere or vacuum. **Low-pressure** turbines are those operating on atmospheric pressure, or a few lb. above it, and exhausting into a vacuum. They are usually connected to the exhaust of non-condensing reciprocating engines, or other source of low-pressure steam (except direct from boilers). **Mixed-pressure** turbines are those designed to run normally on low-pressure steam, but equipped with high-pressure stages which may receive steam from the boilers direct, if the low-pressure supply fails to equal the demands of the turbine load. This type is characterized by a low-pressure end designed to handle a much larger quantity of steam than the high-pressure end.

243. Bleeder turbines are those in which provision is made for taking steam from a stage of the machine normally at atmospheric pressure, or a few lb. above, to be used for heating, or industrial service. The remainder not so used continues through the low-pressure section to the condenser. This type is characterised by a large high-pressure section, as compared to the low-pressure end.

244. The principal features of turbine design relate to balance, leakage, and resistance to high centrifugal stresses. Wheels for small impulse turbines are normally operated at peripheral speeds of 250 to 350 ft. per sec., and 400 to 550 ft. per sec. for large machines, using ordinary high-grade open-hearth steels. For higher speeds up to 700 ft. per sec. chrome-nickel forged steels are used. Reaction turbines are usually designed for much lower speeds, 150 to 350 ft. per sec., or 400 ft. for very large units, and are generally of drum construction, of open-hearth steel.

245. Speed limitations of open-hearth steel. Theoretically, a properly designed disc can be run at from 125 to 160 per cent. of the safe speed of a drum with corresponding blading. In practice, however, the difference due to computable tensile stresses from blades and centrifugal force is less important than the unknown harmonic stresses due to blade and disc vibration, and the drum type is better than the disc type in this respect.

246. Casings for superheated steam above the 50-lb. pressure section of the turbine are made of cast steel; below this, of cast iron; and for all pressures in saturated steam, of cast iron. The casings of most horizontal turbines are split, so that lifting the upper half exposes the whole interior. With one more lift, the whole rotor may be removed, facilitating repairs to all parts. The vertical turbines must be opened in several sections and taken apart wheel by wheel.

247. Glands to prevent leakage from stage to stage, or from the interior of the turbine to the outside air, are nearly always some form of **labyrinth,** with no actual contacts, or at most very light contact on floating rings. The high speeds and lack of lubrication forbid any forms of soft packing except for very small units. The function of the labyrinth is to interpose a large number of constricted passages to the flow of steam

These constrictions usually measure from 0.003 in. to 0.035 in., depending on the size of shaft or dummy ring, and the pressure difference. The clearance is selected according to the vibration at the point of application and is often made a function of the diameter.

248. The principal blade fastenings consist of the dovetail for impulse elements, in all sorts of forms from square T-heads to bulb heads with all corners eliminated; the reaction blading of Parsons make is a caulked type, depending upon some distortion and friction for the grip. Riveted blading is used to some extent in small impulse turbines, but has been a failure in large discs. Fig. 29 shows three sucessful types. **Blade heights** vary from 0.5 in. to 18 in., depending on the size of the machine, and the stage. Widths range from 0.25 in. to 2 in.

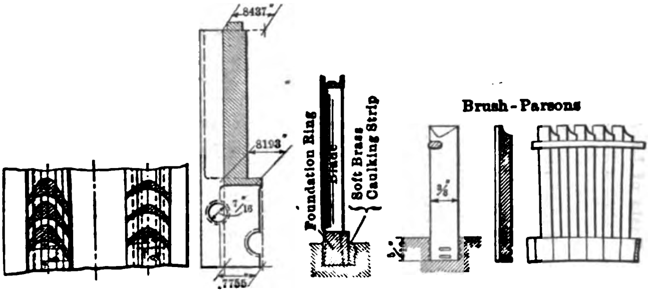


Fig. 29.—Four types of blade fastenings.

249. Pressure stages. In high-pressure Curtis turbines, the usual number of pressure stages is five to seven, with two velocity stages in each pressure stage. In Rateau types, there are about thirteen to twenty-two pressure stages, with one wheel in each; or one Curtis stage of two velocity stages may take the place of two or three high-pressure stages. The Parsons type has from forty to seventy pressure stages.

250. Turbine rating. Impulse turbines are rated on a basis of calculated flow through the nozzles and known efficiencies of different types of wheels. Thus a wheel of given size may be of widely varying horse-power under different areas of nozzles; the efficiencies also are altered. Reaction turbines must be designed for the load, and can only be altered in best load capacity by increasing the initial pressure. Overload is provided for in the impulse types by adding extra nozzles; in the reaction type by by-passing some of the high-pressure stages.

251. Measurement of shaft output. The output of the turbine must be obtained by brake, or electrically; no indicated horse-power exists; in small turbines, throttle governed, the steam-chest pressure bears an accurate relation to the horse-power delivered at any speed, and if the turbine is calibrated, it may be used as an indication of the output thereafter. This is true because the pressure is a measure of the steam flow, and the steam flow is a measure of the output, for any given turbine efficiency.

252. Lubrication is exceedingly simple. No internal oiling whatever is employed; gravity or force feed with copious supply at 15 to 25 lb. pressure is general for large units. The speed of rotation causes a dragging of oil under the journal, by means of viscosity, so that the journal never rides on metal. Some turbines actually rise a few thousandths of an inch after coming to speed due to increase in the oil film under the journal. Small turbines are ring-oiled like motors.

253. The actual Rankine-cycle efficiency ratios obtained in small non-condensing turbines vary from 45 per cent. to 50 per cent., for large units, from 55 to 65 per cent. for the great majority, up to 71 per cent. as about the highest. These figures assume condensing service in each case.

254. Turbine Performance: Data on Commercial Tests of Large Steam Turbines
(Christie[a])

Maker of turbine	Type	Date of test	Load, kw.	R.p.m.	Steam pressure, lbs. abs.	Supht.	Vacuum referred to 29.92" barometer	Pounds of steam per kw.-hr.	Efficiency ratio
1 Erste Brunner M. F. G.	Curtis-Parsons	1910	2,128	1,500	156.2	120.31	27.89	13.82	71.8
2 Erste Brunner M. F. G.	Curtis-Parsons	......	6,000	960	184.9	197.64	28.18	12.56	71.3
3 Erste Brunner M. F. G.	Curtis-Parsons	1910	7,442	960	192.0	205.51	28.18	12.625	70.3
4 Westinghouse Machine Co.	Curtis-Parsons	1910	9,173	1,800	181.7	59.07	27.81	14.57	68.9
5 Erste Brunner M. F. G.	Curtis-Parsons	1910	1,416	1,260	128.2	135.69	27.60	15.18	68.8
6 Brown-Boveri & Cie	Parsons	1910	6,257	1,210	203.7	175.57	29.02	11.95	68.8
7 A. E. G.	Curtis-Rateau	1911	6,518	1,220	198.7	219.66	29.28	11.43	68.7
8 A. E. G.	Curtis-Rateau	1911	6,565	1,220	200.2	214.19	29.18	11.64	68.5
9 Allis-Chalmers	Parsons	1908	4,300	1,800	186.4	107.97	27.96	14.02	68.4
10 Brown-Boveri & Cie.	Curtis-Parsons	......	3,053	1,360	150.2	146.40	29.00	13.01	68.0
11 Brown-Boveri & Cie.	Curtis-Parsons	1911	1,750	1,500	176.4	214.5	27.08	14.23	67.5
12 M. A. N.	Curtis-Zoelly	......	3,584	1,500	178.3	196.63	27.54	13.99	67.5
13 James Howden & Son	Zoelly	1909	6,383	1,000	202.7	136.98	27.33	14.305	67.5
14 M. A. N.	Zoelly	1910	1,400	3,000	180.7	180.53	27.40	14.21	67.4
15 Westinghouse Machine Co.	Curtis-Parsons	......	9,830	750	192.2	96.43	27.22	15.15	67.0
16 British Westinghouse	Curtis-Rateau	1911	5,066	1,500	190.2	174.31	28.68	13.00	67.0
17 Brown-Boveri & Cie.	Curtis-Parsons	1910	3,764	1,500	161.2	196.78	28.77	13.04	66.8
18 Brown-Boveri & Cie.	Curtis-Parsons	1911	1,495	3,000	200.6	180.86	26.41	14.78	66.8
19 Escher Wyss & Co.	Zoelly	1910	2,052	3,000	193.9	205.7	28.39	13.04	66.6
20 British-Thomson-Houston	Curtis	1911	2,987	1,500	154.7	144.07	26.75	15.96	66.5
21 Bergmann	Curtis-Rateau	1909	1,545	1,500	188.5	204.04	28.59	12.97	66.4
22 Oerlikon	Rateau	1911	3,166	1,500	213.9	275.42	29.25	11.44	66.1
23 Brown-Boveri & Cie.	Curtis-Parsons	1911	1,271	3,000	172.1	198.51	27.31	14.61	65.9
24 Escher Wyss & Co.	Zoelly	......	5,118	1,000	133.7	199.48	27.55	15.18	65.7
25 Bergmann	Curtis-Rateau	1910	2,477	1,500	140.0	168.91	28.81	13.93	65.6
26 Brown-Boveri & Cie.	Parsons	1903	3,500	1,360	156.4	137.2	28.84	13.71	65.6
27 Westinghouse Machine Co.	Curtis-Parsons	......	11,466	750	191.7	105.65	28.07	14.45	65.5
28 Escher Wyss & Co.	Zoelly	1910	4,189	1,000	179.7	183.98	28.66	13.30	65.5
29 British Westinghouse	Curtis-Rateau	1911	2,930	1,500	210.2	187.9	28.18	13.72	64.9

254. Turbine Performance: Data on Commercial Tests of Large Steam Turbines.—(*Continued*)

	Maker of turbine	Type	Date of test	Load, kw.	R.p.m.	Steam pressure, lbs. abs.	Supht.	Vacuum referred to 29.92" barometer	Pounds of steam per kw.-hr.	Efficiency ratio
30	A. E. G.	Curtis-Rateau	1908	4,239	1,500	188.3	285.13	29.11	11.97	64.9
31	Escher Wyss & Co	Zoelly	......	3,540	1,500	155.1	107.86	28.21	15.07	64.8
32	F. Ringhoffer	Zoelly	1908	3,000	1,000	170.7	101.18	27.60	15.52	64.8
33	M. A. N.	Zoelly	1910	1,250	3,000	182.1	207.89	28.82	13.09	64.4
34	Brown-Boveri & Cie	Parsons	......	3,000	1,360	165.0	258.91	27.02	14.75	64.3
35	C. A. Parsons & Co	Parsons	......	5,164	1,200	214.3	121.26	28.95	13.18	64.3
36	Escher Wyss & Co	Zoelly	1910	1,641	3,000	221.0	281.63	27.91	13.08	64.1
37	Erste Brunner M. F. G.	Curtis-Parsons	......	1,250	3,000	184.9	197.64	27.89	14.32	63.9
38	Escher Wyss & Co	Zoelly	1908	5,000	1,000	164.4	173.21	26.38	16.13	63.9
39	British-Thomson-Houston	Curtis	1909	2,500	1,500	126.5	68.70	28.47	15.92	63.7
40	General Electric Co.	Curtis	......	3,464	......	210.0	126.98	28.75	13.62	63.6
41	A. E. G.	Curtis	1909	2,236	1,500	191.6	275.69	29.34	11.77	63.6
42	Allis-Chalmers	Parsons	1911	3,850	1,800	164.7	125.06	27.91	15.40	63.5
43	A. E. G.	Curtis	1906	3,000	1,500	191.3	211.82	29.05	12.79	63.4
44	General Electric Co.	Curtis	......	8,880	......	192.5	106.30	28.02	15.05	63.1
45	A. E. G.	Curtis-Rateau	1907	3,169	1,500	184.7	216.73	29.11	12.74	63.0
46	Brown-Boveri & Co	Curtis-Parsons	1910	3,320	1,500	180.9	151.44	29.02	13.50	63.0
47	M. A. N.	Curtis-Zoelly	......	2,507	1,500	175.5	88.91	27.40	16.24	62.8
48	Escher Wyss & Co.	Zoelly	1910	1,235	3,000	176.8	79.32	28.39	15.35	62.2
49	Brown-Boveri & Cie	Curtis-Parsons	......	5,128	1,000	172.2	195.46	28.52	14.35	62.1
50	General Electric Co.	Curtis	......	10,816	750	190.0	174.39	29.39	12.90	61.9
51	General Electric Co	Curtis	......	5,095	......	185.1	198.55	29.40	12.71	61.6
52	Bergmann	Curtis-Rateau	1909	1,562	1,500	186.8	178.97	28.33	14.57	61.4
53	British-Thomson-Houston	Curtis	1911	1,221	3,000	134.7	97.91	27.16	17.75	61.2
54	General Electric Co	Curtis	1910	8,775	750	194.0	71.65	27.95	15.95	61.0
55	British-Thomson-Houston	Curtis	1911	1,541	1,500	149.7	6.66	27.97	17.47	61.0
56	Brietfield Danek & Co	Impulse-Parsons	1909	3,585	896	160.7	93.03	28.32	16.08	60.2

* A. G. Christie, *Trans.* A. S. M. E., 1912.

This table gives efficiency ratios and B.t.u. per kw-hr. The latter figure is obtained from the water rate and the steam conditions.

$$\text{B.t.u. per kw-hr.} = W \times (H_1 - q_2) \qquad (41)$$

Where H_1 = heat contents of steam supplied to turbine, q = heat of the liquid in condensate and W = water rate in lb. per kw-hr.

The thermal efficiency is the product of the efficiency ratio and the thermal efficiency of the Rankine cycle (adiabatic expansion).

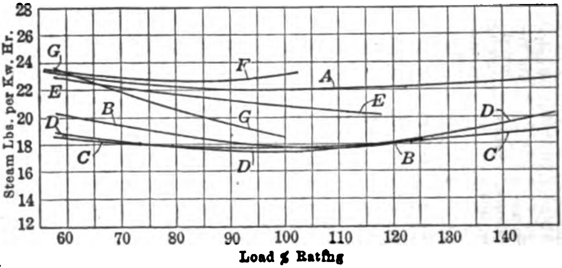


FIG. 30.—Water-rate curves of small condensing turbines, steam, 150 lb. gage; superheat, 100 deg. Fahr.; vacuum, 28 in.

A, 250 kw. Westinghouse, 3,600 r.p.m.; *B*, 400 kw. Westinghouse, 3,600 r.p.m.; *C*, 500 kw. Westinghouse, 3,600 r.p.m.; *D*, 1,000 kw. Westinghouse, 1,800 r.p.m.; *E*, 200 kw. DeLaval; *F*, 400 kw. Kerr, 1,500 r.p.m.; *G*, 1,000 kw. Rateau.

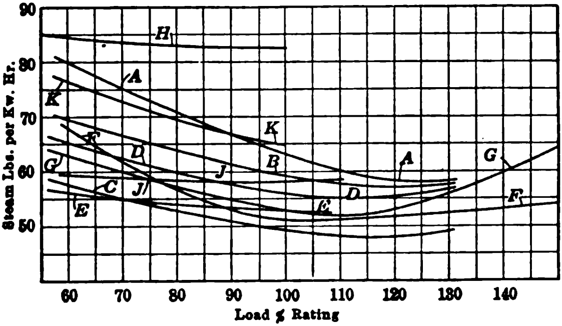


FIG. 31.—Water-rate curves of small non-condensing turbines with dry steam at 100 lb. gage.

A, 35 kw. Curtis, 3,600 r.p.m.; *B*, 75 kw. Curtis, 3,300 r.p.m.; *C*, 100 kw. Curtis, 3,600 r.p.m.; *D*, 125 kw. Curtis, 2,400 r.p.m.; *E*, 300 kw. Curtis, 1,800 r.p.m.; *F*, 250 kw. Westinghouse, 3,600 r.p.m.; *G*, 300 Westinghouse, 3,600 r.p.m.; *H*, 50 kw. Sturtevant, 1,400 r.p.m.; *J*, 150 kw. Sturtevant, 2,100 r.p.m.; *K*, 50 kw. Terry, 2,800 r.p.m.

255. Water-rate curves. Figs. 30, 31, and 32 give characteristic water-rate curves for small and large units. It is found that the **Willans line** (total steam per hour vs. output) is practically straight line from zero load to full (or best) load; on overload, with by-pass, or extra nozzles open, it is usually another straight line, joining the first at best load, but more steeply inclined. This property allows fractional-load water rates to be readily interpolated from one or two load tests or guarantees.

256. The effect of variation in vacuum on a turbine differs somewhat with the type of machine, but can be obtained with reasonable accuracy from Fig. 33, which gives average figures for high-pressure turbines; Fig. 34 applies to low-pressure turbines. A vacuum of 28 in. is taken as the standard for high-pressure, and 27.5 in. for low-pressure units.

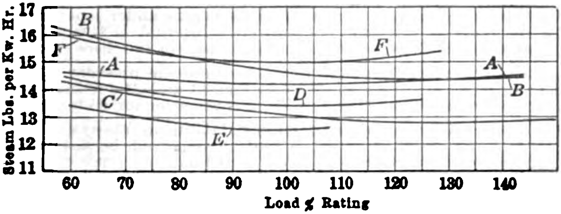


FIG. 32.—Water-rate curves of large condensing turbines. Steam, 200 lb. gage; superheat, 100 deg. Fahr.; vacuum, 28 in.

A, 9,000 kw. Curtis; *B*, 10,000 kw. Curtis; *C*, 4,000 kw. Curtis-Rateau; *D*, 10,000 kw. Westinghouse; *E*, 6,000 kw. Parsons; *F*, 6,000 kw. Zoelly.

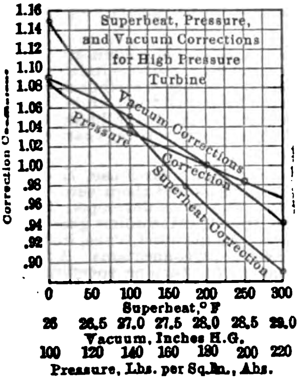


FIG. 33.—Superheater pressure and vacuum corrections for high-pressure turbines.

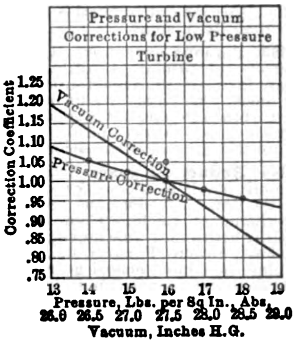


FIG. 34.—Pressure and vacuum corrections for low-pressure turbines.

257. The effect of superheat in improving economy is usually taken at the rate of 10 per cent. for the first 100 deg. of superheat, 8 per cent. for the next 100 deg., and 7 per cent. for the third hundred. Figs. 33 and 34 show the corrections, which are practically identical for all types.

258. The efficiency losses may be subdivided into (a) nozzle friction, 6 to 28 per cent.; (b) blade friction, 6 to 30 per cent. (c) windage, 3 to 15 per cent.; (d) unused exit velocity, 3 to 5 per cent.; (e) leakage 2 to 10 per cent.; (f) mechanical losses, 1 per cent. As all the steam losses in the high-pressure stages reappear in the steam as unused heat, the available heat drop is increased by translation of the expansion lines to higher entropies, as shown by the **Mollier diagram,*** hence the whole turbine-diagram efficiency in a multi-stage turbine is always from 2 to 6 per cent. higher than that of the individual stages.

* Marks & Davis "Steam Tables," Longmans, Green & Co., N. Y., 1912.

259. The efficiency of the turbine, though different for different speeds and pressures, does not change appreciably with time or service. The shaft horse-power or brake horse-power is from 3 to 15 per cent. less than the calculated diagram horse-power (corresponding to i.h.p. in the engine). The usual friction losses are generally less than one-half those of steam engines of the same rating. **Mechanical friction** in the turbine is confined to bearings and governor drive; it is usually under 1 per cent., and in large machines is less than 0.5 per cent. Internal or steam friction is caused by imperfect shape of blades, and windage of the discs or drums.

260. Pressure correction, for variations in steam pressure from guaranteed or desired conditions, is given in Fig. 33 and 34 for high-pressure and low-pressure turbines. The correction is the same for all types.

261. Governors for turbine speed regulation are always of the centrifugal type; the inertia governor cannot be employed, because there can be no sudden angular accelerations. The centrifugal governor can be made nearly isochronous; generally, however, there is a slight decrease in speed as load increases.

262. Throttling governors. For all small turbines (impulse type) and some large makes, the plain throttling governor is employed, simply controlling the admission pressure at the steam chest or first stage. The old Parsons governor for reaction turbines admitted steam at full pressure, in short puffs, lengthening the period the valve was open as the load increased. Many of the Curtis types are governed by multiple-nozzle control, opening and closing individual nozzles, from 6 to 16 in number, and thus controlling the quantity of steam.

263. Parsons governor. In the Parsons machine, the governor not only controls the primary throttle, but also a secondary valve admitting live steam in one-sixth to one-fourth the total number of stages, further down the turbine. This virtually cuts out of service the by-passed rows, and converts the turbine into one of fewer stages, but in effect having larger blade dimensions, and not as economical. The best load for this type is that carried just before the opening of the secondary valve.

264. Reduction gears have recently come into greater use, than was formerly made of them. The de Laval turbine has used them successfully for 20 years, at enormous relative speeds. The type developed by the Westinghouse Machine Company from the Melville-Macalpine gear has a floating hydraulic frame for aligning the gears. All the other types, including the Falk, Fawcus, Parsons, etc., use solid bearings and connections. All types employ the double helical gear. By this means the turbine speed may be kept high, for economy both in cost and steam, and the driven apparatus may be operated at comparatively low speed. Direct-current generators, fans, and centrifugal pumps for large volume and low speed, may thus be successfully combined with the turbine with good economy.

265. Turbine specifications should cover the following items: (a) Number of units and location; character of building. (b) Service, and attachment to driven apparatus (direct, flexible coupling, reduction gear, etc.) (c) Speed, steam and back pressure conditions. (d) Capacity, overload, electric system data. (e) Regulation, variation of speed under change of load. (f) Noise, vibration. (g) Tests and inspection. (h) Mechanical details of connection to driven apparatus. (i) Type and steam system, H. P., L. P., bleeder mixed pressure, giving quantities for L. P., or bleeding steam. (j) Materials—casing, wheels, nozzles, blades, shaft. (k) Piping connections. (l) Bearings. (m) Foundations. (n) Oiling. (o) Auxiliary apparatus—oil pumps, relays, step-bearing pumps (for vertical turbines.) (p) Painting and lagging. (q) Gages and miscellaneous equipment.

266. Turbine supports should always be carefully designed to prevent distortion of the parts; stiffness of the supports is usually very desirable, but great mass is unnecessary; many reaction turbines of large size are running on foundations entirely of steelwork, which is low in mass for the strength and stiffness.

267. The auxiliaries required for horizontal turbines consist only of an oil pump, for large self-contained units: no auxiliaries whatever are needed for small units.

268. The auxiliaries for vertical units include in addition to the oil pump, **step-bearing pumps** for oil or water, capable of handling pressures of 500 to 1,000 lb. per sq. in. (varying with the size of the main unit). These step-bearing pumps, with the piping, are generally in duplicate. In order to steady the oil supply, a frictional resistance called a **baffler** is employed between pump and step bearing; and to remove pulsations of pressure and provide a small reservoir, **accumulators** of the elevator type are also required.

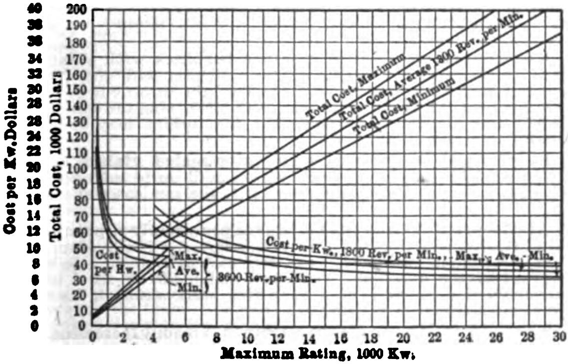


FIG. 35.—Steam turbines. Cost per kw. *vs.* capacity. Total cost *vs.* capacity.

60 Cycles, maximum 24 hr. rating, 50 deg. Cent. rise; power factor, 80 per cent.; pressure 175 lb.; superheat, 100 deg. Fahr.; vacuum, 28.5 in.

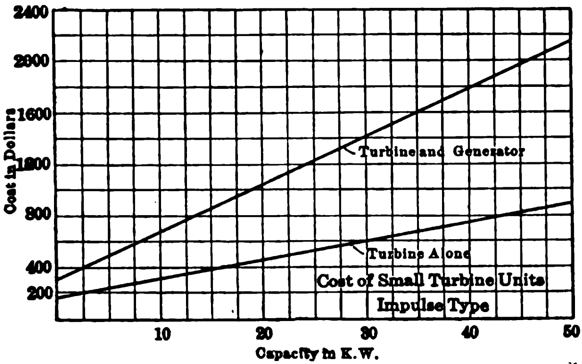


FIG. 36.—Cost of small turbines and generators.

269. The cost of turbines per kw., including generators, varies from $30 for small sizes down to $9 or less for very large units, at normal rating; or at maximum rating, $10. Fig. 35 gives the cost per kw. (normal rating) of large units including generators; Fig. 36 gives the cost per h.p. of small turbines with and without generators.

270. The operation of the steam turbine is remarkable for its simplicity; one oiler can attend to two or three units (on the engine-room floor) aggregating as much as 40,000 or 50,000 kw. But with engines, only 3,000 or 4,000 kw. can be cared for by one man; and in many cases much less. The turbine is practically undamaged by priming which would wreck an engine, and has a maintenance cost but one-fifth as great, approximately. There are very few articulated parts in the turbine; its continuous operation is therefore much more reliable and periods of two to four weeks continuous operation are common. **Inspections** made once a year frequently show no repairs or adjustments to be necessary, and the turbine is continued in service. With large reciprocating engines, both inspections and adjustments are sometimes necessary every 24 hr.

271. The general method of starting turbines with steam-sealed glands is to establish a vacuum on the condenser with the dry-vacuum pump, start the circulating water, and "crack" the throttle in order to send steam through the turbine for warming, without turning the spindle. After the proper time allowance (5 to 15 min.) the turbine may be brought to speed and placed under load.

272. In starting a turbine with water-sealed glands, it is usual practice to start the turbine non-condensing until up to sufficient speed to seal the glands, then establish the vacuum on the condenser and apply the load.

273. At the present time the turbine is practically supreme in large central stations, as a heat-operated prime mover. The hydraulic station is limited to certain localities, while the large gas-engine plant is so unreliable as to be out of the question. For small and moderate-sized plants the internal-combustion engine is on a competing basis, although its reliability has never equalled that of the turbine.

274. The field for small steam turbines is readily increasing, particularly since centrifugal boiler-feed pumps, circulating-water pumps, fans, blowers, etc., are successfully designed for turbine speeds, with good efficiencies. The small amount of attention required by the turbine, its reliability and low maintenance are generally more than sufficient to overbalance a slight inferiority to the steam engine in economy. **Since the item of fuel economy is only one of the factors in operating cost,** this result is natural and the use of the turbine is bound to increase. There is yet much to improve in the turbine, whereas the reciprocating engine has been at a virtual standstill in development for 10 years past.

CONDENSING EQUIPMENT

275. Thermodynamics of condensers. The heat given up by the condensing steam must equal the heat received by the circulating water. In jet or barometric condensers, the steam and water mix; no difference between the temperature corresponding to the vacuum and the temperature of the discharge water need exist. The surface condenser requires some difference of temperature between the steam and the circulating water at all times, or no heat flow from steam to water can take place.

276. Removal of air. The air present in the condensate is chiefly drawn in by leakage at the joints. This air, being non-condensible, must be removed by segregation and pumping.

277. The volume of condensate water is practically negligible compared with the steam volume at the same pressure. The **work in ft-lb made available by the condenser** is the steam volume multiplied by the pressure difference in lb. per sq. ft. existing between the atmosphere and the interior of the condenser; the work required to produce this effect, is merely the product of the number of cu. ft. of condensate and the same pressure difference. At 28 in. vacuum the ratio of these two is 21,000 to 1. To the **condensate pump work** must be added the **work of the circulating-water pump** (chiefly a friction loss) and the **work of the dry-vacuum pump** which removes the air.

278. The principal condenser types are: (a) jet; (b) barometric; (c) eductor or siphon; (d) rotary jet; and (e) surface. These are described in **Par. 279 to 283.**

279. The jet condenser consists of a cast-iron shell into which the exhaust pipe is led, having the circulating water sprayed through the chamber in jets. The steam condenses and mingles with the jets, and is pumped out of the bottom of the shell. **The barometric condenser** is a jet condenser set higher than 34 ft. above the level of the discharge well or tunnel; the water therefore runs away by gravity, but must be pumped in, due to a slight friction loss and velocity head, the vacuum assisting the circulating pump.

280. In the eductor or siphon type, the injection water is pumped in under 25 to 30 lb. pressure, and requires sufficient velocity to carry out not only its own mass but the condensed steam and entrained air as well, by kinetic energy. No vacuum pumps are required.

281. The rotary jet types—originally developed by Le Blanc—consist of a centrifugal impeller throwing segments of water into a nozzle, in such fashion as to form water pistons, which trap and condense the steam, and push before them the air. This type is also used as a dry-vacuum pump. All the above types (Par. 279 to 281) are derivatives of the true jet condenser.

282. The surface condenser consists of a cast-iron shell with two heads or water boxes into one of which the circulating water passes. These two boxes are connected by a large number of small brass tubes, which allow the circulating water to traverse the main shell without contact with the steam; the latter is fed into the shell around the tubes. The circulating water passes to the second box, which may lead to the discharge or redirect the water back to another section of the first box by way of another nest of tubes. If the first type is used it is called **single pass**; if the second, **two pass**; and so on, with three or four passes in some few cases. The cold water passing through the tubes condenses the steam by conduction, and the condensate trickles down to the bottom of the shell, there to be pumped out. The air, which is always heavier than steam at the same temperature, also collects at the bottom and must be pumped out, preferably by another pump.

283. Atmospheric condensers consist of a form of surface condenser in which the cooling medium is a mixture of air blast and water spray. The air takes up some of the spray, becoming cooled thereby, and acts as a cooling medium for the steam. High vacuum is not to be obtained with this type. The chief feature is economy of circulating water, which may be in the ratio of 1 lb. of water per lb. of steam, or slightly less, since the whole latent heat of evaporation (of the water spray) as well as the heat of the liquid is available for cooling.

284. Quantity of circulating water required. In the jet or ordinary surface types, the circulating water must be at least 25 to 30 times the weight of the steam condensed. In the jet condenser, the condensate mixes with the circulating water, and, if the latter is dirty, is necessarily lost. The surface condenser keeps the condensate separate from the circulating water, so that it is available for re-use in the boilers, a pure distilled water (Par. 137 and 138).

285. The proportions of jet condensers are relatively unimportant, the design merely providing for adequate mixture of water and steam. The shell therefore need only be large enough to take the exhaust and water connections. The volume of a jet condenser varies from 0.5 to 2.5 times the volume of the low-pressure cylinder volume of a reciprocating engine; in the eductor types, the volume is somewhat less.

286. Surface condensers are limited in capacity by the rate of heat transfer. For average practice, 300 to 350 B.t.u. per sq. ft. per degree mean temperature difference per hour can be allowed. It follows from this assumption that

$$A = W \times \frac{(H_2 - q_2)}{U \times t_m} \qquad (42)$$

where A = area in sq. ft. of tube surface, W = lb. of steam per hour from exhaust, H_2 = total heat per lb. of exhaust, q_2 = heat of the liquid per lb. (at condensate temperature), $H_2 - q_2$ = 1,000 to 1,050 for most cases, U = transmission coefficient = 300 to 350 B.t.u. per hour, per sq. ft., per degree mean temp. difference (Fig. 37), and t_m = mean temperature difference between steam and circulating water. The arithmetic formula for t_m is:

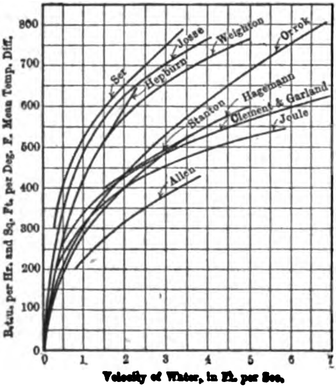


FIG. 37.—Values of the coefficient of heat transmission.

$$t_m = T_0 - \frac{(T_1 + T_2)}{2} \qquad (43)$$

where T_0 = steam temperature at the vacuum, T_1 = injection temperature and T_2 = discharge temperature. The logarithmic formula for t_m is:

$$t_m = \frac{T_2 - T_1}{\log_e\left(\frac{T_0 - T_1}{T_0 - T_2}\right)} \qquad (44)$$

For the majority of cases, Eq. 43 is sufficient.

287. The quantity of circulating water required for jet condensers is given by

$$W_c = \frac{H_2 - T_2 + 32}{T_2 - T_1} \qquad (45)$$

where Wc = lb. of circulating water per lb. of steam, H_2 = heat contents per lb. of steam, T_2 = discharge temperature, and T_1 = injection temperature. The quantity required in gal. per min., taking $H - T_2 + 32$ as 1050 B.t.u., is

$$S_c = \frac{2.1 W_s}{T_2 - T_1} \qquad (46)$$

where W_s = lb. of steam per hour, and S_c = circulating water in gal. per min.

288. Examples of Modern Condenser Proportions

Name of station	Size of turbo-generators on max. 24-hr. rating	Sq. ft., total	Sq. ft., per kw.
Commonwealth Edison Co.			
Northwest Station	20,000 kw.	32,000	1.60
Quarry St	14,000	25,000	1.79
Fisk St	12,000	25,000	2.08
Interborough R. T. Co.			
59th St. Power Station, N. Y., (Engine and low-pressure turbine.)	15,000	25,000	1.67
74th St. Station	30,000	50,000	1.67
Metropolitan St. Ry., Kansas Cy.	10,000	22,000	2.20
Marion Station, P.S.E. Co., N. J.	18,000	25,000	1.39
United El. Lt. & Power Co., N. Y.	15,000	25,000	1.67

289. The quantity of circulating water required for surface condensers is

$$W_c = \frac{H_2 - T_3 + 32}{T_2 - T_1} \qquad (47)$$

where T_3 = condensate temperature, and the other symbols have the same significance as before. For jet condensers T_3 becomes T_2; for surface condensers T_3 is at least 5 deg. Fahr. higher than T_2, and generally 10 or 15 deg. higher.

290. Use of dirty condensing water. For jet condensers, very dirty circulating water may be used, except that if sewage or other gas-producing matter is contained, the work of the dry air pump will be greatly increased. Dirty water in surface condensers causes slime deposits on the tubes, if containing grease and sewage; or it incrusts the tubes with scale, if very hard. In either case, periodic cleaning is necessary, as both deposits lower the efficiency of heat transmission.

291. Screens are usually made of iron mesh or bars, with openings the same size as condenser tubes or ⅛ in. smaller; these screens are set in frames, and operate in slides for cleaning purposes. Small metal screens enclosed in cast-iron boxes in the suction pipe are employed for small sizes and are then usually called "fish-traps." A later development is the use of moving self-cleaning screens, either arranged drum fashion like a stone screen, or like a chain grate set on edge. **The velocity through screens** should not exceed 4 to 5 ft. per sec.

292. Pumps. Circulating-water pumps in modern plants are always centrifugal or propeller types, especially since the advance of the small steam turbine. **Wet vacuum pumps** handle both condensate and non-condensible gases. They are not used to any extent at present. **Dry vacuum pumps** handle non-condensible gases only. Condensate or **hot-well pumps** handle the condensate only. The separate pumps are much more efficient than the combined wet-vacuum pump. The hot well-pump is usually a one-stage or two-stage centrifugal. The dry-vacuum pump may be a reciprocating compressor specia ly designed for tightness and small clearance, or a hydraulic device using a form of centrifugal pump and water jets to entrain the air, such as the Le Blanc pump.

293. Power required for auxiliaries. The circulating pump, if a reciprocating dry-vacuum pump is used, requires 85 per cent. to 90 per cent. of the total h.p. for condenser auxiliaries; the condensate and dry-vacuum pumps, 5 to 7 per cent. each. The total h.p. at 27 in. to 28 in. vacuum is about 2 to 2½ per cent. of the main unit, for reciprocating main engine; 3 to 3.5 per cent. at 28 to 29 in. vacuum for turbine plants.

294. The steam demand of all condenser auxiliaries, using engine-driven circulator, is 3 to 5 per cent. of the total; for direct turbine-driven circulator, 5 to 9 per cent.; for latest type geared turbine-driven circulator, 4 to 6 per cent. The water rate of turbines used for hot-well pumps is 50 to 60 lb. per b.h.p.-hr.; for low-speed direct-connected turbines for circulators, 35 to 45 lb.; for geared high-speed turbines, 29 to 35 lb.

295. Recent High Vacuum Results with Large Surface Condensers

Plant	Surface, sq. ft.	Water per lb., hr.	Hot well temp., deg fahr.	Circ. water		Vacuum 30-in. Bar.	Ratio sq. ft. kw.
				In deg. fahr.	Out deg. fahr.		
Interborough 59th St.	25,000	237,480	71.2	37.7	57.3	28.50	1.67
	25,000	182,508	53.2	33.3	47.6	29.15	1.67
	25,000	164,945	85.5	72.5	86.0	28.55	1.67
Marion, P. S. E. Co.	20,000	128,000	78	60.0	73.5	29.1	2.00
United El. Lt. & Power	25,000	....	71	58	68	29.0	1.67
Boston Elevated	28,000	182,000	74.5	64.0	74.0	29.07	2.00
	28,000	120,000	73.0	64.5	71.5	29.06	2.00
Illinois Steel	25,000	196,000	90.6	73.4	86.1	28.25	....
	25,000	210,000	90.3	73.4	86.9	28.3	....
	25,000	91,000	83.3	73.6	80.0	28.8	....

296. Hydraulic dry-vacuum pumps take from 6 to 12 times as much power as the reciprocating types; but this is relatively unimportant if the exhaust steam is usable in the feed-water heaters.

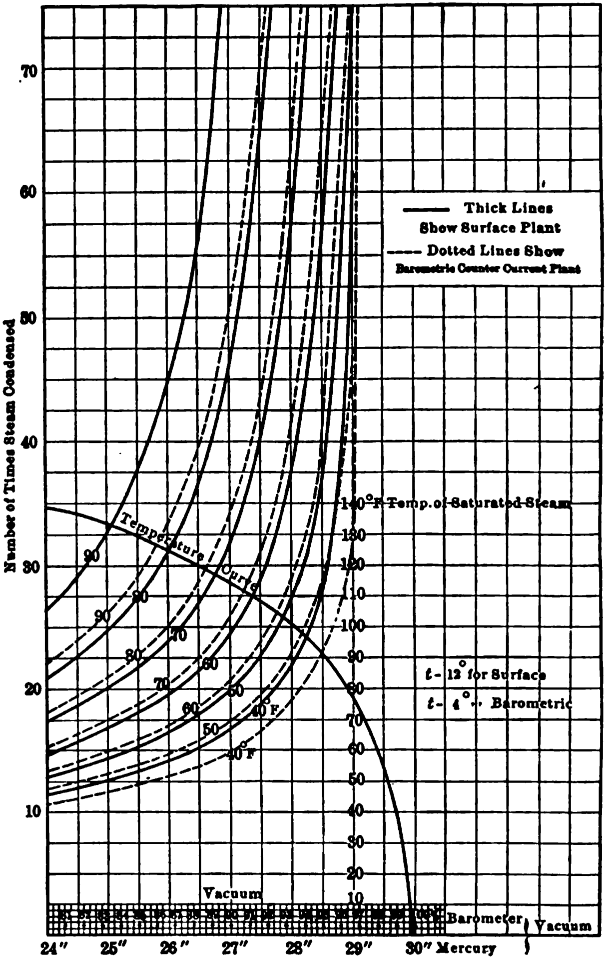


FIG. 38.—Vacuums and circulating-water temperatures.

297. The obtainable vacuum (Fig. 38) depends chiefly upon the temperature of condensing water. The actual results obtained may be less than this due to air leakage or dirty tubes.

298. Cooling towers are employed where condensing water cannot be obtained in sufficient quantity for complete rejection of discharge. The circulating water is broken up into spray or thin sheets and falls through a current of air. The air in becoming warmer, takes up heat from the water; evaporation also takes place and tends to saturate the air. This **evaporation** is from 0.80 to 0.95 lb. per lb. of steam exhaust to the condensers, exclusive of the spray loss in water actually carried away mechanically in the air current. The distance between spray outlets and tank under the tower is usually about 25 ft. so that this head, plus friction in additional piping, must be added to the total pump head. The towers are 50 ft. to 80 ft. high for natural draft; but may be shorter if a forced draft fan is used, provided the rain from the tower is not objectionable. The ground area required is 1 sq. ft. per 20 lb. steam condensed per hr. approximately. The circulating water required is 60 gal. per sq. ft. of ground area, cooled from 95 deg. to 75 deg., which is average performance. The heat transmission to air per sq. ft. of cooling surface in the lattice work or screens runs from 350 to 850 B.t.u. per hr. The circulating water required is 25 to 30 lb. per sq. ft. per hr. The work of the circulating water pump is practically double that of the ordinary installation without towers, or 6 to 8 per cent. of the h.p. of the main unit. If forced draft is used, the fan requires 0.3 per cent. to 0.5 per cent. of the h.p. of the main unit.

299. The operation of condensing equipment becomes very simple with turbine-driven auxiliaries, as these require almost no attention. Depending on the water, condenser tubes should be cleaned from once a week to once a month; brushing the tubes may be necessary. All joints should be very carefully made and maintained tight; shellacing or painting is of great assistance in this respect. The ferrules of the tube ends need taking up from time to time, as the packing shrinks, or as the vibration loosens the ferrules.

300. Starting. The circulator should always be started first, so as to keep the tubes cool at all times when steam may come in contact with them; as soon as the circulator is running, the main unit may be started, and the hot-well pump. Whenever the vacuum is desired, the vacuum breaker valve may be closed and the dry-vacuum pump started.

301. Shutting down: shut off the main unit, break the vacuum with the breaker-valve, shut down the dry air-pump, then the hot-well pump, and lastly, the circulating water pump.

302. The piping should be so arranged that air can be removed from the highest point of the circulating water system; otherwise, air might accumulate and prevent water from entering part of the tubes, besides breaking the siphon. The discharge pipe should be submerged in the discharge tunnel or well, so as to have an inverted siphon, not to exceed 25 ft. head; this reduces the circulating pump head to friction and velocity only.

303. The cost of condensing equipment complete, including pumps, barometric type, is from \$0.16 to \$0.25 per lb., average \$0.21; cost per kw. of main unit, \$0.90 to \$1.95, average \$1.10 for moderate and large size units. For very small units the cost may go up to \$4.00 or \$5.00 per kw. Jet condensers cost from \$1.35 to \$2.10 per kw., average \$1.65, for moderate and large sizes; \$3.00 to \$4.50 for small units. The figures assume 26 in. or 27 in. vacuum and are based on normal kw. rating. Surface condensers, 28 in. to 29 in. vacuum, cost per kw. of main unit from \$2.25 to \$4.22, average \$3.12; this is based on maximum rating of units and applies to large sizes. Small surface condensers cost from \$3.50 to \$10.00 per kw. Cooling towers, \$3.12 to \$6.00, average \$4.30, per kw. rating of units attached.

FEED-WATER HEATERS

304. The heat transfer in closed feed-water heaters is exactly the same as in surface condensers; that in open heaters, the same as in jet condensers, as covered in Par. **285 to 289**. The feed-water heater is merely a condenser operated at atmospheric pressure, with boiler feed-water for condensing water.

305. The open heater is much like a jet condenser in general arrangement, but is usually a rectangular box, or cylindrical tank large enough to provide a little storage capacity for feed water, as the boiler feed pumps usually draw direct from the heater.

306. The closed heater is usually built much like a surface condenser and is then known as the straight-tube type. In some makes the tubes are corrugated, in others coiled, or with a single U-bend; or an expansion joint is placed in the shell; in these cases the tubes are expanded fast in the tube sheets.

307. The water velocities employed in closed feed-water heaters are usually slower than for surface condenser practice, so that the value of the transmission coefficient is reduced. An average figure is 300 B.t.u. per deg. mean temp. difference per sq. ft. per hr.

308. The mean temperature difference given by the arithmetic formula is close enough.

$$t_m = t_s - \left(\frac{t_2 + t_1}{2}\right) \qquad (48)$$

where t_s = temperature of exhaust steam at exhaust pressure (usually 212 to 214 deg.), t_2 = temperature of heater discharge water, and t_1 = temperature of heater inlet water.

309. Temperature rise. If a given quantity of exhaust steam is available, the resulting temperature rise in a closed heater may be found as follows:

$$(t_2 - t_1) = \frac{w_s(H_s - q_2)}{W} \qquad (49)$$

where W = feed water in lb. per hr., w_s = exhaust steam in lb. per hr., H_s = total heat of exhaust steam per lb. (usually 1,150 B.t.u.), q_2 = heat of the liquid (condensed steam), at the temperature leaving the heater (t_2), usually 212 deg., t_1 = temperature of feed water at heater inlet, and t_2 = temperature of feed water at heater discharge. For all ordinary cases, $H_s - q_2 = 970$; t_2 cannot be higher than 208 deg. fahr., if exhaust steam at 212 deg. is employed. If the value of t_2, as found above, exceeds this, it indicates that there is excess exhaust steam. Eq. 56 can be transposed to solve for w_s, if the amount of exhaust steam to heat the feed water to 208 deg. is desired.

310. Temperatures Obtainable in Open Feed Water Heater
(Temperature of steam, 212 degrees F.)
Initial Temperature of Feed Water, Degrees F.

Per cent. of total steam used by auxiliaries		40	50	60	70	80	90	100	110	120	130
	2	60.1	69.9	79.7	89.5	94.4	109.2	119.0	128.8	138.7	148.5
	3	69.9	79.6	89.3	90.1	108.8	118.6	128.3	138.0	147.8	157.5
	4	79.5	89.1	98.8	108.5	118.1	127.8	137.4	147.1	156.7	166.4
	5	89.0	98.5	108.1	117.7	127.2	136.8	146.4	155.9	165.5	175.1
	6	98.3	107.7	117.2	126.7	136.2	145.7	155.2	164.7	174.2	183.6
	7	107.4	116.8	126.2	135.6	145.0	154.4	163.8	173.2	182.5	192.1
	8	116.4	125.7	135.0	144.4	153.7	163.0	172.4	181.8	191.0	200.3
	9	125.2	134.5	143.7	153.0	162.2	171.5	180.7	190.0	199.2	208.5
	10	133.3	143.1	152.3	161.4	170.6	179.8	189.0	198.1	207.3	212.0
	11	142.5	151.6	160.7	169.7	178.9	188.2	197.0	206.2	212.0*	212.0*
	12	150.9	159.9	168.9	177.9	187.0	196.0	205.0	212.0*	212.0*	212.0*

311. The surface required in closed heaters is given by

$$A = \frac{W\,(t_2 - t_1)}{U t_m} \qquad (50)$$

where U = 300 and A = area of tube surface in sq. ft.; the other symbols are as given in Par. 309.

312. Heaters are rated in h.p. One h.p. equals 30 lb. of exhaust steam per hr.

* All of the steam not condensed.

313. The volume required in open heaters is given by

$$V = \frac{HP}{a} \tag{51}$$

where V = volume in cu. ft., $a = 2.15$ for muddy water, $a = 6$ for slightly muddy water, and $a = 8$ for clean water.

314. Operation. The operation of closed heaters is somewhat more expensive than open heaters; the tube packings require attention and the tubes must be cleaned of scale, if this forms. In heaters with corrugated or bent tubes, cleaning is practically impossible. The advantage of the closed heater is the elimination of oil from the feed water, but with the use of turbine-driven auxiliaries, this advantage disappears, as there is no oil in the exhaust steam. In open heaters, the cast-iron trays over which the feed water spills, are readily removable for cleaning. If an open heater is used on oily exhaust, some means of oil elimination must be used, sometimes supplemented by a filter in the body of the heater.

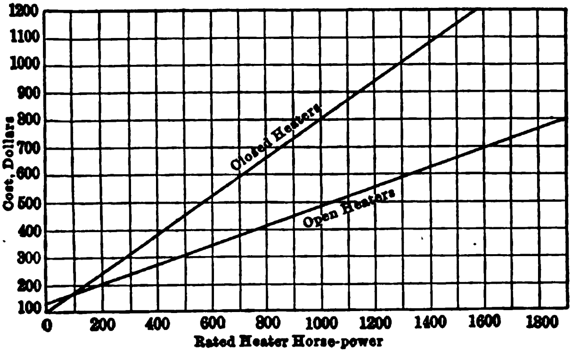


FIG. 39.—Cost of feed-water heaters.

315. Connection to feed pump. Closed heaters may be either the suction or the discharge side of the feed pump; open heaters, only on the suction side. Either type when on the suction side of the pump, must be above it.

316. The cost of heaters is given in Fig. 39.

ECONOMIZERS

317. The laws of heat transfer for economizers are the same as for surface condensers and closed water heaters. But the substitution of a gas for the steam increases the resistance enormously, and the value of the transmission coefficient is much lower and is very uncertain in value.

318. Types. There are two types: the **staggered tube** and the **non-staggered tube.** In both types the tubes are arranged in vertical rows attached to headers at top and bottom of each row, perpendicular to the gas flow. The staggered arrangement serves to break up the gas stream thoroughly. The tubes are always of cast iron and are usually 4½ in. diameter and 10 ft. long.

319. The surface required is based on empirical values, because the temperature and quantity of flue gases per lb. of coal, waterflow and condition of surfaces, introduce so many independent variables that the rational formulæ used for condensers and heaters are useless. The surface installed varies from 3 to 5 sq. ft. per rated boiler h.p. connected.

320. The temperature rise is given by

$$X = \frac{y(T_1 - t_1)}{91 + \frac{5w + GCy}{2GC}} \tag{52}$$

where X = rise in temperature of feed (deg. Fahr.), T_1 = temperature flue gases entering economizer, t_1 = temperature feed water entering economizer, w = lb. of feed water per boiler h.p. per hr., G = lb. flue gas per lb. of combustible (average, 20), C = lb. of coal per boiler h.p. per hr., and y = sq. ft. of economizer surface per boiler h.p. A rough method, if the temperature drop of flue gases is known, is to take 0.5 deg. rise in feed water for every deg. drop in flue gases.

321. The feed water enters the bottom headers by a connecting main and is collected from the top headers by another main, placed at the opposite end of the headers, so that the tubes form equal parallel paths.

322. The draft loss through economizers varies with the velocity of the gases, as in the boiler. At normal full load on the connected boilers the loss is from 0.25 in. to 0.40 in. (of water), increasing to 0.6 in. or 0.7 in. at heavy overloads. In fact, as normally designed and installed, forcing the boilers beyond 200 per cent. of rating is impossible without by-passing the economizer. Induced draft must be employed if the economizer is to be used at high ratings, because the draft losses limit the maximum capacity of the boilers obtainable with natural draft. If the temperature of gases is reduced from 550 deg. to 350 deg., the loss of draft is approximately 25 per cent.

323. The capacity rating of economizers is based on circulating 6.25 gal. of feed water per hr. per tube, and upon a heat transmission coefficient of 2.7 to 3 B.t.u.

324. Economizer Dimensions and Capacities

No. of tubes	No. tubes wide	No. sections	Length of economizer	Clear height req'd	Height over sections	Width between walls	Capacity (lb. water)	Heating surface external (sq. ft.)
			Ft. In.	Ft. In.	Ft. In.	Ft. In.		
96	6	16	9 8	23 6	10 2¼	4 8	6,000	960
144	6	24	14 6	23 6	10 2¼	4 8	9,000	1,440
192	6	32	19 4	23 6	10 2¼	4 8	12,000	1,920
240	6	40	24 2	23 6	10 2¼	4 8	15,000	2,400
128	8	16	9 8	23 6	10 2¼	6 0	8,000	1,280
256	8	32	19 4	23 6	10 2¼	6 0	16,000	2,560
384	8	48	29 0	23 6	10 2¼	6 0	24,000	3,840
512	8	64	38 8	23 6	10 2¼	6 0	32,000	5,120
576	8	72	43 6	23 6	10 2¼	6 0	36,000	5,760
160	10	16	9 8	23 6	10 2¼	7 4	10,000	1,600
320	10	32	19 4	23 6	10 2¼	7 4	20,000	3,200
480	10	48	29 0	23 6	10 2¼	7 4	30,000	4,800
640	10	64	38 8	23 6	10 2¼	7 4	40,000	6,400
800	10	80	48 4	23 6	10 2¼	7 4	50,000	8,000

Any other number of sections in multiples of 4, from 8 to 80, can be employed, giving proportionate dimensions.

325. Accumulation of soot occurs upon the tubes, and the "sweating" which takes place at low feed temperatures tends to catch and hold the soot firmly. **Continuous scraping** of the tubes is employed to overcome this difficulty. The cast-iron scrapers are driven slowly up and down the tubes in pairs, requiring about 1 h.p. to every 300 or 350 boiler h.p. connected to the economizer. There is a friction rig on each scraper drive so that if any solid obstruction stops one scraper, it will neither break the scraper nor interfere with the others.

326. The operation of economizers requires attendance for the scrapers, cleaning the inside of the tubes, and cleaning soot and fine cinder from the bottom of the economiser chamber. The first item is small, as the drive is usually by motor and the mechanism is very slow moving; the second depends on the feed water and should occur with less frequency than in the boilers; the last depends on the rate of driving and the coal, varying from once a month to once in four months.

327. The cost of economizers averages about $15.00 per tube, installed. The tubes are usually 4½ in. by 10 ft.; cast iron is employed throughout, since at the low rate of heat interchange, any other material would be too expensive. From the point of view of increased economy and the cost of securing it, the economiser is the least desirable of all auxiliaries. In many cases it cannot be made to pay; this is generally true if it saves less than 5 per cent. If it saves over 10 per cent., there is reason to conclude that the rest of the plant is being very badly operated.

PUMPS

328. The work done by a pump is given by

$$W = wh \tag{53}$$

where W = ft.-lb. of work per min. performed in lifting the water, w = lb. of water pumped per min. and h = sum of suction lift, discharge head and velocity head gained in the pump inlet and outlet, in ft. The water h.p. is equal to wh divided by 33,000. The water pressure, or suction, in lb. per sq. in. divided by 0.434 equals the head in ft. at the discharge, or the suction, respectively, for water at 62 deg. fahr. The velocity head is

$$h_v = \frac{v}{\sqrt{2g}} \tag{54}$$

where v = velocity of water in ft. per sec. and $\sqrt{2g}$ = 8.08. For most cases, the velocity head in suction and discharge pipes may be disregarded, as it is not over 8 ft. per sec.

329. The duty is expressed

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{weight of dry steam}}\right)1{,}000 \tag{55}$$

or

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{Total B.t.u. used}}\right)1{,}000{,}000 \tag{56}$$

The latter definition of duty is more satisfactory than the first; duty always includes the efficiency of the steam end, as well as the water end.

330. Pumps are broadly classed in four types—reciprocating, centrifugal and turbine, rotary, and jet pumps. The **reciprocating type** can be subdivided into direct-acting, flywheel and power pumps. **The direct-acting type** has steam and water cylinders on a common piston rod, and no flywheel; the valve mechanism for the steam cylinder is actuated direct from the rod by tappets. This type may be single-cylinder, or duplex, and the steam cylinders may be simple, compound or triple expansion. **The duplex simple pump** is the most rugged and reliable of all. Outside-packed plungers are the most desirable, as the packing on the plunger is adjustable while running and the amount of leakage can be seen. **Flywheel pumps** are similar to the direct-acting type, except that a flywheel is added and the steam valve is gear driven from the shaft as in a steam engine. Pumping engines are a development of this type. **Power pumps** are fitted with one or more cylinders, driven from a crank shaft and belted or geared to the source of power. When three cylinders with cranks at 120 deg. are used, the pump is known as a triplex; this type is very frequently gear-driven from a motor or an internal combustion engine.

331. Centrifugal pumps are those in which pressure and flow is produced by a rotating impeller, which gives the water entering it an increase in velocity; this velocity is converted into pressure by a suitable whirlpool chamber or diffuser. **The obtainable head** is proportional to the square of the peripheral velocity of the impeller; this velocity is subject to practical limitations, so that 150 to 200 ft. head is about the upper limit desirable in a single impeller. For higher heads, such as boiler feeding, the pumps are made two, three or more **stages**, consisting merely of single impellers connected in series in a single casing.

332. Rotary pumps are very little used in power-station service; the commonest types are the bi-lobular type, and the gear pump. Neither has very good efficiency.

333. Screw or propeller pumps, while not strictly centrifugal, create pressure in the same manner, and are usually considered in the same class.

334. Jet pumps are covered in Par. **345** to **353.**

335. The characteristic curve of a centrifugal pump is necessary for determining its behav or. The capacity of a reciprocating or a rotary pump varies directly with the speed and is substantially independent of the pressure. The usual graphs are between capacity and efficiency, and capacity and head. Fig. 40 gives results for a 6-in. single-stage pump. Pumps for similar service, but different sizes, will have about the same characteristics, the efficiency increasing slightly with the size.

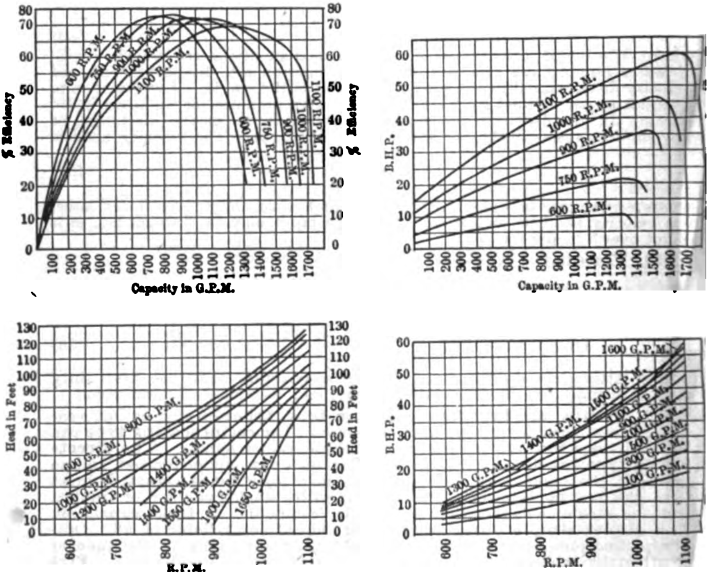


FIG. 40.—Characteristics of a 6-in. single-stage centrifugal pump.

336. Boiler feed pumps are usually the duplex outside-packed plunger type, or the three-stage or four-stage centrifugal. Occasional installations of motor-driven triplex pumps are made, but are undesirable. The principal feature required is reliability, which at once gives the steam-driven apparatus the precedence. The duplex direct-acting type was, until recently, almost exclusively used, but is now being replaced by the turbine-driven centrifugal. Fig. 40 shows that the pump speed is increased slightly as the delivery increases; this gives a more nearly constant head and a better efficiency with the variable loads.

337. Pressure regulators are employed to control the speed of all direct-acting boiler feed pumps and also, in most cases, for the centrifugal types.

338. The efficiency of direct-acting steam simplex and duplex pumps is low mechanically and thermally. The mechanical efficiency (water h.p./indicated h.p.) varies from 0.50 in small pumps to 0.85. The water rates are very high, both on account of the low speed and the lack of expansion.

339. Performance test of boiler feed pump. The following test of economy of Marsh pumps was made at Armour Institute of Technology; size $12 \times 7\frac{1}{2} \times 12$ in.; steam actuated valve gear; initial pressure 100 lb. gage; back pressure 2 lb. gage.

Number of strokes	Pump h.p.	Steam per indicated h.p.-hour	Number strokes	Pump h.p.	Steam per indicated h.p.-hour
10	1.0	400	60	6.4	105
20	2.0	210	70	7.6	101
30	3.0	168	80	8.8	100
40	4.1	130	90	10.0	99
50	5.2	118	100	11.3	99

(G. F. Gebhardt)

340. The mechanical efficiency of geared triplex pumps is high, running up to 0.82 for motor-driven and high-speed pumps; the low-speed geared pumps reach 0.70.

341. The efficiency of centrifugal pumps depends on the size and number of stages. De Laval gives the following data for volute pumps.

Capacity	Efficiency	Capacity	Efficiency
75– 250 g.p.m.	55 to 65	3,000– 6,000	73 to 75
250– 900	70	6,000–10,000	75 to 78
900–3,000	70 to 73	10,000–up	75 to 85

The maximum efficiency of two-stage pumps is about 70 to 75 per cent. of three-stage and four-stage pumps, about 60 to 68 per cent. These values apply to turbine speeds, as in turbine drive. The efficiency of a volute pump is usually stated at the proper speed for the head. At turbine speeds and under low head, the efficiency drops about 20 to 25 per cent; this is the case for turbine-driven circulating pumps, in which the speed is too high for efficient low-head pumping and still too low for efficient turbine water rates. The latest solution is a reversion to the de Laval geared drive, using helical gears.

342. Costs are given in Fig. 41 for simplex and duplex pumps, and for triplex and two-cylinder geared power pumps. All costs are given in terms of displacement. The cost of large geared double-acting pumps is from $2.00 to $3.00 per cu. in. of displacement. The cost of single-stage centrifugal pumps is from $0.50 to $0.75 per gal. per min. of capacity. Multi-stage centrifugal pumps cost from $2.50 to $4.00 per gal. per min. of capacity.

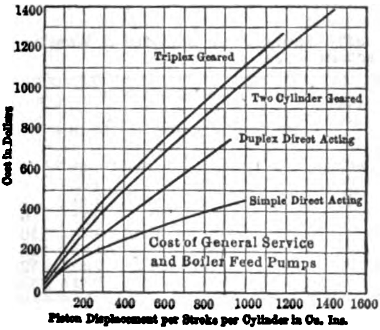


Fig. 41.—Costs of reciprocating pumps.

343. The usual piston speeds at which capacity is calculated for piston pumps, are from 100 to 200 ft. per min. for strokes below 12 in. and 100 ft. per min. for all strokes longer than 12 in.

344. Operation. The direct-acting simplex or duplex steam pump requires almost no attention except occasional packing of glands and lubricating. When controlled by a **pressure governor**, the delivery is suited to the demand. It will run on water as well as steam, and little care need be taken to supply it with dry steam. The geared triplex type requires more careful attention on account of the additional parts to be lubricated; if motor-driven, it must be provided with a suitable speed control, or it cannot be used on variable load. Piston and rotary pumps must always be provided with **relief valves** in the discharge, as they are positive in action and will produce excessive pressures if the discharge is restricted.

Centrifugal pumps cannot discharge under a higher head than that corresponding to the speed, therefore no relief is needed; the reason for using pressure governors with turbine-driven centrifugal boiler feed pumps is to reduce the speed in proportion to the delivery in order to keep up the efficiency. Centrifugal pumps are generally ring oiled and therefore require very little attention. The packing of the glands where the shaft leaves the pump casing is usually water-sealed; for this purpose a clean cool water should be provided. All centrifugal pumps must be primed before they will operate, and if no vacuum apparatus is provided, a foot-valve on the suction pipe must be used to prevent the water draining out of the pump on shutting down. A discharge valve must be provided, to be closed when priming, until the pump develops pressure.

JET PUMPS

345. Jet pumps operate by means of the kinetic energy of a rapidly moving stream of fluid. In those operated by steam, a jet of the high-pressure steam issues into a chamber at approximately atmospheric pressure or a little below, and there strikes the supply of water to be pumped. The impact of the steam transfers momentum to the water, which, together with the condensed steam, is hurled into a second nozzle which converts the kinetic energy of the mass into pressure and the stream enters the pressure chamber through a check valve. Since the water pumped must condense the steam used, it has a limitation in temperature, or the injector will fail to work.

346. Injectors are used for boiler feeding. For low and moderate pressures a single steam tube is used, both for lifting the water and forcing it into the boiler. But for heavier pressures and greater flexibility in handling variable quantities of water, and with wider range of pressure, the double-tube injector is employed. The first jet lifts the water to the second, or forcing jet.

347. Capacity of Schütte & Koerting double-tube boiler-feed injectors, in gal. per minute.

Size No.	Size pipe (in.)	Steam pressure 50 lb.	100 lb.	150 lb.	Size No.	Size pipe (in.)	Steam pressure 50 lb.	100 lb.	150 lb.
00	[illegible]	33	48	60	6	1¼	825	990	1,125
0	[illegible]	83	101	112	7	1½	1,072	1,372	1,612
1	[illegible]	112	143	180	8	1½	1,388	1,800	2,115
2	[illegible]	172	210	232	9	2	1,688	2,100	2,475
3¼	[illegible]	278	338	397	10	2	2,025	2,438	2,850
3½	[illegible]	398	472	547	11	2–2½	2,580	3,050	3,515
4	1	533	622	720	12	2½	3,000	3,638	4,252
5	1½	675	802	922					

The weight ranges from 3 to 108 lb.; No. 2 weighs 10 lb. and No. 4 weighs 20 lb.

348. Ejectors are either single-tube jet pumps, or direct-pressure pumps in which steam, or air, is admitted directly into a chamber filled by gravity with the liquid to be pumped. The pressure closes the inlet check valve and forces the water or other liquid out; when the chamber is emptied, a float therein drops and relieves the pressure, allowing the chamber to fill again. As the liquid reaches the top, the float rises and readmits pressure. The Shone and Albany traps are examples.

349. Inspirators are injectors of the double-tube type (Par. **346**).

350. Siphons, so called, are single-tube jet pumps used for lifting only. Air, steam, or high-pressure water may be the motive force. They are not used for forcing against more than a few feet head.

351. Pulsometers comprise another form of direct-pressure pump like the ejector, and operate in much the same manner. The operating steam is condensed by the cold-water chamber and, in collapsing to water, draws the chamber full of water and operates a ball valve to admit steam again. There are always two chambers, one filling and one discharging, operated by the single ball valve. The pulsometer, therefore, can lift water by suction, whereas the pressure-type ejector must be primed by gravity.

352. Efficiency. If the mechanical efficiency alone is considered, all jet pumps are very inefficient, being more wasteful of steam than the direct-acting steam pump. But thermally considered, the steam injector is nearly 100 per cent. efficient, since the heat of the exhaust steam is returned in the feed water. The siphon and the pulsometer are convenient for temporary use and for drainage of pits under conditions adverse to the use of machinery.

353. The cost of these classes varies so widely that representative figures can hardly be given, $2 to $5 per 100 g.p.m. capacity covers most cases.

PIPING

354. The requirements of piping are: (a) tightness against leakage; (b) reasonably small pressure loss through friction; (c) suitable provision for change of length through change of temperature of the fluid contained; (d) reasonably small loss of heat by radiation if the fluid is hot, and intended to be kept so. Most of these requirements increase the first cost; a balance must therefore be found beyond which it does not pay to carry refinements.

355. The flow of steam is expressed by Babcock as

$$W=87\left\{\frac{\gamma P d^5}{L\left(1+\frac{3.6}{d}\right)}\right\}^{\frac{1}{2}} \tag{57}$$

$$P=0.0001321\left(\frac{W^2 L\left(1+\frac{3.6}{d}\right)}{\gamma d^5}\right) \tag{58}$$

where W = lb. steam flowing per min., L = pipe length in ft., d = inside diameter of pipe in in., γ = mean density of steam at pressures in the pipe and P = pressure drop in lb. per sq. in.

356. Steam-flow for 1-lb. drop computed by Babcock's formula

Initial pressure lb. gage	Weight of steam per min. in pounds with 1 lb. drop of pressure, in length of 240 pipe diameters										
	Nominal pipe diameter (in.)										
	¾	1	1½	2	2½	3	4	6	8	10	12
1	1.16	2.07	5.7	10.27	15.45	25.38	46.85	115.9	211.4	341.1	502.4
10	1.44	2.57	7.1	12.72	19.15	31.45	58.05	143.6	262.0	422.7	622.5
50	2.27	4.04	11.2	20.01	30.13	49.48	91.34	226.0	412.2	665.0	979.5
80	2.71	4.82	13.3	23.82	35.87	58.91	108.74	269.0	490.7	791.7	1166.1
100	2.95	5.25	14.5	25.96	39.07	64.18	118.47	293.1	534.6	862.6	1270.1
150	3.45	6.14	17.0	30.37	45.72	75.09	138.61	343.0	625.5	1009.2	1486.5

357. The flow of water in long pipes is given by Church as

$$Q=3.15\sqrt{\frac{d^5 h}{fl}} \tag{59}$$

where Q = cu ft. per sec., d = diameter pipe in ft., h = head of water in ft., f = coefficient of friction and l = length of pipe in ft.

For pipe under 500 diameters in length,

$$Q=6.3\sqrt{\frac{d^5h}{(1+0.5)d+4fl}} \tag{60}$$

358. The loss of head due to friction is given by Weisbach as

$$H=\left(0.0144+\frac{0.01716}{\sqrt{V}}\right)\frac{V^2}{5.367d^1} \tag{61}$$

where H = friction head in ft., V = velocity of water in ft. per sec. and d^1 = diameter of pipe in in.

359. Equivalent length of valves and elbows. The above formulas for steam and water (Par. 357 and 358) apply to straight pipes. Valves and elbows may be figured as equivalent to lengths of straight pipe as follows, **for steam,**

$$L=\frac{6.33\,d}{\left(1+\frac{3.6}{d}\right)} \text{ for each 90 deg. ell} \tag{62}$$

$$L=\frac{9.5d}{\left(1+\frac{3.6}{d}\right)} \text{ for each globe and angle valve,} \tag{63}$$

where L = equivalent length of straight pipe in ft., and d = diam. of pipe in in. Gate valves are not considered. **For water,**

$$H=C\left(\frac{V^2}{2g}\right) \tag{64}$$

where C = coefficient, 0.182 for 45 deg. ells, 0.98 for 90 deg. ells, 0.182 for gate valves, 1.91 for globe valves, and 2.94 for angle globe valves.

360. The principal piping systems are: high-pressure steam; exhaust or low-pressure steam; hot, cold and circulating water piping; and oil piping.

361. High-pressure steam piping is made chiefly of steel pipe with cast-iron fittings, if saturated steam is used; if superheat is employed, cast-steel fittings and valves must be used, as cast-iron will not stand the temperature. For any pressure up to 125 lb. per sq. in. **standard fittings** are used; above 125 lb. **extra heavy fittings. Screwed** fittings should not be used above 3-in. pipe sizes; all larger material should be **flanged.**

362. On exhaust lines, standard weight pipe and fittings are usually employed; for very large sizes, however, special light-weight fittings may be used to save weight and first cost. Screwed pipe may be used up to 8-in. pipe sizes, but flanged fittings are preferable for everything over 4 in. Spiral riveted galvanized pipe may be used in place of standard pipe, as it is very much lighter and perfectly suitable for moderate pressures. It cannot be used on vacuum work.

363. Hot and cold water mains are made up the same as live steam lines; except that in some cases cast-iron pipe as well as fittings are employed throughout on high-pressure hot-water service, to minimize corrosion effects. No cast-steel fittings are necessary. For circulating water lines, galvanized spiral riveted pipe is useful for fresh water, but cast-iron pipe is generally used throughout for salt water and is preferable even for fresh water.

364. Oil systems were generally installed in brass pipe and fittings on the supply to engines; but it has been found that steel pipe, if well cleaned, is perfectly satisfactory for the service. There is little excuse for the use of brass piping except for appearance, on gage fittings, or for some special service where corrosion would be fatal.

365. There are four principal systems of piping arrangement: individual supply; ring; header; and unit (Fig. 42). The **individual supply** is really not a system, but the lack of it, and should not be employed.

366. The ring system is a development of the duplicate header; all supply lines tap in on one side of the ring, all demand lines on the other; by means of sectionalizing valves in the main, any section may be isolated without interfering with the rest of the plant.

367. In the header system, all supply and demand lines tap to one large main; so that if any section is cut out, it must interfere to some extent with the operation of the plant. This feature may not be serious; but for large power stations it is undesirable.

368. Unit system. The modern tendency is to revert to the unit system. This is the individual supply system—each group of boilers supplying its own turbine, but the units are tied together by equalizer pipes; so that there is really a header of diminished capacity between the units. Fig. 42 gives typical examples.

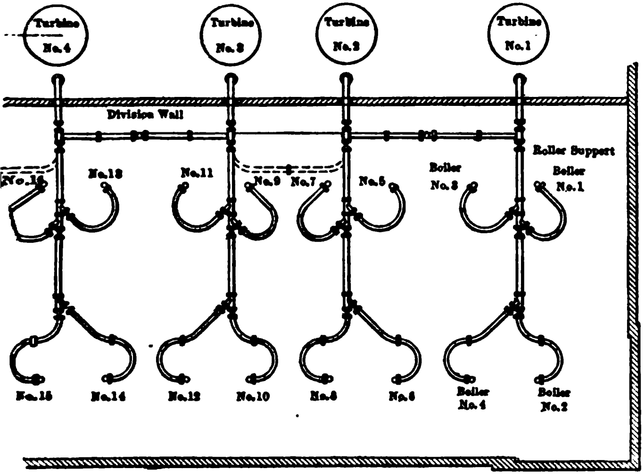


FIG. 42.—Piping systems.

369. Expansion in steel and cast-iron pipe may be taken as 0.9 in. per 100 deg. temperature difference from atmosphere, per 100 ft. of pipe under average conditions. **Expansion joints** should be provided every 50 ft. of straight steam main; every 75 or 100 ft. will do for water or exhaust steam. See Sec. 4, for coefficients of expansion of piping materials.

370. The slip expansion joint is useful for water service and exhaust steam at atmospheric pressure. It should never be used for high-pressure steam or vacuum; its capacity can be anything up to 9 in. or 10 in. of movement.

371. The copper bellows joint is very successful for low-pressure steam and vacuum work, particularly the type having only one corrugation. Its capacity however is never over 0.5 to 1 in. of expansion, and preferably not over 0.25 in. This type of joint is sometimes made up of boiler plate for high-pressure steam service.

372. The pipe bend is the simplest and safest joint for high-pressure steam and is usually made of as large radius as cán conveniently be made, taking care of from 1.5 to 2 in. of expansion per bend.

373. Avoidance of strains in fittings. Piping should always be laid out so that expansion will not bring strains upon cast-iron fittings, but upon the expansion joints, or at least upon the more flexible steel pipe.

374. Condensation in steam pipes is due to radiation; it occurs only in saturated steam mains. All low points in the piping system and all dead ends or pockets where water can collect, must be drained. The usual method for high-pressure steam is to connect a steam trap at each point to be drained and can be returned direct to the boilers, or to the feed tanks. Low-pressure steam mains are usually drained by gravity through an inverted siphon leg, to act as a steam seal.

375. Steam traps are of four principal types: bucket, float, tilting and expansion. The bucket and tilting traps are probably the most reliable.

376. Separators are employed to remove moisture from the steam before it is supplied to an engine. In every instance short and sudden turns are employed to throw out the moisture by centrifugal force, and a large chamber is then provided to reduce the velocity of the steam and act as a reservoir to collect and retain the water. (See Fig. 20a.)

377. Controlling valves are of three types: gate, globe and angle. The **globe valve** is always used for stop or throttle work. The **angle valve** is really a globe valve with the outlet turned through 90 deg. and is used as a globe valve, usually for the stop valve on boilers. For all other steam work the **gate valve** should be used on account of offering practically no obstruction to steam flow. All exhaust valves should be of the gate type. For water service, gate valves should be used wherever possible. **Check valves** may be horizontal, vertical, and swing. The horizontal and vertical check valves ordinarily are built much like a globe valve, but the valve disc has no stem and wheel for closing it.

378. Relief and back-pressure valves are developed from the check valve, with a spring or lever and weight loading device, so that a definite pressure under the valve disc will lift the valve and let off pressure. Relief valves are used on the discharge of reciprocating pumps to prevent excessive pressures; also on cylinders and receivers of steam engines. Back pressure and atmospheric relief valves are used on exhaust steam systems and condensers respectively. All of these types are emergency valves, to pre ent damage under unusual conditions.

379. Reducing valves are usually double-seated, or balanced, valves, with a pressure diaphragm substituted for the spring of the relief valves. This diaphragm is connected to the discharge side of the valve, and operates to close the valve only when the pressure on the discharge side rises above the predetermined amount. They are used to feed high-pressure steam into low-pressure systems.

380. The three principal types of pipe joint used are; screwed, flanged, and bell and spigot. The **screwed joint** is used for all pressures and service up to 3-in. diameter of pipe, and up to 12 in. for low-pressure service. Above 3 in. in high-pressure service and 12-in low-pressure service the **flanged joint** in one of its forms is used.

381. The principal methods of attaching flanges to steel pipe are: screwed flanges, peened flanges and, lately, machine expanded flanges, welded flanges and lap flanges. Of these, **screwed flanges** are in common use for low-pressure work, and high-pressure work up to 100 lb. in any size, or up to 200 lb. in sizes not larger than 6-in. or 8-in. diameter. It is a cheap and satisfactory joint when well made.

382. A much better joint for high pressures is the lap joint, in which the pipe is lapped over onto the flange and then faced off. The **welded joint** is also satisfactory but more expensive. The new **machine-expanded joint,** in which the pipe is rolled into a recess in the flange, promises well and is cheap to make.

383. Gaskets for low-pressure work may be of rubber compounds or asbestos. For high-pressure steam, asbestos, and the metallic gaskets, such as corrugated copper, are better.

384. Bursting pressure of standard mild steel pipe. Tests made at the Armour Institute of Technology on 5-ft. random specimens capped at both ends gave average results as follows: 1-in., 7,730 lb. per sq. in.; 2-in., 5,080 lb.; 4-in., 1,750 lb.; 5-in., 2,550 lb.; 6-in., 3,200 lb.; 10-in., 1,800 lb.; 12-in., 2,500 lb. On the 4-in., 5-in., 6-in., 10-in. and 12-in. sizes failure occurred at the threaded end.

385. Pipe covering is practically always justified for high-pressure steam, and for exhaust also, if used for heating feed water. Hot feed-water pipes should also be covered. The standard coverings are principally magnesia, asbestos and the fossil meal compounds. Moulded sectional covering can be obtained for pipes up to 12-in. diameter in single (1-in.) and double (2-in. to 3-in.) thickness. All exhaust lines should be covered with single thickness; all steam lines, with double thickness. Usually the covering is bought already canvassed. For larger size pipe than 12 in., sectional blocks, about 1.5 in. × 3 in. × 18 in. are used, and wired on; then the joints are pasted with asbestos cement and the whole is canvassed and painted. Moulded covering can be bought in shapes to fit standard fittings, such as tees and ells, but is frequently made up from blocking and asbestos cement.

386. The radiation losses from uncovered pipe are given by

$$Q = A(T_1 - T_2)U \qquad (65)$$

where A = sq. ft. of radiating surface, T_1 = temperature of steam within the pipe, T_2 = temperature of air outside, and U = transmission coefficient = 2.7 B.t.u. per sq. ft. per hr. per degree of temperature difference.

For 1-in. magnesia, 85 per cent., $U = 0.4 - 0.5$ (66)

For 1.5-in. magnesia, 85 per cent., $U = 0.25 - 0.3$ (67)

In a modern plant, with properly covered piping the actual radiation loss from pipe alone should not exceed 1 per cent. of the total heat of steam passing through at full load.

387. Tests of Relative Efficiencies of Steam-pipe Coverings

Kind of covering	Size of pipe, inches	Thickness of covering, in.	B.t.u. per sq. ft. per deg. diff. of temp.	Per cent. heat lost	Authority
Bare pipe	......	....	2.7	100	....
Hair felt	2	0.96	0.387	14.3	Jacobus
Reman t	2	0.88	0.434	16.1	Jacobus
Solid cork	2	1.20	0.427	15.8	Stott
Magnesia	2	1.16	0.439	16.3	Stott
Magnesia	4	1.12	0.465	17.2	Norton
Asbestos sponge felted	10	1.63	0.280	10.4	Barrus
Asbestos sponge felted	2	1.21	0.490	18.1	Barrus
Manville sectional	4	1.25	0.453	16.8	Norton
Manville sectional	2	1.31	0.572	21.2	Paulding
Asbestos air cell	4	1.12	0.525	19.4	Norton
Asbestos air cell	2	0.96	0.716	26.5	Jacobus
Asbestos fire felt	8	1.30	0.502	18.6	Brill
Asbestos fire felt	2	1.00	0.721	26.7	Paulding

(Abstracted from "Book of Standards," National Tube Co., Pittsburgh, Pa.)

388. Exhaust heads comprise a form of separator in which the entrained moisture in atmospheric exhaust is removed so that the issuing steam may not be a nuisance to the neighborhood, or an injury to the roof. They operate on the same centrifugal principle as separators.

389. Blow-off valves and piping, being subject to rapid variation from low to high temperature, must be carefully designed for expansion. As solid scale and rust flakes must be passed, the turns should be easy, and all connections between individual boilers and mains should be by 45-deg. laterals instead of tees.

390. The installation of piping should be done with great care to provide good alignment. Pipe joints can be made when piping is considerably out of line, as the lines are more or less flexible, but satisfactory joints and service cannot be expected. For **high-pressure** work, it is unsafe to strain the pipe in order to joint it. It is therefore good practice to arrange connections for flexibility, in case of variation from drawing dimensions; or better, to leave certain pieces of pipe called **fillers**, to be cut to field dimensions. This entails a slight delay in erection but is safe and eminently satisfactory.

All steam piping, and most water and oil piping, should be carefully cleaned of internal scale (by brushing or hammering), as this may dislodge during operation and cause trouble in the cylinders of engines or other apparatus. Steam and water piping should be tested at the working pressure before being put in service.

391. Hangers. Careful provision for hangers at suitable points must be made in order to support the pipe properly. The interval between hangers should not exceed 12 ft. except for small pipe, which may be supported on centers as much as 18 ft. apart.

392. Costs. Valves cost, in cast-iron body, approximately $0.20 to $0.25 per lb; straight cast-iron pipe, 12-ft. lengths, $34.00 to $50.00 per ton; straight pipe, shorter than 12-ft. lengths, $52.00 to $60.00 per ton; standard fittings, $60.00 to $75.00; special fittings, $73.00 to $113.00 per ton. Wrought-iron and steel pipe, 1-in. to 6-in. sizes, costs from 3.4 to 4.5 cents per lb.; 7-in. and 8-in. 4.3 to 5 cents; 10-in. to 12-in., 5 to 6 cents per lb. All the recent evidence seems to show that wrought-iron pipe is no better than steel for practically all purposes; and as the steel pipe is lower in price and more readily available, it is satisfactory to use it.

PLANT ENSEMBLE

393. The best combination of plant equipment is seldom if ever one in which each piece of apparatus is chosen by reason of its best water rate, or highest efficiency. The characteristic under variable load and the heat relation to the rest of the plant are most important.

394. The question of first cost versus economy is discussed under power-plant economics (Par. 882 to 925). The following paragraphs cover the best capacity and grouping of units for the best overall economy, with given efficiencies in the individual apparatus.

395. The heat analysis in B.t.u. is valuable for the purpose of proving the expected economies of any given combination of apparatus. Starting with the coal supplied, the boiler-room distribution of all the heat contents is followed through, including the B.t.u. delivered to steam, flues, unburned combustible, radiation, leakage, stoker, fan, and boiler feed-pump drives, other auxiliaries and miscellaneous steam such as boiler blow-down, free drip, dusting tubes, etc. In the engine room, the B.t.u. supplied in the steam is separated into pipe and engine radiation, exhaust drips, condenser auxiliaries, oil pumps, exciters, friction, electrical losses and energy delivered to bus bars. Heat returned by feed-water heaters and economizers is credited.

396. The average conditions in a large metropolitan station were given in a paper by H. G. Stott, on "Power Plant Economics" (A. I. E. E. Transactions, 1906), Par. 915. Recomputed several years later, under improved conditions, the same plant showed, using coal having 14,000 B.t.u. per lb. net:

	Per cent.	Per cent.		Per cent.	Per cent.
Coal		100.0	Circ. water pumps	4.0	
Ash loss*	3.0		Boiler feed pumps	1.0	
Stack loss*	19.0		Leakage and drips included in pipe radiation		
Incomplete combustion	5.1		Small auxiliaries	1.3	
Boiler radiation and leakage*	8.0		Heating	0.2	
Returned by F. W. heaters		6.1	Engine friction	1.0	
			Electrical losses	0.3	
Returned by economizers		5.7	Engine radiation	1.1	
			Rejected to condensers	51.3	
Pipe radiation and leakage	4.5		House auxiliaries	0.2	
			To switchboard	11.5	
Tank radiation	0.3		Total	111.8	111.8

* 65 per cent. boiler efficiency, including banking fires.

397. In choosing the number and capacity of prime movers, the **Willans line** of total steam consumption with load is plotted. The arrangement which gives the east area under the curve is the most economical. Fig. 43 shows this curve for 42-in. × 86-in. × 60-in. double compound Corliss engines, 7,500 kw. maximum continuous rating on 190 lb. dry steam, 28 in. vacuum. If the auxiliaries were not considered, the Willans line for engines alone would show the proper points for cutting engines in and out. It is found, however, that the most economical method is to carry up the load on n units until the Willans line for n units intersects the Willans line for $n+1$ units; and *vice versa*. The maximum capacity of individual machines may limit the cutting-in point somewhat when only one or two engines are running, but as the number in service increases, the loads on each engine before and after cutting in another unit become nearer alike.

398. Effect of auxiliaries on Willans line. The condensers and other auxiliaries using steam necessitate the addition of their demand to the main-unit demand, and the resulting Willans lines will give the steam demand of the engine room for any load. This supposes the units to be all alike and equally loaded when on the line; however, for units of unequal capacities, various loadings should be tried and plotted in order to determine the most economical operating conditions (Fig. 43).

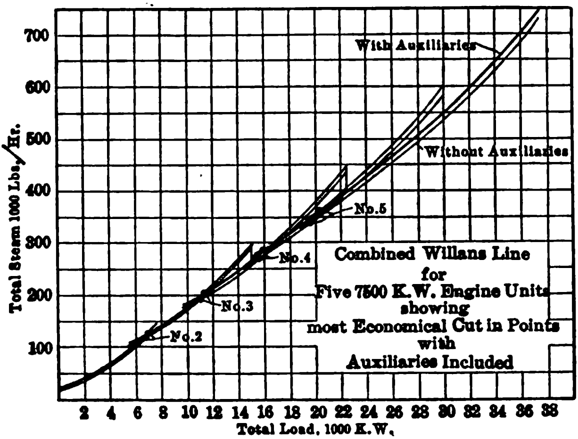


FIG. 43.—Willans line for 7500-kw. engines.

399. The boiler generation curve is determined by the efficiency of the boiler and stoker and by the steam required for forced draft, stoker drive, boiler feed pumps, etc. The economical cutting in and out points can be developed in the same manner as for the engine room, noting always that it is the overall efficiency which is important, not that of the boiler alone.

400. Feed-water heaters recover from 5 to 15 per cent. of the heat of the steam, the source being chiefly the exhaust from auxiliaries operated non-condensing. The feed-water heater always pays for itself.

401. Economizers recover from 3 to 10 per cent. of the total heat; but the re ent increase of boiler efficiency (reducing the stack temperatures), the reversion to all-steam auxiliaries, and the need for more draft at higher capacities, is rapidly limiting the field of the economizer; it does not always economize.

402. Possible reductions in the heat losses. The heat losses are given in Par. 396. It is clear that: (a) the ash loss cannot be much reduced;

(b) the stack loss is probably susceptible of considerable improvement, especially by way of improving combustion, which affects stack temperature indirectly; (c) the incomplete combustion would be decreased with (b); (d) the condenser loss is the only other very considerable item, and this cannot, by nature of the cycle, be appreciably altered.

403. The steam consumption per kw-hr. of the plant will depend upon the water rate of the main unit, the steam required by auxiliaries and the load factor. The no-load steam losses include: banked boilers; pipe radiation and leakage; boiler blow-down; boiler dusting; operation of condenser auxiliaries on emergency units and boiler auxiliaries, and supplying feed water for these losses. If the load factor is low, these bear a larger proportion to the total. In a high-grade plant with a yearly load factor of 30 to 40 per cent., the station water rate is 25 to 35 per cent. higher than the best water rate of the main unit. For ordinary stations of moderate size on less than 25 to 40 per cent. load factor, the station water rate is 80 to 100 per cent. higher than that of the main unit alone. The steam required for condenser auxiliaries is from 2 to 3½ per cent. of the main-unit consumption, for engine units, up to 27 in. vacuum; for turbine plants, 4.5 to 10 per cent for 28 in. to 28.5 in. vacuum. The boiler feed-pump steam varies from 1 to 1½ per cent. for direct reciprocating pumps, and 0.6 to 1.3 per cent. for high-grade pumping engines, or turbine-driven centrifugal types. The steam for forced-draft fans on underfeed stokers varies from 1 to 2 per cent. of main-unit steam; coal-conveying systems require 1.7 to 3 per cent., or the equivalent in electrical energy. The total varies therefore from 8 to 18 per cent.

404. The power taken by the auxiliaries of a 5,000-kw. turbine tested by the Edison Illuminating Co. of Boston was as follows:

Kw. on turbine	2,713.0	3,410.0	4,758.0
Vacuum, in	28.4	28.7	28.6
Barometer, in	29.53	29.95	29.96
I.h.p. of boiler-feed pump	13.9	23.7	27.2
I.h.p. of circulating pump	69.1	69.1	69.1
I.h.p. of dry-vacuum pump	24.3	23.2	23.8
I.h.p. of step-bearing pump	6.4	5.8	5.6
Total power for auxiliaries	122.3	131.0	135.7
Per cent. power of auxiliaries	3.4	2.9	2.1
Per cent. water used by auxiliaries	8.4	7.4	5.7
Electric h.p. of wet-vacuum pump	8.6	9.2	9.8

405. Number of main units. In modern central-station practice, the reciprocating engine is practically defunct. For 24-hr. service, not less than three turbine units should be employed and prefe ably six to eight for large stations. The units should always be of similar size. The analysis given in Par. **397** to **399** will prove that there is very seldom any economy in selecting odd-size units for a plant, and there is always increased risk of shutdown and increased cost, due to lack of interchangeability of units and spare parts.

406. Steam versus electric drive for auxiliaries. The heat analysis shows that the steam auxiliary is always more economical than the motor-driven type, when the amount of steam required for auxiliaries does not exceed the demand for heat in the feed water. Turbine-driven auxiliaries are practically universal except for the dry-vacuum pumps, which are often reciprocating, and small oil pumps, which are more satisfactory if duplex direct acting. Turbine-driven blast fans are becoming very widely used. Turbine-driven centrifugal boiler feed pumps are very satisfactory in units larger than 300 gal. per min.; in smaller units, the impeller passages are small and likely to give trouble from scaling and clogging.

407. General plant layout. The most generally satisfactory scheme is to lay out the plant on the **unit system**, with a complete set of boilers and auxiliaries for each turbine. The advantages become more and more marked, the larger the plant.

408. Plant location. The plant should be located at the edge of a sufficient body of water to supply abundant condensing water; where this cannot be done, wells may possibly supply the required amount, or, failing this, cooling towers will be necessary. The next most important consideration is coal supply; location on a river or at tide-water may automatically take care of coal supply by barge, but otherwise a rail connection will be needed. The third item is suitable ground for the foundations of the building and machinery. Choice of site where rock bottom is available near the surface is most desirable, but hardpan is practically as satisfactory. On marsh land near rivers or tide-water, piling or fill will be necessary. Too great pains to provide solid and permanent foundations cannot be taken.

409. Load factor plays a large part in selection of a plant; for low load factors, the fixed charges are high, and the operating charges relatively small. It is therefore necessary to cut down the first cost, which is done by omitting refinements for efficiency and allowing the thermal economy to go down. For high load factor, the fixed charges are less important and operating charges become the controlling factor; therefore profitable investment in devices for high thermal economy may be made. For low load factors, machines with high overload capacities are desirable, at the sacrifice of economy. It will be desirable to overstoker the boilers a little, to this end, as well as to build the turbines for high overloads.

410. Reserve capacity of one main unit at peak load should be maintained in plants of any number of units up to eight; above this, two reserve units. This applies to plants with duplicate equipment. For plants with dissimilar units, the reserve should be equal to the largest unit in the plant, either as one large unit, or the equivalent load capacity in smaller units.

411. Unit costs of equipment may be taken as given in Par. 57, 88, etc. But on a basis of plant output, the relations will be different. Lyford and Stovel give the following central station costs, high and low, for steam turbo-electric generating stations of 2,000 to 20,000 kw. capacity, based on maximum continuous capacity of generators as 50 deg. Cent. temp. rise.

	Dollars per kw.	
	High	Low
Preparing Site: Clearing structures from site, construction roads, tracks, etc.	$0.25	....
Yard Work: Flumes for condensing water, siding, grading, fencing, sidewalks, etc.	2.50	$1.00
Foundations: Foundations for building, stacks and machinery, excavation, piling, waterproofing, etc.	6.00 6.00	1.00 1.00
Building: Frame, walls, floors, roofs, windows, doors, coal bunker, etc., exclusive of foundations, heating, plumbing and lighting.	12.00	4.00
Boiler-room Equipments: Boilers, stokers, flues, stacks, feed pumps, feed-water heater, economizers, mechanical draft, piping and covering, except condenser water piping.	24.00	12.00
Turbine Room Equipment: Steam turbines and generators, condensers, condenser auxiliaries, condenser water piping, oiling system, etc.	22.00	12.00
Electrical Switching Equipment: Exciters, masonry switch structure, switchboards, switches, instruments, etc., all wiring except for lighting.	5.00	2.00
Service Equipment: Cranes, lighting, heating, plumbing, fire protection, compressed air, furniture, permanent tools, coal- and ash-handling machinery, etc.	5.00	2.50
Starting Up: Labor, fuel and supplies for getting plant ready to carry useful load.	1.00	0.50
General Charges: Engineering, purchasing, supervision, clerical work, construction plant and supplies, watchmen, cleaning up, etc.	6.00	3.00
Total cost of plant, except land and interest during Construction.	$83.75	$38.00

412. Reliability is increased by uniform equipment, and by proper reserves. The turbine plant is superior to the engine plant in this respect, with the same number and capacity of units. It is not good practice to operate a unit regularly at overloads, although the machine may always be overloaded for short periods before cutting in or after cutting out a unit. The analysis given in Par. **397** to **399** will show this to be thermally economical.

413. Labor requirements vary with station arrangements: roughly, for reciprocating engines, one man is required per 750 to 1,000 kw. in the engine room, and one man per 1,000 to 1,500 kw. in turbine stations. This includes switchboard and electrical attendance for operation only. Maintenance and repairs will need about 10 to 15 per cent. additional labor.

For the boiler room, one man is required per 600 to 800 kw. with overfeed stokers and one man per 800 to 1,500 kw. with underfeed types. The total for engine plants will be from 300 to 450 kw. per man for engine plants and 400 to 725 kw. for turbine plants, for operation only; for maintenance add 10 to 15 per cent. to the number of men required for operation.

414. Relative Costs per Kw-hr. Distribution of Maintenance and Operation (H. G. Stott)

	Reciprocating steam plant	Steam turbine plant	Reciprocating engines and low-pressure steam turbines	Gas-engine plant	Gas engines and steam turbines	Hydraulic
MAINTENANCE						
1. Engine room, mechanical.	2.59	0.51	1.55	5.18	2.84	0.51
2. Boiler or producer room.	4.65	4.33	3.55	1.16	1.97	......
3. Coal and ash-handling apparatus.	0.58	0.54	0.44	0.29	0.29	......
4. Electrical apparatus.	1.13	1.13	1.13	1.13	1.13	1.13
OPERATION						
5. Coal............	61.70	55.53	52.44	26.52	25.97	......
6. Water...........	7.20	0.65	0.61	3.60	2.16	......
7. Engine room, labor.	6.75	1.36	4.06	6.76	4.06	1.36
8. Boiler or producer room labor.	7.20	6.74	5.50	1.81	3.05	......
9. Coal and ash-handling labor.	2.28	2.13	1.75	1.14	1.14	......
10. Ash removal......	1.07	0.95	0.81	0.54	0.54	......
11. Electrical labor...	2.54	2.54	2.54	2.54	2.54	2.54
12. Engine-room lubrication.	1.78	0.35	1.02	1.80	1.07	0.20
13. Engine-room waste, etc.	0.30	0.30	0.30	0.30	0.30	0.20
14. Boiler-room lubrication, etc.	0.17	0.17	0.17	0.17	0.17	......
Relative operating cost per cent.	100.00	77.23	75.87	52.94	47.23	5.94
Relative investment per cent.	100.00	75.00	80.00	110.00	96.20	100.00
Probable average cost per kw.	125.00	93.75	100.00	137.50	120.00	125.00
Probable fixed charges per cent.	11.00	11.00	11.00	12.00	11.50	11.00

For steam-turbine plants larger than 60,000 kw. the cost per kw. may be reduced to $75.

TESTING

415. Boiler-testing requires the following essential data: (a) Weight of water fed per hr.; (b) weight of coal fed per hr.; (c) quality of steam; (d) pressure and superheat; (e) feed-water temperature; (f) proximate analysis of coal including moisture and B.t.u. per lb. Additional desirable data includes: (g) Flue temperature, including furnace and pass temperatures; (h) flue gas analysis, and analyses of gas at various points in boiler; (j) weight of refuse; (k) proximate analysis of refuse, moisture and B.t.u. per lb.; (l) siftings, if stoker fired; (m) soot and dust passing through boiler; (n) steam flow by meters. Boiler testing is always interwoven with stoker testing; the fire and the heating surface are tested together. The **duration of test** should never be less than 24 hr., for the most accurate results.

416. For weighing feed water, tanks on platform scales are best: but lacking these, a calibrated recording Venturi meter is satisfactory and accurate within 1 per cent. on reasonably steady flow.

417. For full details as to methods of firing, calorimetry, etc., see standard rules of the A. S. M. E.

418. Heat Balance, or Distribution of the Heating Value of the Combustible

The heat value of 1 lb. of combustible	B.t.u.	
	B.t.u.	Per cent.
1. Heat absorbed by the boiler = evaporation from and at 212° per lb. of combustible × 965.7.		
2. Loss due to moisture in coal = per cent. of moisture referred to combustible ÷ 100 × [(212 − t) + 966 + 0.48 (T − 212)] (t = temperature of air in the boiler-room, T = that of the flue gases).		
3. Loss due to moisture formed by the burning of hydrogen = per cent. of hydrogen to combustible ÷ 100 × 9 × [(212 − t) + 966 + 0.48 (T − 212)].		
4.* Loss due to heat carried away in the dry chimney gases = weight of gas per pound of combustible × 0.24 × (T − t)		
5.† Loss due to incomplete combustion of carbon = $\frac{CO}{CO_2+CO} \times \frac{\text{per cent. C in combustible}}{100} \times 10{,}150$.		
6. Loss due to unconsumed hydrogen and hydro-carbons, to heating the moisture in the air, to radiation, and unaccounted for. (Some of these losses may be separately itemized if data are obtained from which they may be calculated)		
Totals......................................		100

*The weight of gas per lb. of carbon burned may be calculated from the gas analyses, as follows:

† CO_2 and CO are respectively the percentages by volume of carbonic acid and carbonic oxide in the flue gases. The quantity 10,150 = number of heat units generated by burning to carbonic acid 1 lb. of carbon contained in carbonic oxide.

$$\text{Dry gas per lb. carbon} = \frac{11CO_2 + 8O + 7(CO + N)}{3(CO_2 + CO)}, \qquad (68)$$

in which CO_2, CO, O and N are the percentages by volume of the several gases. As the sampling and analyses of the gases in the present state of the art are liable to considerable errors, the result of this calculation is usually only an approximate one. The heat balance itself is also only approximate for this reason, as well as for the fact that it is not possible to determine accurately the percentage of unburned hydrogen or hydrocarbons in the flue gases.

The weight of dry gas per lb. of combustible is found by multiplying the dry gas per lb. of combustible by the percentage of carbon in the combustible, and dividing by 100.

419. Especial care should be taken to isolate the boiler tested so that leakage can be eliminated or measured. No single valve may be considered absolutely tight. Where lines cannot be completely disconnected, there should be two closed valves with a half-inch open bleeder between them to indicate leakage. Variations of water level must be corrected for.

420. Summary of overall results.

TOTAL QUANTITIES

1.	Date of trial...........................	
2.	Duration of trial........................	hr.
3.	Weight of coal as fired....................	lb.
4.	Percentage of moisture in coal.............	per cent.
5.	Total weight of dry coal consumed.........	lb.
6.	Total ash and refuse......................	lb.
7.	Percentage of ash and refuse in dry coal....	per cent.
8.	Total weight of water fed to the boiler.....	lb.
9.	Water actually evaporated, corrected for moisture or superheat in steam.	lb.
10.	Equivalent water evaporated into dry steam from and at 212°.	lb.

For further details, see the standard code of the A. S. M. E.

421. Quality of steam. The percentage of **moisture** in the steam should be determined by the use of either a throttling or a separating steam calorimeter. The sampling nozzle should be placed in the vertical steam pipe rising from the boiler. It should be made of 0.5-in. pipe, and should be extended across the diameter of the steam pipe to within half an inch of the opposite side, being closed at the end and perforated with not less than twenty 0.125-in. holes equally distributed along and around its cylindrical surface, but none of these holes should be nearer than 0.5 in. to the inner side of the steam pipe. The calorimeter and the pipe leading to it should be well covered with felting.

422. Superheating should be determined by means of a thermometer placed in a mercury-well inserted in the steam pipe. The degree of superheating should be taken as the difference between the reading of the thermometer for superheated steam and the reading of the same thermometer for saturated steam at the same pressure, as determined by a special experiment, and not by reference to steam tables.

423. Sampling the coal and determining its moisture. As each barrow-load or fresh portion of coal is taken from the coal-pile a representative shovelful is selected from it and placed in a barrel or box in a cool place and kept until the end of the trial. The samples are then mixed and broken into pieces not exceeding 1 in. in diameter, and reduced by the process of repeated quatering and crushing until a fine sample weighing about 5 lb. is obtained and the size of the larger pieces is such that they will pass through a sieve with 0.25-in. meshes. From this sample two 1-qt., air-tight glass preserving jars, or other air-tight vessels which will prevent the escape of moisture from the sample, are to be promptly filled, and these samples are to be kept for subsequent determinations of moisture and of heating value and for chemical analyses. For further details, see the standard code of the A. S. M. E.

424. Calorific tests and analysis of coal. The quality of the coal should be determined either by heat test or by analysis, or by both. The rational method of determining the total heat of combustion is to burn the sample of coal in an atmosphere of oxygen gas, the coal to be sampled as directed in Article XV of the code. The **chemical analysis** of the coal should be made only by an expert chemist. The total heat of combustion computed from the results of the ultimate analysis may be obtained by the use of Dulong's formula (with constants modified by recent determinations), viz.,

$$14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S, \qquad (68)$$

in which C, H, O, and S refer to the proportions of carbon, hydrogen, oxygen and sulphur, respectively, as determined by the ultimate analysis. It is desirable that a **proximate analysis** should be made, thereby determining the relative proportions of volatile matter and fixed carbon. These proportions furnish an indication of the leading characteristics of the fuel, and serve to fix the class to which it belongs. As an additional indication of the characteristics of the fuel the specific gravity should be determined.

425. Treatment of ashes and refuse. The ashes and refuse are to be weighed in a dry state. If it is found desirable to show the principal characteristics of the ash, a sample should be subjected to a proximate analysis and the actual amount of incombustible material determined. For elaborate trials a complete analysis of the ash and refuse should be made.

426. A throttling or a Thomas electric calorimeter should be used where possible, in preference to separating or other types. **Thermometers** are more satisfactory as indicators of saturated steam pressure than spring gages.

427. Engine testing requires essentially: (a) Weight of steam used; (b) kw. output of generator, or brake h.p.; (c) i.h.p., from indicator cards; (d) rev. per min.; (e) steam pressure, receiver pressure and back pressure or vacuum; (f) quality of steam. Desirable additional data include: (g) receiver and exhaust temperatures; (h) weight of condensation from receiver or elsewhere; (j) reheater steam, if used.

428. The steam consumption is best obtained by weighing the discharge from a surface condenser; but if jet condensers are used or the engine is noncondensing, the feed water must be measured as it enters the boilers, the boiler leakage determined, and the boilers isolated from all other steam piping and apparatus. If the condensate is weighed, the condenser leakage must be ascertained. The test should continue not less than 1 to 3 hr., with surface condensers and 8 hr. when using the feed-water method.

429. Turbine testing involves the following essential data: (a) Steam weight per hr.; (b) initial and exhaust pressures; (c) superheat, or wetness of steam; (d) rev. per min.; (e) b.h.p. or kw. output of generators; (f) steam chest pressure. There is a general similarity to engine testing, the only real difference lying in the absence of indicator cards. In measuring the condensate, provision must be made for measuring also the gland-water, or steam for sealing purposes, which is not strictly chargeable to the turbine, since all the water, or all the heat is recovered.

430. For full data on turbine testing see the standard rules of the A. S. M. E.

431. Condenser testing. The condenser is the chief auxiliary requiring test: generally it is convenient to combine the condenser test with the engine or turbine test on the attached prime mover. The essential readings are: (a) vacuum at exhaust entry referred to standard barometer; (b) condensate weight per hr.; (c) circulating water temperatures at inlet and discharge; (d) hot well temperature. Additional desirable data include: (e) vacuum at hot well; (f) vacuum at dry vacuum pump; (g) temperatures, top and bottom of condenser; (h) temperature of dry air at pump; (j) Pitot or Venturi meter readings on circulating water; (k) temperature of circulating water at beginning and end of each pass; (l) volume of dry air removed per min. A separate test for leakage should be made before the operating test, and tests for salt may be made on the condensate during the operation, if salt water is employed as cooling water.

432. Tests of boiler feed pumps and circulating water or hot-well pumps, of the centrifugal type, require the following readings, for turbine-driven units: (a) weight of steam used per hr.; (b) steam and exhaust pressures; (c) quality of steam, or superheat; (d) suction and discharge heads; (e) weight of water pumped—by scales, tank or Pitot or Venturi tube readings, which are close enough for this work (weirs may be used for large pumps); (f) rev. per min.

433. In testing direct-acting steam pumps, indicator cards should also be taken.

434. For tests of electric driven pumps, readings (a), (b), and (c) in Par. 432 would be replaced by kilowatt readings on the motor.

435. Tests on turbine-driven fans for forced or induced draft require: (a) Steam used per hr.; (b) steam pressure and back pressure; (c) quality of steam or superheat; (d) Pitot static and dynamic readings on suitable fan outlet; (e) rev. per min. For motor drive, kilowatt readings will replace (a), (b) and (c).

436. Complete plants have what amounts to a continuous test in their regular records, if properly kept. Coal is bought and paid for by weight and by analysis; and recording wattmeters give the output. For yearly figures the plant storage usually is not an important factor, as its amount is small compared to the total consumption; but for monthly figures, a survey of the coal stored is necessary. This is usually made by taking readings at predetermined points over the bunkers or storage space and calculating the volume of coal, allowing generally 50 lb. per cu. ft. for bituminous coal and 54 lb. per cu. ft. for No. 1, No. 2 or No. 3 buckwheat anthracite.

437. The apparatus required for weighing water is preferably made up of one or more sets of tanks on platform scales; the accuracy may be kept to 0.25 per cent. quite readily. Where less accuracy is required, 0.5 to 1.5 per cent., measurement by volume in a tank, or by Venturi meter, or V-notch weir, is suitable.

438. For measuring the steam used, the best method is by surface condensers (which may be made substantially tight), using scale tanks for weighing the condensate.

439. For measuring temperature up to 900 deg. Fahr., mercury thermometers of 12 in. length are most convenient; they should be used in iron or brass wells, with a little mercury in the bottom of the cup, and the remainder filled with oil. For temperatures above 500 deg. Fahr., nitrogen-filled mercury thermometers must be employed. Care should be taken to ascertain the immersion for which the thermometer is calibrated. Resistance thermometers are now available, but are in general very much more expensive; their use is a convenience where there are several inaccessible readings to be taken, as all the resistance bulbs may be read from one galvanometer and bridge. For higher temperatures than 900 deg. Fahr., resistance thermometers or thermocouples should be used. For high furnace temperatures, radiation or optical pyrometers are best. (Sec. 3.)

440. For pressure measurements, the spring gage is convenient but usually inaccurate; for pressures up to 15 lb., mercury columns are far better. For steam pressure, the thermometer is a valuable and accurate means of getting results. If the steam is superheated, a thermometer in a pressure chamber separated from the steam main by a condensing coil, and suitably drained, will give correct readings of pressure. If gages are used, they should be carefully checked at the operating pressure, in position if possible, against a standard gage tester.

441. Frequency of observations. Observations of temperatures, pressures and speeds should occur once every 10 or 15 min. Water and coal weighings should be made as often as needed by the capacity of the containers on the scales. Wattmeter readings and coal and water readings should be balanced every hour, as a precautionary measure in checking the steadiness and reliability of the test. Calorimeter readings on boilers and turbines at steady load only need be taken at half-hourly or hourly intervals, as they vary but little. Barometer readings taken three times during a test are sufficient. For short tests, such as occur in motor-driven pumps and fans with Pitot tube or Venturi tube readings, instantaneous values taken once a minute for 10 min. gives good enough results as a rule. Pitot readings for air should be taken at numerous points in the pipe (see Treat, *Trans.* A. S. M. E., 1912, and Rowse, *Trans.* A. S. M. E., 1913, and Taylor, *Trans.* N. A. & M. E., 1905).

442. Duration of tests. Engine or turbine tests by the feed-water method should not be less than 8 hr., as the error introduced by variations of level in the boilers is too great on shorter tests; when weighing the condensate, 1 to 3 hr. will be sufficient, depending on reservoir capacity in the system. Where flow meters can be employed with sufficient accuracy, instantaneous tests of a few minutes duration may be run. The time taken for a boiler test, start to stop, should never be less than 10 hr., 12 are better and 18 to 24 hr. give much more consistent results. This length of time is needed on account of the variable error introduced by the unknown amount of coal on the fire at start and finish.

443. Precision of tests. Boiler tests of 10 hr. duration are seldom closer than 3 per cent. either side of the average; 12-hr. tests, 2.5 per cent.; 24 hr. 1 per cent. Engine tests of 8 hr. duration, will have a probable error of 2 per cent., either way; turbine tests of 3 hr., 2 per cent. It is therefore needless to compute results closer than $\frac{1}{10}$ of 1 per cent.

GAS POWER PLANTS

BY REGINALD J. S. PIGOTT

PRODUCERS

444. Destructive distillation can occur only with fuels containing volatile matter; therefore anthracite and coke producers cannot be said to operate by destructive distillation. **Gas** may be produced from **hard coal** as follows: with air only, $2C + O_2 = 2CO$; with steam only, $H_2O + C = CO + H_2$; with both steam and air, $3C + O_2 + H_2O = 3CO + H_2$. The first process is not often used; the second is used to make **water gas**, but since it does not produce heat, it is used intermittently with the process $C + O_2 = CO_2$, or simple combustion of the fuel in the producer to generate the necessary heat. This is called "blasting up." The third process is the one used in making **producer gas** from anthracite or coke.

445. With bituminous coals, the volatile matter is given off as tar and hydrocarbon gases of the methane series, chiefly. These are again broken up by the heat in the producer to methane, carbon monoxide and hydrogen. In addition, the formation of CO and H from the coke remaining, goes on substantially as in the anthracite producer. In the down-draft types of producers, the tar passes through the fuel bed and is broken down to combustible gases and lampblack, some of which are burned in the passage.

446. Suction producers obtain a flow of air, steam and gas by means of a slight difference of pressure due to the pump action of the four-cycle gas engine on the charging stroke, or by an exhauster.

447. Pressure producers obtain a flow of gas, etc., by means of a pressure fan or blower for the air, or a boiler for the steam. A pressure producer is independent of the engine, and does not affect the capacity of the latter.

448. Up-draft producers are arranged with the steam and air admitted at the bottom and gas removed from the top; tar passes off with the gas and must be removed by scrubbers and purifiers.

449. Gasification of Anthracite Coal (R. D. Wood Co.)

Process	Products		
	Lb.	Cu. ft.	Anal. by Vol.
80 lb. C burned to CO	186.66	2,529.24	33.4
5 lb. C burned to CO_2	18.33	157.64	2.0
5 lb. vol. HC (distilled)	5.00	116.60	1.6
120 lb. Oxygen are required, of which			
30 lb. from H_2O liberate H	3.75	712.50	9.4
90 lb. from air as associated with N.	301.05	4,064.17	53.6
	514.79	7,580.15	100.0

Energy in the above gas obtained from 100 lb. anthracite: 85 per cent. F.C.; 5 per cent. V.M.; 10 per cent. ash.

186.66 lb. CO	807,304 B.t.u.
5.00 lb. CH_4	117,500 B.t.u.
3.75 lb. H	235,500 B.t.u.
	1,157,304 B.t.u.
Total energy in gas per lb	2,248 B.t.u.
Total energy in gas per cu. ft	152.7 B.t.u.
Efficiency of conversion	86 per cent.

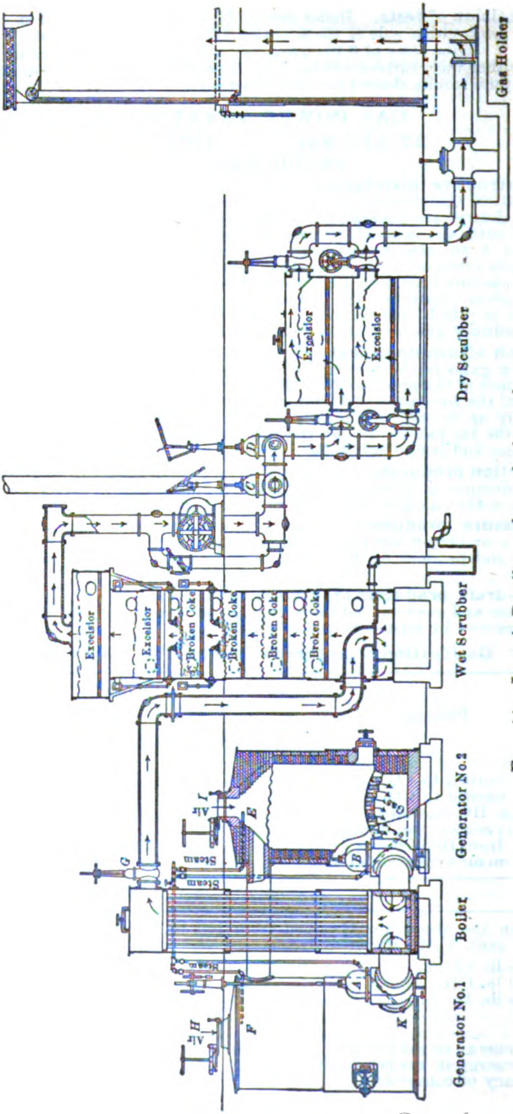


FIG. 44.—Loomis-Pettibone down-draft producer.

450. Down-draft producers are arranged with air and steam supply at the top, and gas removal under the firebrick grate at the bottom. The **double-zone producer** has down draft in the upper zone and up draft in the lower.

451. Suction producers have the advantage of not allowing gas to escape into the operating room from the producer, as the carbon monoxide is intensely poisonous; and poke openings, etc., can be conveniently operated. For small sizes, no exhaust fan is used, the necessary draft being provided by the engine suction. Most of the down-draft producers are suction types with exhaust fans. In this class belong the Loomis-Pettibone, De Lavergne, Körting, United Gas Machinery Co., Westinghouse double-zone, Otto, and Mond (small size).

452. Pressure producers require forced draft supplied by a fan or a steam jet blower, the steam thus admitted being used in the gasification. The tar formed is carried over with the gas and requires more extensive cleaning, but access to the grates is better than with the down-draft and suction types and mechanical stoking or poking may be employed either by mechanical water-cooled pokers, or by rotating the ash table and in some cases the producer shell. Examples of this type are the Mond large size, Taylor, and Chapman.

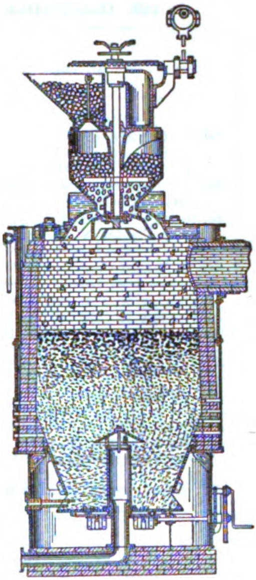


FIG. 45.—Taylor or Mond up-draft producer.

453. The capacity of a producer is based on 0.065 to 0.075 sq. ft. of cross-sectional area per brake h.p. of engine and about 0.105 to 0.118 cu. ft. of volume per h.p. (Snell).

454. The continuous rate of gasification with high-grade coal will not exceed 16 lb. of coal per hr. per sq. ft. of fuel bed; 10 lb. is a good average figure (Fernald, Bulletin 13, Bureau of Mines).

455. Gasification of Bit. Coal, Low Volatile

Process	Products		
	Lb.	Cu. ft.	Per cent. by vol.
65 lb. C burned to CO	151.6	2,054	30.8
5 lb. C burned to CO_2	18.3	157	2.3
20 lb. vol. HC (distilled)	20.0	466	7.0
25 lb. O, from water liberate H	3.1	588	9.0
75 lb. atmos. O mixed with N	251.2	3,391	50.9
	444.2	6,656	100.0

Calorific energy of the gas.................. 1,247,870 heat-units.
Calorific energy of the gas per lb.......... 2,809 heat-units.
Calorific energy of the gas per cu. ft....... 187.4 heat-units.
Calorific energy of the coal............... 1,415,000 heat-units.
Efficiency of the conversion............... 88 per cent.
Prox. Anal.: 70 per cent. F.C.; 20 per cent.; 10 per cent. ash.

456. Gasification of Bituminous Coal, High Volatile

Process	Products		
	Lb.	Cu. Ft.	Per cent. by Vol.
50 lb. C burned to CO	116.66	1,580.7	27.8
5 lb. C burned to CO_2	18.33	157.6	2.7
32 lb. vol. HC (distilled)	32.00	746.2	13.2
80 lb. O are required, of which 20 lb. derived from H_2O, liberate H	2.5	475.0	8.3
60 lb. O, derived from air, are associated with N	200.70	2,709.4	47.8
	370.19	5,668.9	99.8

Energy in 116.66 lb. CO .... 504,554 heat-units.
Energy in 32.00 lb. Vol. HC .... 640,000 heat-units.
Energy in 2.50 lb. H .... 155,000 heat-units.

1,299,554

Energy in coal 1,437,500
Per cent. of energy delivered in gas 90.0
Heat-units in 1 lb. of gas 3,484
Heat-units in 1 cu. ft. of gas 229.2
Prox. Anal.: 55 per cent. F.C.; 32 per cent. V.M; 12 per cent. ash.

457. Space required for Single-unit Gas Power Plants (Approximate)

H.p.	Suction			Pressure*			Gas holders	
	Length feet	Width feet	Head room feet	Length feet	Width feet	Head room feet	Cubic feet	Tank diameter
25–50	13–14	9–11	13–15	....	......	.....	1,000	15 ft.
50–75	14–15	10–12	14–17	....	......	.....	2,000	17 ft.
75–100	15–19	11–14	15–20	....	......	.....	2,500	19 ft. 6 in.
150	20–21	13–15	19–20	....	......	.....	3,000	21 ft. 6 in.
200	22–23	15–16	22–23	32	16	22–25	4,000	21 ft. 6 in.
300	25–26	16–17	23–25	34	18	23–25	5,000	24 ft.
400	......	......	.....	36	20	23–26	6,000	30 ft. 6 in.
500	......	......	.....	2 units 39	22	23–26	10,000	35 ft.
1,000	......	......	.....	3 units 39	47	23–26	15,000	43 ft.

Area depends of course on number and size of units for the total power given.

458. The efficiency of large producers will vary from 70 per cent. to 80 per cent. if the gases are used cold, and 80 to 90 per cent., if used hot (for furnace work). The losses include: (a) Sensible heat in gases; (b) producer radiation and conduction; (c) combustible in ash. The carbon in the ash of a properly operated large producer will be from 4 per cent. to 12 per cent. for about 0.5 to 1.5 per cent. total heat loss, with a coal having 10 per cent. to 12 per cent. ash. For small producers, suction type, the carbon in the ash may be as much as 60 per cent. of the total refuse, and the efficiency of the whole producer from 44 to 75 per cent. The sensible heat in the gases varies from 4 to 19 per cent., usually about 15 per cent. average.

459. Heat balance. The following data on the test of a Loomis-Pettibone producer were taken from the N. E. L. A. report on gas engines.

* Pressure plants exclusive of holder.

1908.

Total heat in fuel	100	per cent.
Total heat in gas at 60 deg. fahr	84.7	per cent.
Total heat removed by scrubber	8.16	per cent.
Total heat removed by water cooled valves	1.56	per cent.
Total heat lost by radiation, etc	5.58	per cent.
	100.00	

460. Tests on a 60-h.p. Otto Suction Producer

No. of test	21	16	17	27	25
Duration, hr	12	12	12	12	12
Kind of fuel	Lehigh chestnut			Scranton pea	
Proximate analysis	......	......	......	......	......
Fixed carbon	80.11	73.59	77.39	75.54	78.45
Volatile matter	4.27	8.47	6.70	6.34	5.99
Moisture	1.95	3.98	1.11	2.90	2.75
Ash	13.67	13.96	14.81	15.22	12.81
Sulphur	1.08	1.41	0.63	1.71	1.10
B.t.u. per lb., dry coal	12,750	12,780	12,680	12,540	13,040
B.t.u. per lb., combustible	15,570	15,550	15,700	15,700	15,700
Dry coal fired per hr. (lb.)	12.78	49.49	82.90	24.75	64.70
Water to producer per hr. (lb.)	22.2	30.40	42.05	16.30	28.50
Dry air per hr. to producer (lb.)	58.8	202.5	386.0	87.5	259.2
Calorific value gas, b.t.u./cu. ft.	104.8	111.8	103.4	120.0	137.3
Wt. dry gas per hr. (lb.)	69.0	248.6	456.0	105.0	326.0
Gas analysis, CO_2 (per cent.)	9.17	6.46	6.94	5.90	4.20
............CO	16.06	27.77	21.33	21.70	27.01
............O_2	0.53	0.49	0.37	0.40	0.23
............H_2	9.55	9.53	7.06	10.70	10.40
............CH_4	2.10	1.74	1.90	1.60	1.77
............N_2	62.65	59.01	62.50	59.70	56.40
Cold gas efficiency (per cent.)	54.3	65.8	64.6	56.4	76.2

461. Tests of Westinghouse Double-zone Producer

Fuel	Pocahontas	Texas lignite
Duration	96 hrs.	46.5 hrs.
Total coal fired	14,452 lb.	12,693 lb.
Heat value per lb	13,983 B.t.u.	8,007 B.t.u.
Heat value per cu. ft. (total)	126.9 B.t.u.	128.3 B.t.u.
Heat value per cu. ft. (effective)	117.8 B.t.u.	117.1 B.t.u.
Efficiency (total)	80%	77.3%
Efficiency (effective)	74.5%	70.5%

Gas Analysis

Carbon dioxide (CO_2)	7.9%	12.4%
Oxygen (O)	0.5	0.9
Carbon monoxide (CO)	18.1	13.3
Marsh gas (CH_4)	2.6	3.6
Hydrogen (H)	12.6	14.7
Nitrogen (N)	58.3	55.1

In the above table all values are computed on the assumption that the gas is at a temperature of 62 deg. Fahr., and that the absolute pressure is 30 in. of mercury.

462. Tests of Wood Pressure Producer

(Gas plant test—24 days continuous running)

*COAL	per cent.	GAS: Average	per cent.
Moisture	14.68	Carbon dioxide	CO_2 = 9.2
Volatile combustible	30.98	Oxygen	O_2 = 0.0
Fixed carbon	42.93	Ethylene	C_2H_4 = 0.4
Ash	11.41	Carbon Monoxide	CO = 20.9
		Hydrogen	H_2 = 15.6
	100.00	Methane	CH_4 = 1.9
Sulphur	1.33	Nitrogen	N_2 = 52.0

Calorific power 12,343 B.t.u. per lb. of dry coal.
Average heat value of gas for 24 days = 156.1 B.t.u. per cu. ft.

On the average of the Government tests generally Prof. Fernald gives the following:

463. Tests by Geological Survey

Load 90—100 Per cent. 30 to 50 hr.	Bituminous		Lignites		Peat	
	As fired	Dry	As fired	Dry	As fired.	Dry
B.t.u. per lb. of fuel	12,280	13,150	8,350	11,290	8,127	10,289
Cu. ft. of gas per lb.	60.5	64.7	35.8	45.7	30.3	38.3
B.t.u. per cu. ft. of standard gas.	152.1	......	158.4	......	175.2	......
Total lb. per b.h.p. hr.	1.36	1.26	1.99	1.68	2.57	2.03

464. Quantity of gas per lb. of fuel in up-draft pressure producers is given in Par. **462** (Fernald, Tech. Paper No. 9, Bur. Mines., 1912).

465. The addition of excess steam over that theoretically required, if not too large, has little or no effect on efficiency, but gives more control over clinker formation. The steam required at 30 to 60 lb. gage is 0.33 to 2.5 lb., averaging 0.7 to 1.0 lb., per b.h.p. The highest figures are for by-product recovery plants.

466. Analyses of gas are given in Par. **128, 459, 460,** and **463.**

467. The operation of gas producers presents three main features: (a) maintenance of uniform resistance of bed, which includes regulation of feed and poking; (b) removal of ash; (c) prevention of clinker. In the case of up-draft producers coal is fed usually by an air-lock device and spreader; poking is done through holes in the top, to fill up holes or channels which may have formed by clinkering and arching, or by localized combustion. Poking must be carefully done to avoid starting the evils it is intended to correct. A moderate rate of driving will tend to keep fires in better condition, as the producer cannot be forced to the same extent as a boiler and give satisfactory results. The down-draft producer can be poked in the same manner as the suction producer.

468. The cost of producers ranges as follows:

Suction producers, up to 300 h.p., total cost $= 252 + 14.2 \times (\text{h.p.})$ (69)

Pressure producers, up to 300 h.p., total cost $= 860 + 15.15 \times (\text{h.p.})$ (70)

The foregoing figures were given by A. A. Potter, *Power*, 1913, p. 938. R. H. Fernald (Bull. 55, Bur. mines) gives values averaging, for producers of both types:

Total cost $= 250 + 9.70$ b.h.p. for sizes from 15 to 300 h.p. (71)

Repairs and maintenance vary from $0.15 to $0.25 per h.p. per year. Guarantees on maintenance are usually 2 to 3 per cent. of first cost a year.

* Prof. R. H. Fernald.

SUPERHEATERS AND CONDENSERS

469. **The laws of heat transfer** for superheaters have been covered in Par. 15 to 29, and for economizers in Par. 320, for vaporizers in Par. 2, 3 and 4.

470. **Superheaters** are attached to the vaporizers of some types of producer, to superheat the steam fed to the fuel bed. They are usually of the protected type, heated by the hot gas leaving the producer, and delivering superheated steam for use in the fuel bed. Some additional economy is gained by their use.

471. **Wash boxes** are water seals and serve the purpose of a check valve to prevent blowing back of gas. They are made of cast iron generally, with a cross-section equal to about 25 times the delivery pipe. The submersion of the entering pipe is about 3 in.

472. **Economizers** are employed for preheating the air fed to the producer and operate on the sensible heat of the gas leaving the producer.

473. **Vaporizers** or boilers are attached to nearly all producers, and serve to yield the necessary steam for gasification, abstracting sensible heat from the hot gas. They are usually built much like a vertical fire-tube boiler, or of cast-iron cooling chambers forming the top or side, of the producer.

474. **Condensers** are employed to remove the tar, and consist usually of chambers with iron baffles upon which the viscous tar impinges and collects; suitable drainage allows the tar to be recovered and removed. The general design is similar to an oil separator. Some are made with helical passages to secure centrifugal action. There are also one or two designs of mechanical tar extractors built like centrifugal fans, to throw out the tar by centrifugal force. They are generally made entirely of cast-iron.

475. **Operation.** The operation of superheaters requires practically no labor; vaporizers in this respect are the same as boilers; **tar separators** require periodic cleaning and continuous drainage. The tar is inclined to accumulate and thicken with the dust in the gas. The standby period for lignite or bituminous producers is from 6 to 10 hr. a week for cleaning purposes and repairs, on the average. Anthracite producers may be run 60 to 90 days continuously. (Latta, 1910.)

476. **The cost of these auxiliaries** is included in the cost of the producer, given in Par. 468, since they are essential to operation.

SCRUBBERS AND PURIFIERS

477. **The impurities found in producer gas** are dust, tar and ammonia. Dust is blown over from the fuel bed, being usually the ash from the fines in the coal. In some cases, lampblack is also carried over in the down-draft and double-zone types. Tar is the result of partial decomposition and is a combustible material. Ammonia is produced by the union of H dissociated in the producer with N in the air supplied.

478. **Two methods of cleaning** are used; (a) wet scrubbing, with stationary towers and water spray in some form, or mechanical scrubbers more or less like fans with water injection; (b) dry scrubbing, with purifiers or filters made with excelsior or shavings, which require periodic removal and cleaning.

479. **Wet scrubbers** consist of steel towers filled with coke, wire netting or wood latticing, somewhat after the fashion of a cooling tower. Water is sprayed down from the top, and divides into fine streams or spray, washing out solid impurities and tar, dissolving out ammonia and sulphur gases. The amount required varies from 1.5 gal. to 2.5 gal. per b.h.p. per hr.

480. **The mechanical washers** are chiefly heavy-built fans with water spray devices, or Theisen washers. The simple fan washer consists of centrifugal fans of heavy construction, usually with cast-iron casing, with a water spray device at the inlet to produce a spray curtain or fog through which the gas passes. The efficiency averages about 12 to 1, gas containing 1.75 to 1.65 gr. per cu. ft. being cleaned to 0.15 to 0.22 gr. per cu. ft. The h.p.

required per 1,000 cu. ft. per hr. is 0.066. With two fans in series, the cleaning is from 50 to 1, to 200 to 1 and the h.p. required is 0.184 to 0.283 per 1,000 cu. ft. per hr. The water required per fan is 0.0125 to 0.0150 gal. per cu. ft. cleaned per hr.

481. The Theisen washer consists of three elements in one casing: (a) a primary cleaning fan at the suction end; (b) an annular chamber between a drum fitted with helical vanes and a coarse mesh grating surrounding the drum; (c) a discharge fan chamber. Water spray is fed in at the suction chamber and tangentially in the grating. The water consumption is 0.0272 gal. per 1,000 cu. ft. per hr.; the h.p. required is 0.184 per 1,000 cu. ft. per hr. cleaned.

482. The by-products recovered from bituminous coal gasification are ammonium sulphate and tar. The recovery of ammonium sulphate requires the addition of an acid tower, through which dilute sulphuric acid is circulated as in a purifier. The acid removes the ammonia gas as ammonium sulphate. Tar is removed by separators or condensers, and may be used as a fuel in certain oil engines; it usually contains considerable moisture—up to 20 per cent., on account of the water employed in washing the condenser trays.

483. Purifiers or dry scrubbers consist of a steel tank or tower, filled with shavings, excelsior, coke, or Laming composition. Laming composition is a mixture of bog iron ore and shavings. It is used in 6-in. to 8-in. layers, on gratings, and absorbs cyanides and sulphur compounds. The Laming mixture is removed and exposed to the air from time to time, which regenerates the materials for use again. Shavings and other mechanical dry purifying material must be removed and replaced by fresh material as often as they become clogged. Wet scrubbers are automatically cleaned by the water used to precipitate dust.

484. Cost of the apparatus is included in the cost of producers, Par. 468.

HOLDERS

485. Gas storage is required to provide reserve capacity for sudden increase of demand, and to absorb excess generation when sudden decrease of load occurs.

486. The holder is of the regular collapsing gasometer type, in no way different from the ordinary illuminating-gas tank. In some cases the water seal in the base is used as an additional wash-box for incoming producer gas.

487. The capacity required varies from 40 to 25 cu. ft. up to 100 h.p.; 20 to 15 cu. ft. up to 1,000 h.p. The larger the number of units the less storage usually required, as manipulation is more flexible.

488. The operation of gas holders requires only occasional painting to protect the tank, yearly cleaning of sediment from the water reservoir, and suitable steam-supply to the lift seals to prevent freezing in winter.

489. The cost of gas-holders varies from $0.60 to $0.45 per cu. ft. including foundations.

PROPERTIES OF GAS

490. Calorific Value of elementary gases. (From Gas Engine Design—Lucke.)

Fuel	B.t.u. per lb.		Lb. per cu. ft. at 62 deg. fahr.	B.t.u. per cu. ft.	
	High	Low		High	Low
H	61,524.0	51,804.0	.00538	331.0	278.7
CO	4,395.6	4,395.6	.07498	329.58	329.58
CH_4	24,021.0	21,592.8	.04308	1,037.22	932.38
C_2H_4	21,222.0	19,834.2	.07631	1,619.45	1,513.55

491. Producer gas has a specific gravity, referred to air, of 0.97, average specific heat, 0.25. It varies in composition, not only with the type of producer, but from variations in operation of the same producer. The hydrogen content, being usually high, limits the compression, usually from 100 to 160 lb. per sq. in., with 18 to 5 per cent. of hydrogen, average pressure 135 lb. Careful jacketing of valves and pistons for large engines raises the obtainable compression.

492. Natural gas is the richest of the power gases, and is obtainable chiefly through the soft coal and oil regions. Ohio, Indiana, Illinois, Pennsylvania and Virginia are most favored in this way. The allowable compression varies from 75 to 130 lb. The specific gravity referred to air is approximately 0.40 to 0.50; density, 0.043 to 0.049 lb. per cu. ft.

493. Illuminating gases, either coal or water gas, are usually too expensive for use in any but the smallest engines, up to say 75 h.p. The allowable compression is 60 to 100 lb. average 80; specific gravity approximately 0.40 to 0.43 for coal gas, 0.57 for water gas.

494. Blast-furnace gas is the leanest of the gases and will stand compression from 120 to 190 lb., averaging 155 lb.; this is on account of the dilution with N, and low hydrogen. It is used only in large gas engines at steel mills.

GAS ENGINES

495. Gas-engine cycles. The thermodynamics of the gas engine is complicated by the fact that not only the change of state by expansion and compression occurs in the cylinder, but also the combustion. The order of events in the usual Otto or **four-stroke cycle** is as follows: aspiration of a charge into the cylinder (suction stroke); compression, approximately adiabatic on the instroke; ignition and explosive combustion at constant volume, while the piston is on or near the dead centre; and approximately adiabatic expansion on the second outstroke; partial expulsion of the burnt gases at constant volume when on the outer dead center, further expulsion on the second instroke, at atmospheric pressure. **The two-stroke cycle** eliminates the suction and exhaust strokes, by admitting the incoming charge under a few pounds pressure while the piston is on or near the outer centre, after the partial exhaust to atmospheric pressure and constant volume has just taken place. This incoming charge sweeps before it, by displacement, most of the remaining burnt gases.

496. The standard reference diagram put forward by Lucke is useful in investigating the performance or design. This diagram is an assumed indicator card based on the assumption that the mixture in the cylinder will behave the same as pure air. The general relations are as given below.

497. Compression pressure.

$$p_b = p_a\left(\frac{v_a}{v_b}\right)^{1.41} \quad \text{and} \quad t_b = t_a\left(\frac{v_a}{v_b}\right)^{1.41} \qquad (72)$$

where $p_a = 14.7$ lb. per sq. in., suction pressure; p_b = final compression pressure; v_a = total cylinder volume in cu. ft. = displacement plus clearance; v_b = compression volume, or clearance, in cu. ft.; t_a = absolute initial temperature (deg. Fahr. + 461); and t_b = absolute compression temperature.

498. The pressure rise on explosion depends on the amount of heat per cu. ft. of mixture.

$$p_e = p_b\left(\frac{Q}{C_v t_b} + 1\right) \quad \text{and} \quad t_e = t_b + \frac{Q}{C_v} \qquad (73)$$

where p_e = explosion pressure; Q = B.t.u. per lb. of mixture; C_v = specific heat at constant volume; t_e = absolute explosion temperature; and the other symbols are as above (Par. 497).

$$p_e - p_b = \frac{2.2\,Q}{\left(\frac{p_a}{p_b}\right)0.71\,v_a} \text{ (in lb. per sq. in.)} \qquad (74)$$

499. B.t.u. per cu. ft.

$$\frac{Q}{v_a} = \frac{H}{n + a' + 1} \qquad (75)$$

where H = B.t.u. per cu. ft. of mixture, hot; a' = cu. ft. of air required to burn 1 cu. ft. gas; and n = cu. ft. of neutral added. The actual pressure ratio p_c/p_b obtained is from 40 per cent. to 65 per cent. of the air card ratios.

500. Expansion is taken according to the law

$$p_d = p_c\left(\frac{v_c}{v_d}\right)^{1.41} \tag{76}$$

which is the same as for compression.

501. Efficiency.

$$E = 1 - \frac{t_a}{t_b} = 1 - \left(\frac{p_a}{p_b}\right)^{0.29} \tag{77}$$

where E = thermal efficiency of the cycle; other symbols are as above. The thermal efficiency of the ideal cycle is only dependent upon the ratio of compression to suction pressure.

502. Four-cycle engines are built in all sizes; the terms single and double acting have the same application as for steam engines. The majority of engines of small and moderate size are single acting. Large engines are generally made double acting, to economize space, as the gas engine is even more bulky per h.p. than the steam engine.

503. Two-cycle engines are also used in all sizes, but are found to the greatest extent in large units, double acting. For small units they are never built double acting, as separate pumps are then required to give the pressure for charging at the end of each stroke. In the small single-acting types, the mixture is compressed between the piston and the crank case.

504. Cylinder jackets are essential to practically all gas engines. The enormous heat developed during explosion would soon destroy the cylinder and piston if they were not protected by cooling. In most cases this is done by **water jacketing**; in a few small engines, **air cooling** is employed. Pistons smaller than 15 in. in diameter are not separately cooled by water jacketing; but above this size, the area of piston head is too large to be properly cooled by conduction to the jacketed cylinder walls, and the air in the crank case; therefore water cooling becomes necessary.

505. The quantity of jacket water should be about 6.5 gal. per b.h.p.-hr. at 50 deg. Fahr., 7.75 gal. per b.h.p.-hr. at 60 deg. Fahr., 9.75 gal. per b.h.p.-hr. at 70 deg. Fahr., and 12 gal. per b.h.p.-hr. at 80 deg. Fahr., for large units. Most of this may be recovered and re-used if cooled. If a cooling tower is used, for recooling the jacket water, about 8 per cent. is lost by evaporation. The heat loss to the jacket is from 25 to 50 per cent., generally the largest with small engines.

506. Mean effective pressure is computed from the indicator card in the same manner as for a steam engine. The m.e.p. of the reference diagram is given by

$$\text{M.e.p.} = \frac{5.41Q}{(v_a - v_b)}\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} \tag{78}$$

or

$$\text{M.e.p.} = 5.41\left(\frac{H}{a'+1}\right)\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} = C\left(\frac{H}{a'+1}\right) \tag{79}$$

where the symbols have the same meaning as in Par. 497 to 500.

For constants to be used with these equations see Par. 507.

507. Constants used in Calculation of M.E.P. (Par. 506)

Compression		Value of factor $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.29}$	Compression		Value of factor $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.29}$
Atmospheres	Lb. per sq. in.		Atmospheres	Lb. per sq. in.	
3	44.1	1.474	8	117.6	2.446
4	58.8	1.787	9	132.3	2.554
5	73.5	2.014	10	147.0	2.630
6	88.2	2.187	11	161.7	2.711
7	102.9	2.327	12	176.4	2.775

508. Observed mean effective pressures obtained by test are given by Lucke:

Fuel	Compression, lb. per sq. in. abs.	M.e.p. actual lb. per sq. in.	Fuel	Compression, lb. per sq. in. abs.	M.e.p. actual lb. per sq. in.
City gas......	45	45	Producer gas..	103	63
	60	80		108	88
	66	95		125	51
	91	90		141	83
	70	60		170	73
				95	100
Natural gas ...	127	68		95	90
	130	82		90	62
	135	90		115	103
			Blast-furnace gas..........	....	60
				140	47
				155	81

509. The ignition of gas engines is practically entirely electric. The jump-spark or high-tension spark system is not used for power-station engines. Make-and-break systems are used, because more reliable and effective. The principal troubles are insulation breakdowns, worn and dirty contacts or short-circuiting by jacket leaks.

510. The timing of ignition affects the work done by a given charge and the economy. Ignition should take place so as to give a nearly vertical explosion line. The spark should be advanced, theoretically, as the rate of propagation is decreased by weakening the mixture or the compression, but in practice the spark is usually fixed to give the best results at the average load condition, and is not varied.

511. The speed of gas engines is about the same as for steam engines of the same class. See Par. 170. In small engines the speed may be 10 to 25 per cent. higher.

512. Indicated horse-power is obtained in the same manner as for steam engines, except that care must be used in planimetering the card to go around the negative work areas in the right direction. For throttle governed engines, the number N in formula 34a, is the same as rev. per min. for 2-cycle engines and rev. per min./2 for 4-cycle engines; with engines governed by the hit-and-miss method, the number of explosions must be counted to get N, as it has no fixed relation to rev. per min.

513. The friction is usually higher in the gas engine than in the steam engine; the mechanical efficiency at full-load is seldom over 85 per cent., even for large engines. Lucke gives.

	Mech. Efficiency	
	4-cycle	2-cycle
Large engines, 500 h.p. and over......	0.81 to 0.86	0.63 to 0.70
Medium, 25 to 500 h.p..............	0.79 to 0.81	0.64 to 0.66
Small, 4 to 25 h.p.................	0.74 to 0.80	0.63 to 0.70

514. Lubrication is entirely by machine oil, as the cylinder walls are water cooled. Lubrication in general is handled exactly as with the steam engine. About 1 gal. of oil is required per 4,000 b.h.p.-hr.

515. The rated capacity of a gas engine is preferably based on cu. ft. of cylinder displacement. The displacement per h.p. per lb. of mean effective pressure is 229.17 cu. ft. per min. For a given b.h.p. required, the mechanical efficiency is assumed and the i.h.p. found; and with a suitable m.e.p. for the fuel employed (Par. 505), the required displacement per h.p. divided into required i.h.p. gives total cylinder displacement per minute: Internal combustion engines are usually rated at 15 per cent. to 20 per cent. below the capacity of the cylinder as given above. Torrance and Ulbricht (*Power*, 1912) give the following **formulæ for builders' rating** in America.

$$\text{Producer gas, b.h.p.} = \frac{d^2ln}{18{,}500} - 2.0 \tag{80}$$

$$\text{Illuminating gas, b.h.p.} = \frac{d^2ln}{15{,}700} - 2.0 \tag{81}$$

$$\text{Natural gas, b.h.p.} = \frac{d^2ln}{15{,}200} - 5.0 \tag{82}$$

$$\text{Blast-furnace gas, b.h.p.} = \frac{d^2ln}{21{,}000} - 5.0 \tag{83}$$

where d = diameter of cylinder, inches; l = stroke in inches; and n = rev. per. min.

516. The fuel consumption of gas engines on producers ranges from 0.99 to 3 lb. per b.h.p.-hr. From 75 to 90 cu. ft. of gas per b.h.p.-hr. are required, of approximately 150 B.t.u. per cu. ft.

517. Test of 300-h.p. Illmer 2-stroke cycle double acting horizontal engine. (*Power*, May, 1913.) Duration of test, 33.5 hr.; coal, Westmoreland bituminous, 14,100 B.t.u. as fired; average b.h.p., 284; average B.t.u. per cu. ft. of gas, 144; Producer efficiency, 67 per cent.; B.t.u. per h.p.-hr., 10,300; total coal per b.h.p.-hr. 1.14.

518. Fuel consumption, Ulbricht and Torrance (Power, 1912) give average fuel consumption as below: (B.t.u. and cu. ft. per h.p.-hr.)

	50 b. h.p.			100 b.h.p.			Over 100 b.h.p		
	B.t.u.	cu.ft.	Eff.	B.t.u.	cu. ft.	Eff.	B.t.u.	cu. ft.	Eff.
Water gas......	10,690	35.2	23.8	10,160	33.4	25.0	10,160	33.4	25.0
Carburetted gas.	10,690	18.1	23.8	10,160	17.2	25.0	10,160	17.2	25.0
Coal gas........	10,690	17.6	23.8	10,160	16.7	25.0	10,160	16.7	25.0
Producer gas:									
anthracite....	10,380	82.6	24.5	9,630	76.6	26.4	9,600	76.3	26.5
bituminous...	10,380	83.0	24.5	9,630	77.0	26.4	9,600	76.7	26.5
coke.........	10,380	82.0	24.5	9,630	76.2	26.4	9,600	76.0	26.5
lignite........	10,380	77.5	24.5	9,630	71.8	26.4	9,600	71.6	26.5
oil............	10,380	68.7	24.5	9,630	63.7	26.4	9,600	63.5	26.5
peat..........	10,380	73.6	24.5	9,630	68.3	26.4	9,600	68.0	26.5
wood.........	10,380	80.6	24.5	9,630	74.8	26.4	9,600	74.6	26.5
Blast-furnace gas	10,860	114.0	23.4	10,500	110.0	24.2	9,860	104.0	25.8
Coke-oven gas..	10,690	22.0	23.8	10,160	20.9	25.0	10,160	20.9	25.0
Natural gas avg..	10,380	12.2	24.5	9,420	11.0	27.0	9,320	10.9	27.3

519. Test of a 310-h.p. engine, horizontal double-acting (Buckeye), running on coke-oven gas, 560 B.t.u. per cu. ft., gave the following results.

Load	B.h.p.	B.t.u. per h.p. hr.	Per cent. efficiency
$\frac{1}{2}$	165	13,000	18.5
$\frac{3}{4}$	210	11,700	23.0
full	310	11,100	22.5

The B.t.u. per kw.-hr., with blast-furnace gas engines (Freyn, 1913), varies from 16,200 to 26,000, average 18,400; thermal efficiency 13.0 to 21.0 per cent., average 18.5.

520. Test of a 500-h.p. engine of the Borsig-Oechelhäuser 2-cycle type, on coke-oven gas (Junge, in *Power*) gave results as follows:

I.h.p.	B.t.u. per b.h.p.	Per cent. of i.h.p. to pumps	I.h.p.	B.t.u. per b.h.p.	Per cent. of i.h.p. to pumps
616	8,650	10.3	488	9,642	14.2
627	8,650	11.1	474	9,761	15.5
574	8,650	11.4			

521. Test of a 600-h.p. engine, Körting 2-cycle type, gave these results: b.h.p. 616; pump work, 11.2 per cent. of total; mechanical efficiency, 0.78; lb. of coal per b.h.p-hr., 0.787.

522. Thermal efficiency of gas engines is given in Par. 518 and 519 in connection with some of the tables. Further data is given as follows by Diederichs:

Engine	Fuel	B.h.p.	Thermal efficiency	Authority
Otto........	Illuminating gas.........	8	29.4	Meyer
Deuts......	Suction producer, low grade soft coal.	....	22.4	Meyer
Nürnberg...	Blast-furnace gas.........	750	24.6	Linde
Deuts......	Anthracite producer......	450	22.0	Josse
Güldner....	Suction anthracite producer.	29	23.2	Schroter

523. The overload capacity (Par. 515) is generally 10 to 20 per cent. more than the rated capacity. The maximum capacity is limited by the dimensions of the cylinder and not by a variable cut-off. Maximum economy occurs at or near, maximum capacity.

524. Governing is accomplished by hit-or-miss, throttling or quality methods. **Hit-or-miss governing** is arranged with a movable pick-blade operating the gas inlet valve; it is now used only for low-grade agricultural engines. **Throttle governing** is employed on a great many engines of small and medium size, and consists simply of restricting both the gas and the air intakes, so that the suction stroke pressure is lowered, a smaller charge is taken in, and compression is reduced. **Quality or cut-off governing** consists of throttling the gas supply only, as the load drops. In this way no reduction of suction pressure occurs, but a reduction of gas in the charge only. The compression pressure is unaltered. This method is the best of the three, being more efficient at light load than throttling, and allowing better regulation than hit-or-miss.

525. Operation of a gas engine requires the same care as a steam engine, and a higher maintenance. Power-station gas engines are started by compressed air in most cases, although motor starters have been employed. Special valve gear is thrown into service, and the engine runs for a revolution or two as an air engine. **Before starting,** (a) the load must be off, (b) ignition system inspected and made ready in the retarded position, (c) lubricating oil feeds turned on, (d) fuel shut-off valve opened and (e) cooling water turned on. Failure to start may be due to (a) faulty ignition, (b) very abnormal mixture, either too rich or too lean, (c) broken valve rods or (d) closed fuel connections. **Ignition** should be adjusted to give a fairly sharp rise at the average load conditions, and the mixture should be a little leaner than theoretical proportions—say 15 to 20 per cent. **Shutting down** is best accomplished by, (a) cutting off fuel supply, (b) cutting out ignition, if on battery, and placing set in "retarded" position, (c) oil feed stopped, (d) cooling water shut off and jackets drained.

526. The cost of gas engines is given by Fernald (Bull. 55, Bureau of Mines).

Total cost = 250 + 34.8(b.h.p.), for 40 h.p. to 2,000 h.p. (84)

A. A. Potter (*Power*, 1913) gives, for engines of 50 to 300 h.p., on illuminating gas. Total cost = 33.6 × b.h.p. − 115. (85)

The following figures are given by Stott, Pigott and Gorsuch, *Transactions* A.I.E.E., June, 1914. Horizontal producer-gas and natural-gas engines, 4-cycle tandem and twin-tandem, direct connected to 60-cycle generators, 200-2,000 kw. @ 80 per cent. power-factor delivered and erected.

$$\text{Average total cost} = 2{,}000 + 70\ (\text{kw.}) \qquad (86)$$

527. The maintenance and repair costs are approximately 42 per cent. to 55 per cent. of the net operating cost. For oil and supplies the cost is about double that of a steam plant.

528. Weight. The net weight of large tandem double acting types averages 680 to 740 lb. per kw. Moderate sizes of single-cylinder, single acting engines weigh from 200 to 300 lb. per b.h.p., the unit weight going up with the b.h.p.

PIPING

529. General requirements. As all pressures are light, standard pipe and fittings may be used throughout. **Expansion** must be provided for in the same manner as steam piping (Par. 369 to 372).

530. Gas piping from producer to scrubbers and purifiers should be cast iron with standard flanged joints, asbestos or metallic packing. In most cases it is advisable to line the piping between scrubber and producer with fire-brick. Explosion doors should be installed at intervals, and if the gas is dusty, ells should be replaced by tees where possible, to provide for raking and cleaning.

531. Water piping for supply to jackets, vaporizers and purifying apparatus may be of ordinary galvanized standard pipe. The discharge from scrubbers and purifiers is preferably of cast iron, on account of corrosive action.

532. Exhaust piping can be built of wrought-iron standard pipe, or cast-iron standard pipe; light riveted pipe is not advisable as it may collapse on the return wave of a muffler or exhaust pipe explosion. **Mufflers** for small engines are usually cast-iron pots; for large plants, concrete tunnels, with water in the bottom to cool and silence the exhaust, are frequently used.

533. The cost of piping varies from $5 to $9 per kw. of maximum rating of the plant, being much the same as for steam plants.

PLANT ECONOMY AND DESIGN

534. The auxiliaries to be considered in the engine room are: compressors for starting; exciter units and cooling water pumps; station lighting. In the producer room the auxiliaries are: the blowers or exhausters, as the case may be; power for rotating ash table, producer body, or mechanical pokers, if these are used; coal and ash handling apparatus; mechanical washers and tar extractors; scrubber and washer water-supply pumps.

535. The heat losses in a producer plant will be indicated by the following analysis. (Snell, "Power House Design.") Loss in producer and auxiliaries, 20 per cent.; loss in jacket water, 19 per cent.; loss in exhaust gases, 30 per cent., loss in engine friction, 6.5 per cent., loss in generator 0.5 per cent., total losses, 76 per cent., converted to electrical energy, 24 per cent.

536. The Willans line for the several main units should be plotted with kw. output and cu. ft. of gas as ordinates. On this curve should be superposed the gas used by auxiliaries, or if these are electric driven, their requirements should be subtracted from the gross output of the generators before plotting the Willans line. By taking the gas required at any load from this curve, and plotting for the load curve of the plant, the gas demand of the engine room is obtained. Similarly, an input-output curve for the producer can be drawn, between coal fired and gas generated; on this is superposed the gas or power demands of producer room auxiliaries and the standby coal. In conjunction with the engine-room gas demand curve, this gives the coal demand for the station under load.

537. Power for auxiliaries. The power required for the blower or exhauster will be from 1 to 2.5 per cent. of the total horse-power of the producer.

The horse-power requirements of washers are given in Par. 480. The coal and ash handling system will not usually require more than 0.2 to 0.4 per cent. of the total horse-power; compressor equipment, not over 0.1 per cent. The total power requirements of the auxiliaries will be about 5 per cent. The **standby losses** of a producer banked 14 hr. in 24 are about 1.5 to 2.0 per cent. of the total.

538. Water consumption per h.p., for the plant will run from 5 to 8 lb. per kw-hr., at the switchboard for non-recovery plants, and 40 lb. per kw-hr. for recovery plants, using cooling towers in both cases.

539. Vertical vs. horizontal engines. Design practice in plants up to 2,000 b.h.p. will allow vertical engines; these usually are not built over 750 to 1,000 h.p. per unit. Above this size only horizontal engines are used.

540. Ammonia recovery. It is not worth while to attempt the recovery of ammonia from bituminous plants of less than 2,000 b.h.p., and then only when the load factor is above 25 per cent. Each ton of coal produces approximately 100 lb. of sulphate of ammonia; the sulphuric acid required is about 1 to 1 in weight ratio to the sulphate of ammonia. In cities, the recovery plant is practically out of the question on account of space requirements. Extra labor, the acid tower, extra repairs and the cost of bagging the sulphate must be taken into account.

541. The floor space required is from 5 to 8 sq. ft. per kw., or 3 to 4 times the floor space for a turbine plant. The producer room requires from 15 to 4 sq. ft. per kw.

542. The load factor should be high for a successful gas plant. The gas engine is not well suited for heavily swinging loads partly on account of its lack of much overload capacity.

543. The subdivision of generating units should be the same as for a steam plant—six to eight units if possible. For small units, up to 400 b.h.p. one reserve unit in 5 or 6 is sufficient; but for large units (which have never been brilliantly successful), one in four is necessary for continuity of operation. The **reliability** of the gas engine is still open to much question in very large units, but the units of moderate and small size are as reliable as steam engines, if given the same grade of attention.

544. Labor required is usually one man per engine above 750 h.p. and one man to four or five producers of good size and equipped with mechanical apparatus for feed and stoking. About one man for 1,000 to 1,200 h.p. of engine, and one man per 2,000 to 2,500 h.p. of producer, represent the average.

545. Total plant cost. The following data is taken from the 1909 report of the N. E. L. A. on gas power plants.

360 to 2,700 kw. maximum rating

Item	Dollars per kw.		
	Maximum	Minimum	Average
Building	44	16	33
Producer equipment incl. piping	49	33	38
Gas engines	55	38	47
Foundations	....	....	5
Generators	15	12	14
Switchboards	....	....	3
Total	171	107	140

If the costs for gas engines given in Par. 526 are used, these totals will be from $10 to $20 higher.

TESTING

546. The essential mesurements for determining producer efficiency and capacity are:—(a) weight of coal per hr.; (b) proximate analysis, B.t.u. per lb. and moisture in coal; (c) cu. ft. of gas made; (d) temperature of gas, humidity; (e) calorific value and analysis. Additional data required for full information include: (f) weight of dry ash per hr.; (g) proximate analysis and B.t.u.; (h) wt. of steam per hr.; (j) wt. of vaporizer and scrubber water per hr., and temperatures; (k) h.p. required for blowers or exhausters and tar extractors or washers; (l) grains of dust per cu. ft. in gas.

For most purposes, only the efficiency of the producer itself is desired. For full details of tests, see Gas Power Committee reports, A. S. M. E.

547. The testing of gas engines is very similar to that of steam engines. The essential data are: (a) i.h.p.; (b) b.h.p. or kw. output and generator efficiency; (c) r.p.m.; (d) explosions per min., if hit-or-miss governed; (e) cu. ft. of gas per min.; (f) calorific power of gas per cu. ft. Desirable additional data include: (g) jacket water per hr.; (h) inlet and outlet jacket water temperatures; (i) gas, air and exhaust temperatures; (k) amount of lubricant. All physical dimensions of the engine should of course be taken.

548. The essential data for a plant test consist of kw.-hr. output at switchboard and coal used in producers; or cu. ft. of gas and calorific power, if coke oven, blast-furnace, natural, or illuminating gas is used.

549. For gas measurement the gas meter is chiefly used; the method of measuring the fall of a gas holder for volume should never be employed as the change of temperature ordinarily possible, entirely vitiates the accuracy. The Venturi meter furnishes an accurate and inexpensive measuring device if properly handled and kept clean in the throat.

550. Indicated h.p. is obtained by the usual indicator, but equipped with 0.5 in. area piston for this work.

551. The calorific value of gas can be obtained by the Junkers or other make of gas calorimeter. **Grains of dust per cu. ft.** are obtained by a special filter apparatus and test gas meter; the dust of a measured quantity of gas is collected and weighed. **Other measurements** are similar to those for steam engines (Par. **427**).

552. The duration of test should be about the same as for engine and boiler tests generally. For Venturi readings, a record is best, or very frequent readings, say once a minute. The producer test should preferably not be less than 24 hr. except with small producers intended for intermittent use; the longer the test the better.

553. For full calculation of results the heat balance is required. The reports of the gas power committee, A. S. M. E., furnish full data for the elaborate tests.

OIL POWER PLANTS

BY REGINALD J. S. PIGOTT

OIL ENGINES

554. The thermodynamics of the explosion cycle (Otto) type of oil engine are exactly the same as for gas engines (Par. **495** to **506**). **The constant-pressure cycle** (Brayton cycle), of which the **Diesel** is the principal example, has slightly different events. For the **four-cycle type,** the inspiration and compression strokes are the same, but are made upon air only; at the end of compression, the oil fuel is injected, and burned, in such a way as to maintain a practically constant pressure during the early part of the working stroke. Expansion and exhaust then follow as in the gas engine.

555. Thermodynamic equations. For the air card, or ideal cycle p_b, t_b, and v_b are obtained as for the Otto cycle. Par 497 to 501., when burning fuel at constant pressure:

$$p_c = p_b \qquad (87) \qquad\qquad p_d = \left(p_c \frac{v_c}{v_d}\right)^{1.41} \qquad (91)$$

$$t_c = t_b\left(1+\frac{Q_1}{c_p\, t_b}\right) \qquad (88)$$

$$v_c = v_b\,\frac{t_c}{t_b} \qquad (89)$$

$$v_d = v_c \qquad (90)$$

$$t_d = t_a\frac{p_d}{p_a} \qquad (92)$$

$$Q_2 = C_v(t_d - t_a) \qquad (93)$$

$$E = \frac{Q_1 - Q_2}{Q_1} \qquad (94)$$

where p_a, p_b, p_c, p_d = inspiration, compression, combustion and release pressures, respectively, in lb. per sq. ft.; v_a, v_b, v_c, v_d = volumes in cu. ft. at beginning of compression, end of compression, end of combustion or beginning of expansion, respectively; t_a, t_b, t_c, t_d = absolute temperatures, at the same points in deg. Fahr.; Q_1 = heat added per lb. of gases, in B.t.u.; Q_2 = heat abstracted per lb. of gases in exhaust, in B.t.u.; E = thermal efficiency; C_v = specific heat at constant pressure.

556. The thermal efficiency would be the same as for the Otto cycle, if complete expansion occurred for the same compression pressures. But as expansion is always incomplete, the efficiency is less; this is more than offset by the much higher compression possible with the Diesel cycle.

557. Types. The types are the same as for gas engines; see Par. **502** and **503**.

558. Mean effective pressure of the Diesel type is given by

$$\text{M.e.p} = J\,\frac{[Q_1 - C_v t_a(Y^{1.41} - 1)]}{144\, v_a\left[1 - \dfrac{p_a}{p_b}^{0.71}\right]} \qquad (95)$$

$$Y = 1 + \frac{Q}{C_p t_a} \qquad (96)$$

where J = Joule's equivalent, 777.5; C_v and C_p = specific heat at constant volume and constant pressure, respectively; t_a, v_a, p_a, p_b are the same as in Par. **554**.

Lucke gives the following usual m.e.p.

Kerosene		Gasolene	
Absolute compression pressure	Observed m.e.p.	Absolute compression pressure	Observed m.e.p.
46	40	66	106
63	69	70	75
65	68	75	100
68	40	86	70
70	72	86	72
50	35	95	60
55	85	..	..

559. Speed and power. The speed is the same as for gas engines of the same power (Par. **511**). For indicated and b.h.p. see Par. **512**.

560. Kerosene engines of the Mietz and Weiss and Hornsby-Akroyd types are built in sizes up to 250 h.p. and operate in the same general manner as gas engines, the fuel being pumped in and vaporized in a hot tube, hot bulb, or vaporizing chamber. The hot tube and the hot bulb are kept warm by being left unjacketed, and by the combustion of a portion of the charge in the hot bulb chamber. Compression forces up the temperature of the charge enough for ignition to take place. Kerosene engines are the least efficient of the oil engines.

561. Gasolene engines are practically unused for power-station purposes, on account of expensive fuel, and low relative economy.

562. The crude oil engine is arranged like the kerosene engine, except that more careful arrangements must be made for preheating the oil for vaporization, and in most cases, the air also. Exhaust gas jackets are generally used for the purpose of providing the necessary heat.

563. The Diesel engine is now the most important of the oil engines on account of its remarkable efficiencies. It is built in both two-cycle and four-cycle types, and practically always vertical, single acting. It requires separate compressed-air starting sets, at about 1,000 lb. per sq. in. pressure. In the two-cycle type, separate air pumps (cylinders driven from the cross-head) are employed, as well as the fuel pump, which is always necessary.

564. Weights. The Diesel and the Junkers engines are the heaviest of prime movers, running from 400 to 600 lb. per b.h.p. The enormous weight is due chiefly to the heavy pressures, 500 lb. per sq. in. being an ordinary compression, with safe design allowance up to 1,000 lb. per sq. in. to safeguard against breakage due to preignition.

565. The capacity of oil engines is based on cu. ft. of cylinder displacement, as for gas engines (Par. 515).

566. Builders' rating. Ulbricht and Torrance (*Power*, 1912) give average practice in builders' rating (for oils and distillates), as

$$\text{b.h.p.} = \frac{d^2\, ln}{21,875} - 0.75 \qquad (97)$$

where d = cylinder diameter, in in; l = stroke in in. n = r.p.m. The rating is about 10 to 20 per cent. less than the ultimate capacity.

567. The fuel consumption is poorest for the gasolene and kerosene engines, running from 13,000 to 15,600 B.t.u. per b.h.p.-hr.; 9,400 to 10,000 B.t.u. per b.h.p. hr., for American Diesel engines. The German Diesel and Junkers engines run as low as 7,100 to 8,500 B.t.u. per b.h.p.-hr. All figures are for full load. These figures correspond to 0.65 to 0.78 lb. of gasolene or kerosene per b.h.p.-hr.; 0.48 to 0.52 lb. of oil for American Diesels; 0.37 to 0.44 for German Diesel and Junkers Engines. Fuel consumption decreases with size.

568. Test of Falk kerosene oil engine (H. D. Wile, Elec. World, 1913)

Cooling water, lb. per hr.	632	445	391	244
Inlet temperature, deg. Fahr.	47.5	44	71	47.5
Outlet temperature, deg. Fahr.	106	123	157	182
Rev. per min.	448	448	449	446
B.h.p.	9.05	9.05	8.73	9.05
Indicated h.p.	11.04	11.31	10.65	11.84
Mechanical efficiency, per cent.	82	80	82	76
Kerosene, lb. per b.h.p.-hr.	1.14	1.09	0.98	1.0
Thermal efficiency	11.2	11.7	13.1	12.8

Angle ignition, deg.	34	38	41
Rev. per min.	446	450	442
B. h.p.	8.73	9.05	8.73
Indicated h.p.	11.7	10.65	12.0
Mechanical efficiency	77	82	75
Kerosene, lb. per b.h.p.-hr.	0.97	0.98	0.95
Thermal efficiency	13.2	13.1	13.4

Mixed water-kerosene, per cent.	34.4	62.8	85
Rev. per min.	442	440	444
B.h.p.	8.7	8.7	8.7
Indicated h.p.	12.3	11.7	11.4
Mechanical efficiency	71	74	76.7
Kerosene, lb. per b.h.p.-hr.	1.06	1.14	1.19
Thermal efficiency	12	11.1	10.5

B.h.p.	4.2	5.5	7	8.73	10.3	11.9
Indicated h.p.	6.4	7.5	9.17	11.2	12.5	14.38
Rev. per min.	457	457	450	448	437	436
Mechanical efficiency	66	74	76	77	82.5	82.8
Cooling water, lb. per hr.	236	290	306	262	309	304
Kerosene, lb. per b.h.p.-hr.	1.55	1.26	1.05	0.93	0.87	0.94
Thermal efficiency	7.3	10.1	12.1	13.8	14.7	13.6
Maximum pressure, lb. per sq. in.	68	94	124	170	206	242

$$\text{Total cost} = 141 + 24.8 \text{ (b.h.p.)} \qquad \text{(dollars)} \qquad (98)$$

Gasolene, up to 75 h.p., throttle governed,

$$\text{Total cost} = 309 + 36.1 \text{ (b.h.p.)} \qquad \text{(dollars)} \qquad (99)$$

Oil engines, up to 400 h.p.,

$$\text{Total cost} = 63.8 \text{ (b.h.p.)} - 316 \qquad \text{(dollars)} \qquad (100)$$

Diesel engines, from 100 to 1,000 h.p., approximately (price varies very widely),

$$\text{Total cost} = 58.0 \text{ (b.h.p.)} + 2{,}000 \qquad \text{(dollars)} \qquad (101)$$

Stott, Pigott, and Gorsuch, A.I.E.E. *Proceedings*, June, 1914, give 95.00 per kw. for all sizes of Diesel engines. This is due to the fact that weight per kw. *increases* with size.

576. Test of a low-compression heavy oil engine. (A. A. Potter and W. W. Carlson, *Elec. World*, 1913)

Cylinder diameter, in.	16 ⅛
Length of stroke, in.	24
Kind of fuel	Solar oil
Specific gravity at 60 deg. Fahr.	0.8145
Deg. Beaumé	42.0
Lb. per gal	6.79
Heat units per lb., high	17,240
Heat unit per lb., low	16,322
Heat units per gal	117,100

Data and results	Number of test		
	1	2	3
Duration of heat, hours	3	1	1
Barometer, in.	26.95	26.94	26.95
Speed of engine, rev. per min.	183.5	201.2	202.0
Mean effective pressure	75.9	37.1	27.50
Indicated h.p.	85.6	45.5	34.0
B.h.p: Average	73.5	39.70	20.2
Mechanical efficiency, per cent	85.8	87.4	59.4
Fuel used, total lb.	222.75	50.1	42.55
Fuel used per i.h.p. per hour, lb.	0.868	1.10	1.20
Fuel used per b.h.p. per hour, lb	1.010	1.26	2.1
Heating value of fuel consumed:			
Per b.h.p. per hour, b.t.u.	17,400	21,750	36,200
Temperature of cooling water, deg. Fahr.			
Inlet	82.25	79.0	84.25
Outlet	164.0	133.0	125.55
Rise	81.75	54.0	41.2
Cooling water used per hour:			
Total, lb.	1,775	2,868	2,712
Per b.h.p., lb	24.2	72.2	134.2
Thermal efficiency, per cent.	14.62	11.7	7.0

Heat distribution per lb. of fuel	1		2		3	
	B.t.u.	Per cent.	B.t.u.	Per cent.	B.t.u.	Per cent.
Converted into i.h.p.	2,935	17.0	2,315	13.4	2,036	11.30
Converted into b.h.p.	2,520	14.26	2,020	11.7	1,210	7.01
Friction and losses	415	2.40	295	1.7	826	4.79
Losses in jacket water	1,955	11.32	3,090	17.9	2,635	15.28
Losses in exhaust, radiation, etc.	12,350	71.68	11,835	68.9	12,569	73.42

577. The cost of piping for oil plants, per installed kw., ranges from $0.50 to $1.70.

PLANT DESIGN

578. General. What has been given in Par. 394 to 414 can be applied in principle to the oil plant. But inasmuch as the only auxiliaries are the exciters, jacket pumps and air compressors for starting, the problem is much simpler, and the economy of the plant is much more nearly that of the main unit.

579. Plant costs. The buildings will cost from $10.00 to $24.00 per kw., as no producer room or boiler room is required. The oil storage tanks require approximately 0.06 to 0.08 gal. capacity per kw. and cost from $3.00 to $6.00 per kw. of rated capacity. All other auxiliaries, including crane, oil pumps, air compressor and compressed air tanks, cost from $2.50 to $5.00 per kw. of rated capacity, installed. The total costs will range as follows, per kw.:

	High	Low
Diesel engine	$100.00	$95.00
Building	24.00	10.00
Tanks	6.00	3.00
Auxiliaries	5.00	2.50
Piping	1.70	0.50
Totals	136.70	111.00

There are no plants in this country much larger than 1,500 kw. in total capacity.

TESTING

580. The testing of oil engines is exactly similar to the testing of gas engines, except that weight of oil per hr. is substituted for cu. ft. of gas per min. All other data and instruments required are the same.

POWER PLANT BUILDINGS AND FOUNDATIONS

BY REGINALD J. S. PIGOTT

581. The building housing any kind of power plant should be entirely fireproof. In many cases, no fire insurance is carried, and therefore all wood and other unnecessary combustible should be kept out of the structure.

582. The approved constructions are: (a) Steel structure, brick walls, concrete, slate or tile roof. For small low-grade plants corrugated iron may be employed to a very limited extent. (b) Steel framework, walls and roof concrete. (c) Reinforced concrete throughout. Type (c) is exploited chiefly in the hydroelectric plants; type (a) is the most widely employed. Concrete **foundations,** for all work, are practically universal.

583. The general arrangement of engine rooms in the older plants and in the most modern, is parallel to the boiler room. About 8 years ago the sudden increase in capacity of the turbine without much increase in size made the use of cross firing aisles necessary, to get in enough boilers. But the underfeed stoker has so increased the forcing capacity of the boiler that this is now unnecessary.

584. In gas-producer plants, the producer room is generally arranged parallel to the engine room, although it may be entirely separate and some distance away, as in some recovery plants.

585. The coal bunkers in larger power plants are of steel framing with concrete arch lining. For moderate size plants, and for outdoor bunkers for producer plants, the suspended type, catenary-curve bunker is widely used; also steel with concrete lining. Hoppers and chutes for coal, are made of plate steel or cast iron; ash hoppers, of plate steel lined with red brick, or reinforced concrete.

586. Brickwork for power-station buildings varies about as given below.

Heavy basement work, labor cost only	$7.00 to $9.00 per M.
18 in. walls	8.00 to 10.00 per M.
13 in. walls	9.00 to 11.00 per M.
18 in. wall, faced on one side with pressed brick	12.00 to 14.00
18 in. wall, faced on both sides with pressed brick	16.50 to 19.00
13 in. wall, faced on one side with pressed brick	14.00 to 17.00

This is for straight wall work. For work much cut up by windows and corners, these prices must be increased. Common red brick costs about $8.00 per M delivered in or near cities.

587. Concrete. Taylor and Thompson give the following approximate cost for concrete:

Item	Per cubic yard	
	Range	Average
Mass foundations	$4.00 to 6.00	$7.00
Conduits and sewers	5.00 to 16.00	9.50
Tunnels, subways	6.00 to 42.00	15.00
Reinforced retaining walls	12.00 to 15.00	13.50
Reservoirs, filters	6.00 to 23.00	10.50
Tanks, standpipes	4.00 to 20.00	12.00
Buildings, total structures	8.00 to 26.00	14.00
Walls in building construction	12.00 to 25.00	17.50
Encasing structural steel in concrete	14.00 to 21.00	18.50
	Per linear ft.	
Concrete piles	0.51 to 1.60	1.15

588. Structural steel for building purposes costs from $55 to $120 per ton, erected. For any amount over 200 tons, it should not ordinarily exceed $65 per ton.

589. Building foundations are made almost exclusively of mass concrete (Par. 587).

590. The bearing power of soils for computing the proper spread of footings is given below.

Soil	Tons per sq. ft.	Remarks
Good solid natural earth	4.0	New York Building Laws
Pure clay, 15 ft. with no admixture of foreign substances except gravel.	1.75	Chicago Building Ordinances
Dry sand, 15 ft. thick, no admixture of foreign substances.	2.0	Chicago Building Ordinances
Clay and sand mixed	1.5	Chicago Building Ordinances
Hard rock on native bed	2.50	Richey
Ledge rock	36.0	Richey
Hard-pan	8.0	Richey
Gravel	5.0	Richey
Clean sand	4.0	Richey
Dry clay	3.0	Richey
Wet clay	2.0	Richey

591. For making concrete in any quantity, machine mixing always pays, both in first cost and in reliable quality. **Form work** is usually of 1.25-in. tongued and grooved, short-leaf yellow pine lumber dressed one side, with 2 in. x 4 in. rough spruce or yellow pine studs and bracing for the greater part; 4 in. x 4 in. studs, and larger, are used only where necessary.

592. Loads on Foundation

(Chicago Building Ordinances)

Foundation	Tons per sq. ft.	Foundation	Tons per sq. ft.
Concrete	4.0	Iron rails in concrete	6.0
Foundation piers, dimension stone.	5.0	Steel rails in concrete	8.0
Brick piers in cement	9–12.5	Piles	12.0

593. Machinery foundations are generally of mass concrete, as for buildings. But lately the demands for condenser and auxiliary space under steam turbines have forced the use of **structural steel foundations.** There is no objection objection to this, provided the turbine is properly balanced and the maximum permissible deflection of about 0.02 in. is not exceeded. Foundations should extend up to 1 in. or ¾ in. below the bottom line of the machine base to be set; and when the latter is lined up, the whole should be grouted with cement grout, mixed 1 : 2, of cement and sand. **Foundation bolts** are now seldom set from templates, but are accurately located in the forms by drawing dimensions. Each bolt is mounted in a pipe sleeve large enough to allow a play of at least one diameter for taking care of inaccuracies in the casting and in the setting. With some turbines, no bolts whatever are needed.

594. Drainage should if possible be arranged for by placing the whole station above sewer or tide-water level, so that gravity flow from sumps and traps is possible. Where this cannot be done, suitable reservoir sumps must be provided, emptied by ejectors or pumps, float controlled. Galvanized iron or cast-iron roof leaders may be employed, with cast-iron soil pipe in the ground, or glazed clay tile pipe.

595. Lighting and ventilation. The use of all-glass monitors is the most desirable way of lighting and ventilating plants. The rolled steel section windows and monitors now produced have rendered easy the problem of fireproof, permanent window and ventilator fixtures. The operating devices should be arranged for quick opening and closure, to provide for storm protection. The continuous sash for monitor use is the latest device in this line. Care should be taken to make windows rain- and snowproof, and to allow opening for ventilation without letting in rain during ordinary storms.

596. Lighting by daylight is accomplished by the monitors above mentioned and by high side windows in some cases. The night illumination in most cases is by incandescent lamp. The arc and Nernst lamps are generally underairable; the mercury vapor lamp is very successful where used, and is the least injurious to eyesight, but there is much general objection to the color of the light. The usual demand for illumination in a power station will take from 0.2 to 0.5 per cent. of the output.

597. Fire risks in well constructed plants are exceedingly low; in many of the largest plants, no insurance against fire is carried. The use of wood roofs or other inflammable structures, makes insurance imperative.

598. The cost of buildings for various types of power plant is given in Par. **412**, **545** and **579** per kw. of capacity. The cost per cu. ft. of contents is less variable, and runs from $0.20 to $0.35.

HYDRAULIC POWER PLANTS

BY ARTHUR T. SAFFORD

Consulting Hydraulic Engineer, Member, American Society of Civil Engineers, Member, American Society of Mechanical Engineers

HYDRAULICS

599. Pressure and depth. Water is but slightly compressible, therefore the pressure, P, is for all practical purposes directly proportional to the depth, H, and can be represented by a diagram as shown in Figs. 46 to 49.

The total pressure on any submerged surface is equal to the area of the pressure diagram (*abc*, Fig. 46; *decb*, Figs. 47 and 48) and the centre of pressure passes through its centre of gravity, G, perpendicular to the submerged surface. The moment of the pressure about c is (Fig. 49),

$$M = Py \qquad \text{(ft-lb.)} \qquad (102)$$

The pressure in lb. per sq. in. at any point is

$$p = 0.433 \times \text{Depth} \qquad (103)$$

The pressure is always normal to the submerged surface. **The total pressure exerted on a submerged body is**

$$P = 62.4HA \qquad \text{(lb.)} \qquad (104)$$

wherein H is the depth of water in feet over the geometrical centre of the body and A is the area of the surface in sq. ft.

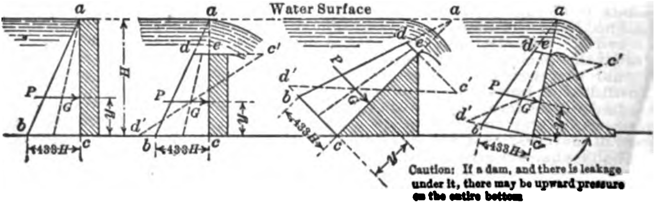


FIG. 46. FIG. 47. FIG. 48. FIG. 49.

600. Possible upward pressure under dams. If the structure is a dam and there is leakage under it there may be upward pressure over the entire bottom. If there is no leakage then there will be no upward pressure. The truth in any given case probably lies between these two extremes and the foundations and underlying material must be carefully studied to make a proper design.

601. The dynamic properties of water in motion are theoretically the same as those of falling bodies *i.e.*:

$$V = \sqrt{2gh} = 8.02\sqrt{h} \qquad \text{(ft. per sec.)} \qquad (105)$$

where $g = 32.16$.

Actually this formula is rarely exact and expressions based upon it must be modified by empirical coefficients.

602. The quantity of water passing a given point in a unit of time is equal to the product of the net cross-sectional area taken perpendicular to the line of flow and the mean velocity in that time parallel to the line of flow. This may be expressed by the equation

$$Q = AV \qquad \text{(sec-ft.)} \qquad (106)$$

If A is the area in square feet, V the velocity in feet per second, then Q is the quantity in cu. ft. per sec., or, in its briefer form, second-feet. This in the United States is now the common expression in water-power practice for flow of streams, capacity of canals and raceways and discharge of water-wheels.

603. At every section of a continuous and steady stream the total energy is constant; whatever head is lost as pressure is gained as velocity. This is known as **Bernoulli's theorem**, and in terms of head can be expressed as follows: Total head = velocity head + pressure head + head due to elevation = constant; or in every stream section,

$$H_T = h_v + h_p + h_e = \frac{V^2}{2g} + \frac{p}{y} + h_e \qquad \text{(ft.)} \qquad (107)$$

where y is the constant to reduce lb. per square inch to head in feet, or 0.433.

In order to make this equation of practical application, a term representing the head lost in overcoming friction, h_λ, must be added on the right-hand side of the equation. This formula, properly modified to include the effect of frictional resistances, is the basis of all empirical formulas for the flow of water.

604. Power and energy. The potential energy of water held in reserve is its weight multiplied by the net available distance through which it can fall in the performance of work. As power expresses the rate of doing the work, it is convenient to deal with the flow of water in cu. ft. per sec. falling through a given vertical distance in feet. Power $= 62.4QH$ ft-lb. per sec., where Q is the flow in cu. ft. per sec., and H the vertical distance or "head" in feet and 62.4 is the weight in pounds of 1 cu. ft. of water.

$$\text{Horse-power} = \frac{62.4QH}{550} = \frac{QH}{8.8} \qquad (108)$$

This is the maximum horse-power that might be obtained from Q cubic feet of water per second falling a distance H feet, assuming an efficiency of transformation of energy of 100 per cent. This expression multiplied by the known efficiency of a water wheel will give the power at the water-wheel shaft. Ordinarily $QH/11$ or $QH/12$ will give approximately the net water horse-power, corresponding respectively to efficiencies of 80 per cent. and 73.3 per cent.

FLOW FORMULAS

605. Orifices employed as meters, are limited in use; experimentally they have given very consistent results, but in practice these results often cannot be reproduced with sufficient accuracy for precise work. Orifices of relatively small sizes, of regular shapes (usually round or rectangular), with carefully made edges, and used with full contraction of the jet, have been carefully experimented upon and may be used with confidence provided there is practically no velocity of approach (less than 0.5 ft. per sec.).

606. The flow of water through an orifice (Fig. 50) in a vertical wall expressed in cubic ft. per sec. is

$$Q = CAV = CA\sqrt{2gh} \quad \text{(cu. ft. per sec.)} \qquad (109)$$

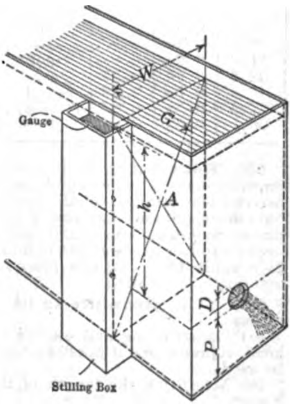


Fig. 50.—Circular orifice with sharp edges, giving full contraction.

where A is the area of the opening in square feet, h the head in feet measured from the surface of the water to the center of the opening, and C is the coefficient of discharge which depends on the form of the orifice. For sharp-edged orifices, 4 sq. ft. or less in area, with full contraction of the issuing stream (Fig. 50), discharging under heads from about 1 to 20 times the depth of the orifice (practically no velocity of approach), a value of C may be taken as 0.6. If the orifice is large and the head acting is small, the exact or integral form of the equation* must be used when C is taken as 0.6. For high heads and relatively small orifices this is not necessary. If the contraction is even partly suppressed the results are unreliable; if wholly suppressed the orifice becomes a short tube or nozzle and the coefficient varies greatly, depending on the shape and proportions; but always more than 0.6 (see Par. 635).

607. In treating head gates and sluice gates as orifices, the forms of cross-section, the channel of approach and that leading away from the orifice, and the velocity of approach are all very important; these factors modify any computed discharge based upon the opening and observed head.

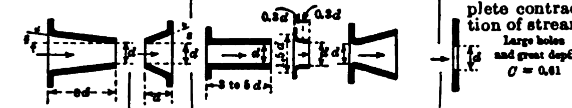
* Water Supply and Irrigation Paper No. 200.

The coefficient of discharge for gates on the basis of their cross-sectional area and the head measured above and below them may vary all the way from that of a standard sharp-edged orifice (0.6) to over 1.0 if there is much velocity of approach. For these reasons, if head gates or sluice gates are to be used as measuring devices they should be given their own rating by some independent method of measurement.

608. Weisbach's Coefficients

$$C \text{ in } Q = C\frac{\pi d^2}{4}\sqrt{2gh} \qquad (109A)$$

wherein C is a coefficient which depends on the form and head h acting on orifice, Q is given in cubic feet per sec. when h and d are measured in feet; h is head in feet above centre of orifice; and d is diameter of orifice in feet.



Thin plate orifice and complete contraction of stream

S. deg.	C	C	Inlet slightly round C=0.90	Depending upon smoothness surface C=0.96 to 0.99	Depending on the length and velocity C=0.96 to 1.5	d	h=1.148 C	h=1.969 C
0.	0.97	0.54						
5.75	0.95	......						
11.25	0.92	......	Inlet very round C=0.97			0.0144	0.68	0.66
22.5	0.90	0.55				0.0328	0.64	0.63
45.	0.75	0.58				0.0656	0.63	0.62
67.5	0.68	0.60				0.0984	0.62	0.61
90.	0.63	0.63				0.1312	0.614	0.607

609. Weirs,* if properly constructed and used with faithful regard to reproducing the exact conditions which obtained when the experimenter derived his formula, should give good results. Some extraordinary results have been obtained because these precautions were not observed; and weir measurements unless standardized will gradually lose their hold. A weir installation in a power plant must necessarily cut down the available head by roughly 3 ft. For this reason the weir should be used only for testing, and not for operating.

610. "The procedure to be followed in weir measurements comprises:†

(*a*) Constructing and setting up the weir and the gage for measuring the head; reproducing, if possible, the experimental conditions of the formula to be used.

(*b*) Measuring the length of the crest and determining its irregularities if any.

(*c*) Taking a profile of the crest if not sharp-edged.

(*d*) Determining by actual measurements the cross-sectional area of the channel of approach.

(*e*) Establishing by leveling the relative elevations of the crest of the weir, and the zero of the gage.

(*f*) When the desired regulation of flow is established, determining the head by hook gage or other observations at intervals as frequent as the conditions require.

* For the most extended compilation and examination of existing weir data Water Supply and Irrigation Paper No. 200 (Weir Experiments, Coefficients, etc., by R. E. Horton) should be consulted.

† Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911, page 196.

(*g*) If possible, measure the actual velocity in the channel of approach by a current meter or some other direct method; and

(*h*) Compute the discharge by the formula selected. Three of these operations require especial consideration, viz.: construction and setting, the measurement of the head, and the selection of the formula."

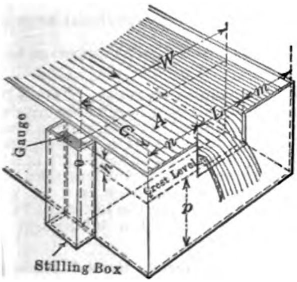


Fig. 51.—Weir with end contractions.

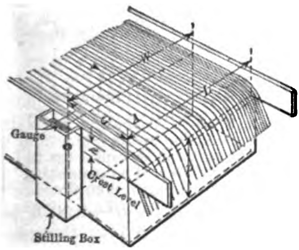


Fig. 52.—Weir with end contractions suppressed.

611. "Construction and setting of weirs.* In order to eliminate as far as possible factors for which precise allowance cannot be made, the construction and setting should meet the following conditions:

(*a*) A sharp-crested weir with complete crest contraction should be used.

(*b*) The crest should be level, and its ends vertical.

* Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911.

612. Standard Weir Formulas (Par. 613 to 621)

Experimenter	Formula (cu.ft. per sec.)	Limits of head recommended (ft.)	Distance of crest above bottom (ft.)	Correction for end contraction	Correction for velocity of approach: Suppressed weir	Correction for velocity of approach: Contracted weir
Fteley & Stearns	$Q=3.31L\sqrt{H^3}+0.007L$	0.07 to 0.50	At least 2.0	$L=\left(L-\frac{NH}{10}\right)$ *	$H=(h+1.50h_v)$	$H=(h+2.05h_v)$
Francis	$Q=3.33L\sqrt{H^3}$	0.50 to 2.00	At least 3 times the observed head	$L=\left(L-\frac{NH}{10}\right)$	$\sqrt{H^3=(h-h_v)^3-h_v^3}$	....
Hamilton Smith	$Q=(C_e \text{ or } C_s)\frac{2}{3}L\sqrt{2gH^3}$	0.10 to 1.70	At least 3 times the observed head	Use proper coefficient	$H=(h+1-\frac{1}{3}h_v)$	$H=(h+1.4h_v)h_v$
Bazin**	$Q=mLh\sqrt{2gh}$	0.20 to 2.00	....	....	....	....

* Fteley & Stearns found that in this expression $\frac{H}{10}$ was not constant but varied with perfect contraction from $0.061H$ to $0.124H$, H being equal to $(h + \alpha h_v)$; α being equal to 1.5 and 2.05 according to form of weir.

** *For suppressed weirs only.* m being a coefficient including effects of crest contraction and velocity of approach.

(c) The end contractions should be complete, or, if suppressed, entirely suppressed.

(d) The upstream face should be vertical; the downstream face so designed that the nappe has free overfall.

(e) Free access for air under the nappe should be made certain.

(f) The weir should be set at right angles to the direction of flow.

(g) The channel of approach should be straight for at least 25 ft. above the weir, of practically uniform cross-section and of slight slope (preferably none).

(h) Screens of coarse wire or baffles of wood should be set in the channel, if necessary, to equalise the velocities in different parts of the channel, but not nearer the crest than 25 ft.

(i) The channel of approach should have a large cross-sectional area in order to keep the velocity of approach low."

A weir with complete end contractions is shown in Fig. 51; suppressed end contractions are shown in Fig. 52.

613. Francis formulas. The best known formulas are those of James B. Francis and M. Basin. The Francis formulas are strictly applicable only to **vertical, sharp-crested weirs** with free overfall and either with no end contractions ("suppressed weir"), or with complete end contractions and: (a) when the length of the weir is at least 5 ft.; (b) when the head (H) is not greater than one-third the length (L); (c) when the head is not less than 0.5 ft. nor more than 2 ft.; (d) when the velocity of approach is 1 ft. per second or less; (e) when the height of the weir crest above the bottom of the channel of approach is at least three times the head. For tabulation of standard formulas see Par. 612.

614. Smith's formulas. For **short weirs** (shorter than 5 ft.) the experiments and studies made by Hamilton Smith, Jr., afford the best guide (See Smith's weir coefficients, Par. 620).

615. Bazin's formula. The best weir experiments abroad are those of M. Basin whose general formula is $Q = mLh\sqrt{2gh}$ for suppressed weirs only. At about 1.0 ft. depth on the crest, with no velocity of approach, the results from his standard 8.56-ft. (2-meter) weir are practically those of James B. Francis' standard 10-ft. weir (See Par. 621).

616. Fteley and Stearns' formula. For heads from 0.07 to 0.5 ft. the Fteley and Stearns formula* $Q = 3.31L\sqrt{H^3} + 0.007L$ is recommended.

617. Weir discharge tables. The following table of discharges for weirs without end contractions, and velocity head is given for heads from 0.00 to 2.98 ft. and includes figures from the Fteley and Stearns formula up to 0.5 ft. and the Francis formula from 0.5 ft. to 2.98 ft. The quantity of water is given in cu. ft. per sec., per foot of weir, with complete contraction on the crest, and no end contractions. $Q = 3.31L\sqrt{H^3} + 0.007L$ for depths up to 0.5 ft. and $Q = 3.33L\sqrt{H^3}$ for depths above 0.5 ft.; the velocity due to the head is computed by formula, Vel. $= \sqrt{2gh}$.

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* Fteley and Stearns, in "Sudbury River Experiments" (page 84) state that this formula is based upon experiments in which the depths on the weir ranged from 0.07 to 1.63 ft. *Trans.* Amer. Soc. Civil Eng., Vol. XII.

H (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)	*H* (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)	*H* (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)
0.00	....	....	0.50	1.18	5.67	1.00	3.33	8.02
.02	.02	1.13	.52	.25	5.78	.02	.43	8.10
.04	.03	1.60	.54	.32	5.89	.04	.53	8.18
.06	.06	1.96	.56	.39	6.00	.06	.63	8.26
.08	.08	2.27	.58	.47	6.11	.08	.74	8.33
0.10	0.11	2.54	0.60	1.55	6.21	1.10	3.84	8.41
.12	.14	2.78	.62	.63	6.32	.12	.95	8.49
.14	.18	3.00	.64	.70	6.42	.14	4.05	8.56
.16	.22	3.21	.66	.79	6.52	.16	.16	8.64
.18	.26	3.40	.68	.87	6.61	.18	.27	8.71
0.20	0.30	3.59	0.70	1.95	6.71	1.20	4.38	8.79
.22	.35	3.76	.72	2.03	6.81	.22	.49	8.86
.24	.40	3.93	.74	.12	6.90	.24	.60	8.93
.26	.45	4.09	.76	.21	6.99	.26	.71	9.00
.28	.50	4.24	.78	.29	7.08	.28	.82	9.07
0.30	0.55	4.39	0.80	2.38	7.17	1.30	4.94	9.14
.32	.61	4.54	.82	.47	7.26	.32	5.05	9.21
.34	.66	4.68	.84	.56	7.35	.34	.16	9.28
.36	.72	4.81	.86	.66	7.44	.36	.28	9.35
.38	.78	4.94	.88	.75	7.52	.38	.40	9.42
0.40	0.84	5.07	0.90	2.84	7.61	1.40	5.52	9.49
.42	.91	5.20	.92	.94	7.69	.42	.63	9.56
.44	.97	5.32	.94	3.03	7.78	.44	.75	9.62
.46	1.04	5.44	.96	.13	7.86	.46	.87	9.69
.48	.11	5.56	.98	.23	7.94	.48	6.00	9.76
1.50	6.12	9.82	2.00	9.42	11.34	2.50	13.16	12.68
.52	.24	9.89	.02	.56	11.40	.52	.32	12.73
.54	.36	9.95	.04	.70	11.46	.54	.48	12.78
.56	.49	10.02	.06	.85	11.51	.56	.64	12.83
.58	.61	10.08	.08	.99	11.57	.58	.80	12.88
1.60	6.74	10.14	2.10	10.13	11.62	2.60	13.96	12.93
.62	.87	10.21	.12	.28	11.68	.62	14.12	12.98
.64	.99	10.27	.14	.42	11.73	.64	.28	13.03
.66	7.12	10.33	.16	.57	11.79	.66	.45	13.08
.68	.25	10.40	.18	.72	11.84	.68	.61	13.13
1.70	7.38	10.46	2.20	10.87	11.90	2.70	14.77	13.18
.72	.51	10.52	.22	11.01	11.95	.72	.94	13.23
.74	.64	10.58	.24	.16	12.00	.74	15.10	13.28
.76	.77	10.64	.26	.31	12.06	.76	.27	13.32
.78	.91	10.70	.28	.46	12.11	.78	.43	13.37
1.80	8.04	10.76	2.30	11.61	12.16	2.80	15.60	13.42
.82	.18	10.82	.32	.77	12.22	.82	.77	13.47
.84	.31	10.88	.34	.92	12.27	.84	.94	13.52
.86	.45	10.94	.36	12.07	12.32	.86	16.11	13.56
.88	.58	11.00	.38	.23	12.37	.88	.27	13.61
1.90	8.72	11.05	2.40	12.38	12.42	2.90	16.44	13.66
.92	.86	11.11	.42	.54	12.48	.92	.62	13.70
.94	9.00	11.17	.44	.69	12.53	.94	.79	13.75
.96	.14	11.23	.46	.85	12.58	.96	.96	13.80
.98	.28	11.29	.48	13.00	12.63	.98	17.13	13.84

618. Examples of weir calculations. A weir 5 ft. long is set in a channel 10 ft. wide and the crest is 4.36 ft. high. If the observed head is

0.64 ft., compute the discharge (*a*) by the Francis, (*b*) by the Fteley and Stearns, (*c*) by the Smith formula.

(*a*) Francis formula: $Q = 3.33\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} = 3.33 \times 4.872 \times 0.512 = 8.31$ cu. ft. per sec.; not corrected for velocity of approach V_A Area of channel of approach $A = (4.36 + 0.64)\ 10 = 50$ sq. ft. Velocity of approach $V_A = Q/A = 8.31/50 = 0.1662$ ft. per sec. Velocity head $h_v = (0.1662)^2/64.32 = 0.0004$; $\sqrt{H^3} = \sqrt{(0.64+0.0004)^3} - \sqrt{0.0004^3} = 0.5125 - 0.000008 = 0.5124$; $Q = 3.33 \times 4.872 \times 0.5124 = 8.313$ cu. ft. per sec.

(*b*) Fteley and Stearns formula: $Q = 3.31\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} + 0.007 \times 5 = 3.31 \times 4.872 \times 0.512 + 0.007 \times 5 = 8.29$ cu. ft. per sec.; h_v (as above) $= 0.0004$; $H = 0.64 + 2.05 \times 0.0004 = 0.6408$; $\sqrt{H^3} = 0.513$; $Q = 3.31 \times 4.872 \times 0.513 + 0.007 \times 5 = 8.31$ cu. ft. per sec.

(*c*) Hamilton Smith formula: $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times \sqrt{0.64^3} = 8.308$ cu. ft. per sec.; h_v (as above) $= 0.004$; $H = 0.64 + 1.4 \times 0.0004 = 0.6406$; $\sqrt{H^3} = 0.5127$; $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times 0.5127 = 8.320$ cu. ft. per sec.

In the foregoing solutions it is seen that the effect of velocity of approach is negligible, as is usually the case when the velocity is less than half a foot per second.

619. Further examples of weir calculations. Given a suppressed weir 7 ft. long, with crest 4.5 ft. above the bottom of the channel; the observed head is 1.36 ft. Compute the discharge by the Francis, Fteley and Stearns, and Basin formulas: (*a*) not correcting for the velocity of approach; (*b*) correcting for the velocity of approach.

(*a*) Francis formula: $Q = 3.33 \times 7 \times \sqrt{1.36^3} = 36.97$ cu. ft. per sec. Fteley and Stearns formula: $Q = 3.31 \times 7 \times \sqrt{1.36^3} + 0.007 \times 7 = 36.80$ cu. ft. per sec.

(*b*) Francis formula: $A = 7 \times 5.86 = 41.02$ sq. ft.; $V_A = Q/A = 36.97/41.02 = 0.90$ ft. per sec.; $h_v = (0.90)^2/64.32 = 0.0126$ ft.; $\sqrt{H^3} = \sqrt{(1.36+0.0126)^3} - \sqrt{0.0126^3} = 1.610$; $Q = 3.33 \times 7 \times 1.61 = 37.50$ cu. ft. per sec.

Fteley and Stearns formula: $V_A = 36.70/41.02 = 0.894$; $h_v = (0.894)^2/64.32 = 0.0124$; $H = 1.36 + 1.50 \times 0.0124 = 1.379$; $\sqrt{H^3} = 1.620$; $Q = 3.31 \times 7 \times 1.620 + 0.007 \times 7 = 37.58$ cu. ft. per sec.

Basin formula: Basin's coefficient (Par. 621) includes effect of velocity of approach; $Q = 0.4266 \times 7 \times 1.36\ \sqrt{64.32 \times 1.36} = 37.97$ cu. ft. per sec.

620. Smith's weir coefficients. C_s = coefficient for weirs with the contraction suppressed at both ends and complete crest contraction.

Effective head in feet, H	Length of weir in feet				
	$L = 0.66$	2	3	4	5
0.1	0.675	....	....	....	0.659
0.15	0.662	0.652	0.649	0.647	0.645
0.2	0.656	0.645	0.642	0.641	0.638
0.25	0.653	0.641	0.638	0.636	0.634
0.3	0.651	0.639	0.636	0.633	0.631
0.4	0.650	0.636	0.633	0.630	0.628
0.5	0.650	0.637	0.633	0.630	0.627
0.6	0.651	0.638	0.634	0.630	0.627
0.7	0.653	0.640	0.635	0.631	0.628
0.8	0.656	0.643	0.637	0.633	0.629
0.9	....	0.645	0.639	0.635	0.631
1.0	....	0.648	0.641	0.637	0.633
1.1	....	....	0.644	0.639	0.635
1.2	....	....	0.646	0.641	0.636
1.3	....	....	0.648	0.643	0.638
1.4	....	....	....	0.644	0.640
1.5	....	....	....	0.646	0.641
1.6	....	....	....	0.647	0.642
1.7	....	....	....	....	....

C_e = coefficient for weirs with complete contraction at two ends and complete crest contraction.

Effective head in feet, *H*	Length of weir in feet						
	L = 0.66	1	2	2.6	3	4	5
0.1	0.632	0.639	0.646	0.650	0.652	0.653	0.653
0.15	0.619	0.625	0.634	0.637	0.638	0.639	0.640
0.2	0.611	0.618	0.626	0.629	0.630	0.631	0.631
0.25	0.605	0.612	0.621	0.623	0.624	0.625	0.626
0.3	0.601	0.608	0.616	0.618	0.619	0.621	0.621
0.4	0.595	0.601	0.609	0.612	0.613	0.614	0.615
0.5	0.590	0.596	0.605	0.607	0.608	0.610	0.611
0.6	0.587	0.593	0.601	0.604	0.605	0.607	0.608
0.7	0.585	0.590	0.598	0.601	0.603	0.604	0.606
0.8	....	....	0.595	0.598	0.600	0.602	0.604
0.9	....	....	0.592	0.596	0.598	0.600	0.603
1.0	....	....	0.590	0.593	0.595	0.598	0.601
1.1	....	....	0.587	0.591	0.593	0.596	0.599
1.2	....	....	0.585	0.589	0.591	0.594	0.597
1.3	....	....	0.582	0.586	9.589	0.592	0.596
1.4	....	....	0.580	0.584	0.587	0.590	0.594
1.5	....	....	....	0.582	0.585	0.589	0.592
1.6	....	....	....	0.580	0.582	0.587	0.591
1.7	....	....	....	....	....	....	....

621. Bazin's coefficients.

Values of *m* corresponding to heads (*h*) and heights of weir (*p*) in feet for use in Bazin's formula.

$$Q = mL\sqrt{2gh^3}$$

h (ft.)	*p* = 0.656	*p* = 1.0	*p* = 1.5	*p* = 2	*p* = 2.5	*p* = 3	*p* = 4	*p* = 5	*p* = 6	*p* = 6.56
0.2	0.456	0.449	0.446	0.444	0.444	0.443	0.443	0.443	0.443	0.443
0.3	0.457	0.446	0.440	0.438	0.436	0.436	0.435	0.435	0.434	0.434
0.4	0.463	0.448	0.439	0.435	0.433	0.432	0.431	0.430	0.430	0.430
0.5	0.469	0.451	0.440	0.435	0.432	0.430	0.428	0.427	0.427	0.427
0.6	0.476	0.455	0.442	0.435	0.431	0.429	0.427	0.425	0.425	0.424
0.7	0.482	0.460	0.444	0.436	0.432	0.429	0.426	0.424	0.423	0.423
0.8	0.489	0.465	0.447	0.438	0.433	0.430	0.426	0.424	0.423	0.422
0.9	0.495	0.470	0.451	0.440	0.434	0.430	0.426	0.424	0.422	0.422
1.0	0.501	0.475	0.454	0.443	0.436	0.432	0.426	0.424	0.422	0.421
1.1	.....	0.479	0.457	0.445	0.438	0.433	0.427	0.424	0.422	0.421
1.2	.....	0.483	0.461	0.448	0.439	0.434	0.428	0.424	0.422	0.421
1.3	.....	0.487	0.464	0.450	0.441	0.435	0.428	0.424	0.422	0.421
1.4	.....	0.491	0.467	0.452	0.443	0.437	0.429	0.425	0.422	0.421
1.5	.....	0.495	0.470	0.455	0.445	0.438	0.430	0.425	0.422	0.421
1.6	.....	.....	0.473	0.457	0.447	0.440	0.431	0.425	0.422	0.421
1.7	.....	.....	0.475	0.459	0.448	0.441	0.431	0.426	0.422	0.421
1.8	.....	.....	0.478	0.461	0.450	0.442	0.432	0.426	0.422	0.421
1.9	.....	.....	0.480	0.463	0.452	0.444	0.433	0.427	0.423	0.421
2.0	.....	.....	0.483	0.465	0.453	0.445	0.434	0.427	0.423	0.421

622. Other forms of weir notches have been proposed and used, the most common of which are of Cippoletti, a trapezoidal notch, and the **triangular notch** (Fig. 53). The object of the Cippoletti weirs was to eliminate the effect of the end contractions. According to experiments by Horton*

* Water Supply and Irrigation Paper No. 200 U. S. Geol. Survey; Washington, D. C.

when the batter of the sides is 1 in 4 this aim is accomplished. The formula for any **trapezoidal weir** takes the usual form

$$Q = CL\sqrt{H^3} \qquad \text{(cu. ft. per sec.)} \qquad (110)$$

in which C for the special form cited has been experimentally determined as 3.367. Correction for velocity of approach may be made as for the Francis weir. The advantage of this weir is that a constant length L may be used for all heads so that for continuous measurements with varying heads it saves much labor. This form has been much used in irrigation projects in the Western United States. By adding 1 per cent. to the value of Q found in the weir table in Par. **617** the discharge for this weir may be computed.

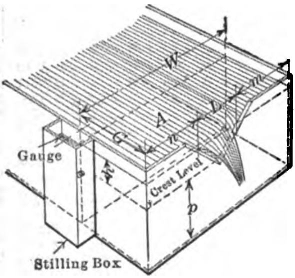


Fig. 53.—Triangular weir.

623. Triangular (notch) weirs. The common triangular notch is right angled, set with the apex down and the bisector of this angle vertical (Fig. 53). It has been found by experiment that the coefficient of such a triangular weir is remarkably constant for all heads. The formula for a right-angled notch set as described reduces to

$$Q = C\sqrt{H^5} \qquad \text{(cu. ft. per sec.)} \qquad (111)$$

in which C may be taken as 2.54 when H is measured to the apex of the angle. For measuring small quantities of water where the necessary head consumed is unimportant the V notch furnishes an accurate means and has been developed commercially as the **Lea Recorder**.

624. Flow of water in channels, whether open or closed, is subject to the same fundamental laws, and the formulas in common use are based on the two primary conceptions stated in Par. **602** and **603**. Head is required to produce velocity, to overcome obstructions such as bends, sudden constrictions or enlargements and head is required to overcome friction. Friction in turn depends on the velocity of flow and on the surface over which the water flows, its extent, and its character. In any formula for discharge the extent of the rubbing surface in contact with the water may be cared for directly by a numerical factor known as the **mean hydraulic radius,** which is found by dividing the cross-sectional area of the stream by its wetted perimeter; the latter is the linear dimension of that part of the boundary line of the cross-section of a channel in contact with the water. The effect of the character of the surface must be cared for by empirical coefficients. Head may be provided by natural topographical conditions as in the slope of a river bed, or created artificially as in the case of an elevated reservoir feeding into a pipe line. In the formulas most commonly in use the head appears in the slope of the **hydraulic grade line** which is the fall in feet, per foot of distance, measured along the longitudinal axis. The hydraulic grade line is a line in the plane of the longitudinal axis of the stream and at all points distant from it an amount equal to the net effective head. In an open channel the hydraulic grade line is coincident with the surface of the water. In the case of a pipe or conduit flowing under pressure the hydraulic grade line is above the centre line of the pipe and distant from it as defined above.

625. The Chezy formula is probably the most satisfactory one to use, certainly for open channels. It is usually stated as follows:

$$V = C\sqrt{RS} \qquad \text{(ft. per sec.)} \qquad (112)$$

where C = coefficient increasing with the mean hydraulic radius, and for new clean channels usually increasing with the mean velocity of flow, and decreasing with the roughness of the channel; R = mean hydraulic radius, and S = sine of the slope of the hydraulic grade line. The common text-book formula which, as nearly as may be determined, was proposed by Weisbach,*

* Weisbach's "Mechanics" (Coxe's translation), page 866. This formula is not uncommonly designated as Weisbach's, Darcy's, Weston's, or Chezy's.

and which is used only for pipes under pressure, is as follows (for steady uniform flow under pressure in circular pipes):

$$h_f = f\left(\frac{LV^2}{2gD}\right) \qquad \text{(ft.)} \qquad (113)$$

where h_f = the head lost in friction, f = the friction factor or coefficient of friction, decreasing with an increase in the diameter of the pipe and commonly with an increase of velocity of flow; and increasing with the age and roughness of the surface in contact with the water (Par. 626). L = the length (in ft.) of the pipe measured on its axis; D = the internal diameter (in ft.) of the pipe; V = the mean velocity of flow in ft. per sec.; g = the acceleration due to gravity, taken here as 32.16. The above equations are merely different expressions for the same formula. Either may be used to suit convenience.

Values of C suggested for use in Eq. 112 are as follows: New cast-iron pipe laid carefully without abrupt changes in grade or alignment: sizes 6 in. to 10 in., velocities 3 to 8 ft. per sec., C = 102 to 108; sizes 12 in. to 20 in., velocities 1 to 5 ft. per sec., C = 105 to 115; sizes 20 in. to 60 in., velocities 1 to 6 ft. per sec., C = 120 to 150. Riveted steel pipe (new): sizes 16 in. to 102 in., velocities 2 to 5 ft. per sec., C = 100 to 115. Tunnel or aqueduct with smooth cement or hard brick lining of relatively small cross-sectional areas (15 to 50 sq. ft.): velocities 1 to 5 ft. per sec., C = 115 to 140. Small canal, cross-sectional area about 100 sq. ft. in loose gravel or rock: velocities 1 to 5 ft. per sec., C = 60 to 85. Large canal, wide and shallow, smooth bottom and sides: velocities 2 to 5 ft. per sec., C = 50 to 70. Large canal, wide and deep, fairly smooth bottom and sides: velocities 2.5 to 3.5 ft. per sec., C = 75 to 90. Large river, tortuous channel: C = 40 to 80. Large river, easy bends: C = 70 to 100. Where the carrying capacity of any pipe or channel is very important about 30 per cent. depreciation should be figured in advance.

626. Friction factors (f in Eq. 113, Par. 625) for pipes may be computed by Weston's formula.* This formula, which must only be applied to pipes having interior sides similar to lead and brass pipes, from one-half inch to three and one-half inches in diameter is as follows:

$$f = 0.0126 + \frac{0.0315 - 0.06d}{\sqrt{v}} \qquad (114)$$

in which d = internal diameter of the pipe in feet; and v = the velocity in feet per second.

For pipes with interior sides similar to new cast-iron pipes the following formulas are used:

$$f = \left(0.017379 + \frac{0.0015965}{d} + \frac{0.0040723 + \frac{0.000020816}{d^2}}{v}\right)\frac{l}{d}\,\frac{v^2}{2g} \qquad (115)$$

$$f = \left(0.0198920 + \frac{0.00166573}{d}\right)\frac{l}{d}\,\frac{v^2}{2g} \qquad (116)$$

The first formula (Eq. 115) is for velocities of flow less than 0.33 ft. per sec., the second for higher velocities.

627. The Kutter formula though intended and largely used for pipes as well as for open channels, is not recommended for general use in either case.

$$V = \left[\frac{41.66 + \frac{1.811}{n} + \frac{0.00281}{S}}{1 + \left(41.66 + \frac{0.00281}{S}\right)\frac{n}{\sqrt{R}}}\right] \times \sqrt{RS} \qquad (117)$$

To estimate directly a value of C (Par. 625) is simpler, and probably quite as accurate as to estimate a value of n. The value of n depends on the value of S. Considering that in picking out the value of n a variation of 0.001 for small values of n and R may change the value of C as much as 17 per cent.,

* "Tables showing Loss of Head due to Friction of Water in Pipes" by Edmund B. Weston, C. E., D. Van Nostrand Co., 3rd Edition, 1903.

and for moderate values as much as 5 to 8 per cent., it should be obvious that hair-splitting calculations with the Kutter formula are a needless waste of time, producing merely numerical accuracy instead of a high degree of precision. Though it seems evident that we shall never have one formula to fit accurately all kinds of channels, it appears probable that we may have a small group of formulas each of which will fit some particular class of channels.

Values of n to be used in the Kutter formula for calculating values of C to be used in the Chesy formula are as follows:

$n=0.01$: should never be used except for temporary work and then only for perfectly smooth, clean iron pipes under 8 in. diameter and for high velocities, or for temporary and new planed wooden stave pipes, at high velocity 10 in. and under in diameter.

$n=0.011$: for above pipes, and low velocity.

$n=0.012$: for above pipes 3 ft. or more in diameter and high velocities; old iron pipes 8 in. diameter or under, low velocities; old city water mains above 8 in. diameter. Also for concrete tunnels having $R=2.5$; wood flumes, open, planed plank, long bends.

$n=0.013$: for above pipes 36 in. to 120 in. diameter, old pipes and low velocities; 1-to-2 cement-lined pipes; new penstocks lined with unplaned lumber and running full at all times; large concrete-lined tunnels of area 100 to 200 sq. ft.

$n=0.0135$: Ashlar masonry and well laid brickwork penstocks over 3 ft. in diameter; cast-iron concrete or steel-riveted pipes 8 in. to 20 in. diameter, long in use, short joints and under pressure of 75 to 150 lb. per sq. in.

$n=0.015$: rough concrete pipes where the interior cannot be smoothed or kept clean, moderate velocities and diameters above 3 ft.; penstocks of poorly laid rough brickwork; concrete-lined, open canals, low velocities.

$n=0.017$: canals with gravel bottom and sides well rammed, stones being 0.3 to 0.7 in. diameter; tunnels through hard rock, well trimmed and roughly faced; very large open concrete-lined canals.

$n=0.02$: rough rubble masonry; canals through rock, or with bottoms and sides paved with cobble stones; canals in earth with bottoms and sides well trimmed; small rough lumber penstocks with battens and poor alignment.

$n=0.0225$: canals in earth in good condition, but long in use, having moss growing freely.

$n=0.025$: canals in clay, long in use; small rivers, deep and narrow and with no sharp bends, smooth sand bottoms and smooth uniform banks.

$n=0.0275$: canals and rivers as for $n=0.025$, but having an occasional bend and snag also the same, but with gravel bottoms; earth canals as left by dredging.

$n=0.03$: rivers having loose boulder beds, irregular banks, sharp bends, shallow, normal flow.

$n=0.035$: rivers with rough, irregular beds having shallows and pools, snags, bends, gravel bottoms, average flood stages.

$n=0.05$: large shallow rivers, having sharp bends, low heavily wooded banks, snags, shallows, pools, rough bottom and moderate flood conditions.

$n=0.055$: large torrential streams during high floods, with the banks heavily-wooded and inundated; mountain streams with many falls, large boulders, rapids, etc.

628. Beardsley's formula for C. Assuming values for n, S and R, C may be calculated from the formula as given by R. C. Beardsley.

$$C=\frac{\left(23+\frac{1}{n}+\frac{0.00155}{S}\right)}{\left(0.5521+\left[23+\frac{0.00155}{S}\right]\frac{n}{\sqrt{R}}\right)} \tag{118}$$

or in its original form

$$C=\frac{\left(41.66+\frac{1.811}{n}+\frac{0.00281}{S}\right)}{\left(1+\left[41.66+\frac{0.00281}{S}\right]\frac{n}{\sqrt{R}}\right)} \tag{119}$$

629. Bazin's formula for C. Bazin proposed a formula for computing the value of C to be used in the Chesy formula which differs from the Kutter formula in eliminating S and making the variation in C depend only upon variations in the mean hydraulic radius and the coefficient of roughness. It is as good as any general formula and has the advantage of simplicity. His formula is

$$C = \frac{157.6\, R^{\frac{1}{2}}}{R^{\frac{1}{2}} + \gamma} \tag{120}$$

Values of γ

$\gamma = 0.109$: very smooth surfaces; neat cement; planed wood.
$\gamma = 0.290$: smooth surfaces; planks, bricks, ashlar.
$\gamma = 0.833$: rough surfaces; rubble masonry.
$\gamma = 1.54$: canals with mixed linings; very regular earth or paved with stones.
$\gamma = 2.35$: earth canals in ordinary conditions.
$\gamma = 3.17$: earth canals in bad condition.

Bazin's formula represents the results of a very careful study of existing data and is extremely valuable in designing relatively small channels and those with very smooth linings; it also meets the conditions of design for all open channels as well as, if not better than any general formula available. It has the additional merit of simplicity.

630. Friction loss in iron pipes increases with age. Under ordinary conditions of service at the end of 30 years we may expect to find the losses in cast-iron pipes due to friction about doubled. This is satisfactory for rough approximations and the loss for intermediate years may be taken as proportional to the age.

631. Loss of head at entrance. The flow formulas which have been given (Par. **605** to **629**) take into account only the head necessary to overcome friction. There is in addition to this a further loss of head in creating

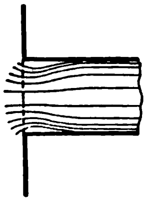


FIG. 54*a*.

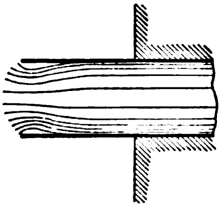


FIG. 54*b*.

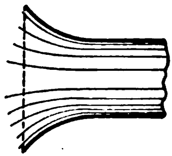


FIG. 54*c*.

the velocity of flow and in overcoming the resistance of entrance into the pipe. The **velocity head** is equal to $V^2/2g$. The head lost at entrance varies with the form of entrance and is expressed as a constant times the velocity head $\xi_o V^2/2g$. Values of ξ are given below.

$$0.5\frac{V^2}{2g} \qquad (0.11 \text{ to } 0.02)\frac{V^2}{2g} \qquad 0.93\frac{V^2}{2g}$$

632. Nozzles, properly designed, furnish one of the simplest and most accurate methods of measuring small quantities of water. Coefficients of discharge for various forms of nozzles from about ¾ in. to 5 in. have been determined with great accuracy by John R. Freeman.* Nozzles are especially useful in measuring the discharge through pipes, fire hose, and in testing the performance of pumps and impulse water wheels. With nozzles to which Freeman's coefficients are applicable, discharge measurements can be made with an error not exceeding 2 per cent.

633. Loss of head due to bends, elbows, valves, etc. Experimental data are either meager or lacking from which to compute the loss of head due to bends, elbows, valves, etc. Their effect only becomes important with high velocities and may be considered as corresponding to so many additional

* *Trans.* Am. Soc. C. E., Vol. XXI, pp. 303–482.

feet of straight pipe. In long uniform pipe lines laid with easy curves the friction loss predominates and the minor losses may be neglected. The following table gives approximate values determined by experiments made by the Inspection Department of the Associated Factory Mutual Fire Insurance Companies, and may be used when no exact information is available:

Name of fitting	Number of feet of clean, straight pipe of same size which would cause the same loss as the fitting. (Loss in straight smooth pipe as given by Weston).
2.5-in. to 8-in. long-turn ells.........	4
2.5-in. to 8-in. short-turn ells........	9
3-in. to 8-in. long-turn tees..........	9
3-in. to 8-in. short-turn tees.........	17
1/8th bend........................	5

634. Freeman's formula for nozzles is given as follows:

$$G = 29.83\ Cd^2\sqrt{\frac{P_e}{1 - C^2\left(\frac{d}{D}\right)^4}} \quad \text{(gal. per min.)} \qquad (121)$$

where G = discharge in gallons per minute, C = coefficient of discharge, d = diameter in inches of the nozzle orifice, D = diameter in inches of the piezometer ring at the base of the nozzle, and P_e = piezometer reading in pounds

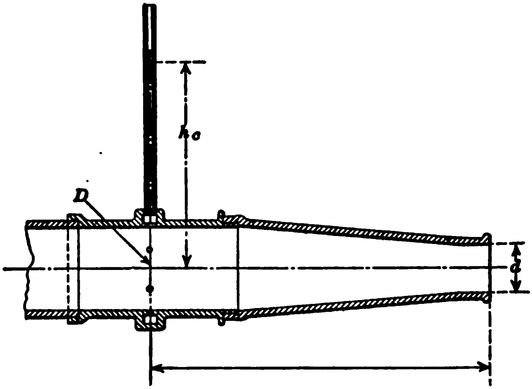


FIG. 55.—Section of nozzle and piezometer ring.

per square inch at the centre of the nozzle orifice. For water-power practice in engineering units the same formula becomes:

$$Q = 6.3Cd^2\sqrt{\frac{h_e}{1 - C^2\left(\frac{d}{D}\right)^4}} \quad \text{(sec-ft.)} \qquad (122)$$

where Q = discharge in cubic feet per second, C = coefficient of discharge, d = diameter in feet of the nozzle orifice, D = diameter in feet of the piezometer ring at the base of the nozzle, and h_e = piezometer reading in feet of water above the center of the nozzle orifice.

635. Coefficients for nozzles. A value of 0.974 may be taken as a suitable coefficient (C) for the ordinary smooth fire nozzle with a nominal diameter between 0.75 in. and 1.375 in. and under pressures varying from 20 to 100 lb. per sq. in. For pressures less than 20 lb. per sq. in. the same coefficient may be used, but without so great a confidence in the accuracy of the result. For larger sizes of smooth nozzles ranging from 1.75 in. and 2.5 in. Freeman's coefficients lie between 0.987 and 0.999 for pressures ranging from 15 to 55 lb. per sq. in. For smooth nozzles from 2.5 in. up to 6 in. and under heads of more than 10 ft., Freeman suggested a coefficient of 0.995. The following coefficients have been obtained by experiment for a set of specially made smooth **meter nozzles** (Fig. 56): 2.5 in., 0.98; 3 in., 0.985; 4 in., 0.99; 5 in., 0.995. The coefficients will vary somewhat in different sets of nozzles and it is important to know at what point the pressure is registered (Fig. 55). If special accuracy is desired a set of meter nozzles which have been carefully rated by volumetric measurement should be used. With square ring nozzles the jet suffers contraction and the coefficients according to Freeman's experiments range from 0.65 up to 0.975 according to the proportions of the orifice.

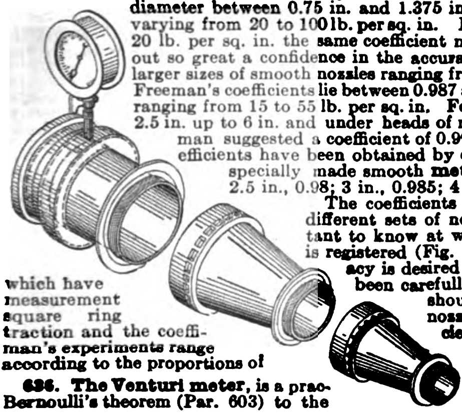


Fig. 56.—Meter nozzle.

636. The Venturi meter, is a practical application of Bernoulli's theorem (Par. 603) to the measurement of water in pipes flowing under pressure. The formula for discharge is

$$Q = \frac{C\pi D_b^2 D_a^2 \sqrt{2gh}}{4\sqrt{D_a^4 - D_b^4}} \quad \text{(sec-ft.)} \qquad (123)$$

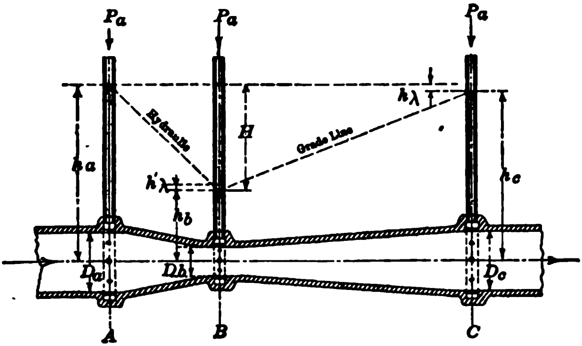


Fig. 57.—Section of Venturi meter.

The symbols will be understood by reference to Fig. 57. For meters with a given ratio of throat and inlet diameters the formula may be simplified. Let the ratio $R = D_a/D_b$ and let

$$K = \frac{\pi R^2}{4}\left(\frac{2g}{R^4 - 1}\right)^{\frac{1}{2}} \qquad (124)$$

Then $$Q = CKD_t^2\sqrt{H} \quad \text{(cu. ft. per sec.)} \qquad (125)$$

Values of R =	3.0	2.5	2.0
Values of K =	6.338	6.381	6.505

The value of C varies wth the velocity at the throat, the ratio R and the actual dimensions of the meter. As the Venturi meters* are ordinarily constructed the coefficient C is between 0.97 and 1.03. These meters may be rated backward and a coefficient of correction found to apply to the manometer reading (Fig. 58). The total loss of head through the meter tube is relatively unimportant compared with other types of commercial meters and is so small that the insertion of the meter in the mains of a water supply is rarely objectionable, and the use of this appliance is growing constantly. It may be used particularly well in high-pressure power plants where a continuous reading may be obtained by the recording apparatus; also to measure boiler feed and for measuring liquids heavier and lighter than water. Experience has shown that with the register, continuous measurements have been made with an error not exceeding 3 per cent.

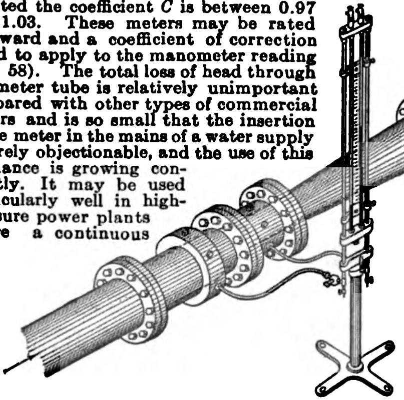


Fig. 58.—Venturi meter with manometer.

637. The Pitometer† (Figs. 59 and 60), by means of the differential gage registers the difference in pressure on the two orifices, one pointed directly against the current, the other in the exactly opposite direction. This difference in pressure is not a measure of the velocity head directly, but is greater than the velocity head. For these instruments the coefficient (K) of correction has been found to be nearly a constant, and equal to 0.84. The formula for velocity therefore becomes

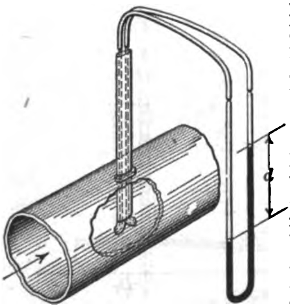


Fig. 59.—Principle of pitometer.

$$V = K[2g(s'-1)d]^{\frac{1}{2}} \quad \text{(ft. per sec.)} \qquad (126)$$

where s' = specific gravity of the heavier liquid, d = the deflection (Fig. 61) in feet, V the velocity in feet per second, and K the Pitometer coefficient. The liquid used in the differential gage is usually carbon tetrachloride and, gasoline, colored red. The specific gravity as put up for use is usually either 1.25 or 1.50 (for very accurate work the specific gravity should be determined for the temperature at which it is used). The formula (Eq. 126) then reduces to:

$$\text{For } s' = 1.25;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{4}} = 3.368d^{\frac{1}{2}} \quad \text{(ft. per sec.)} \qquad (127)$$

$$\text{For } s' = 1.50;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{2}} = 5.671d^{\frac{1}{2}} \quad \text{(ft. per sec.)} \qquad (128)$$

* Made by the Builders Iron Foundry, Providence, R. I., in standard sizes for pipe lines from 2 to 60 in. in diameter, and much larger sizes are in use; they may be furnished with either direct reading or recording apparatus.

† Developed by John A. Cole and Edward S. Cole and owned by the Pitometer Co., N. Y.

To determine the discharge the cross-section of the pipe must be divided into one or more known areas (Fig. 61), the velocity for each found and hence the mean velocity for the entire cross-section; the discharge being simply the product of the area and the mean velocity. For pipes the following table (Par. 639) is useful and the example (Par. 641) illustrates how the discharge is calculated. The Pitometer is set so that the velocity is determined for the points as shown in Fig. 61. The pipe coefficient (see example) being first determined, it is subsequently necessary only to get a reading for the centre of the pipe and apply the coefficient to the centre velocity to obtain the mean velocity and hence the discharge by the formula:

$$Q = KCV_cA \qquad \text{(cu. ft. per sec.)} \qquad (129)$$

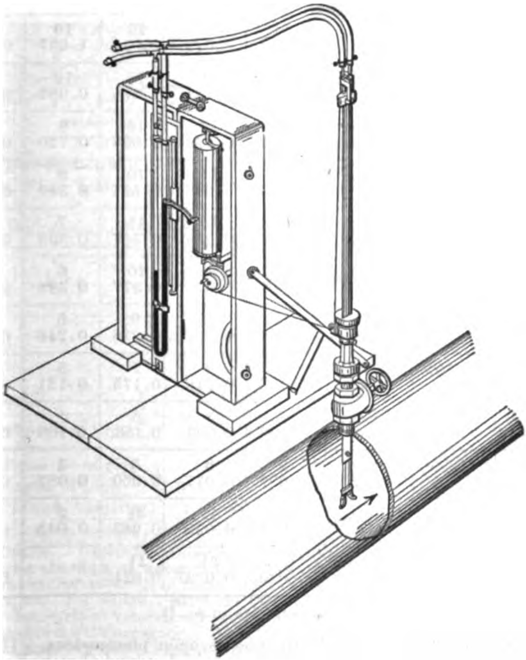


Fig. 60.—Portable pitometer.

638. The principal use of the pitometer is for measuring the flow in water mains where it has proved its great value in detecting leaks and waste, and in measuring the slip of pumping engines. It can be installed and operated for relatively small expense, without interfering with the flow. For large penstocks and in silt-bearing water it is not recommended. When used in old pipes, allowance must be made for incrustations reducing the cross-sectional area and a traverse of several points through more than one diameter is preferable to the single observation and the use of the pipe coefficient.

639. Traverse table for pitometer gagings, showing inner diameter of each ring for ordinary sizes of mains in inches; and giving the area of each ring and centre circle in square feet.

Diameter of pipe (in.)	Area of pipe (sq. ft.)		Ring A	Ring B	Ring C	Ring D	Centre circle E
48	12.566	Diam. Area	44 2.007	36 3.490	28 2.793	16 2.880	16 1.396
42	9.621	Diam. Area	38 1.745	32 2.291	24 2.443	14 2.073	14 1.069
36	7.069	Diam. Area	34 0.764	28 2.029	20 2.094	10 1.637	10 0.545
30	4.909	Diam. Area	28 0.633	24 1.134	18 1.375	12 0.982	12 0.785
24	3.142	Diam. Area	22 0.502	18 0.873	14 0.698	8 0.720	8 0.349
20	2.182	Diam. Area	18 0.415	14 0.698	10 0.524	6 0.349	6 0.196
18	1.767	Diam. Area	17 0.191	15 0.349	11 0.567	7 0.393	7 0.267
16	1.396	Diam. Area	15 0.169	13 0.305	10 0.377	6 0.349	6 0.196
14	1.069	Diam. Area	13 0.147	11 0.262	9 0.218	6 0.246	6 0.196
12	0.785	Diam. Area	11 0.125	9 0.218	7 0.175	5 0.131	5 0.136
10	0.545	Diam. Area	9 0.103	8 0.093	6 0.153	4 0.109	4 0.087
8	0.349	Diam. Area	7 0.082	6 0.071	5 0.060	3 0.087	3 0.049
6	0.196	Diam. Area	5½ 0.031	4½ 0.055	3½ 0.043	2 0.045	2 0.022
4	0.0873	Diam. Area	3½ 0.0205	2½ 0.0327	1½ 0.0218	....	1½ 0.0123

NOTE.—Diameter given in inches; area in sq. ft.

640. Piezometers. "Mills' experiments upon piezometers. Hiram F. Mills* published in 1878 the results of some six thousand observations made with extraordinary accuracy to determine the proper form of piezometer orifice. With twenty-two openings varied in shape and direction and a range of velocities from 0.6 to 8.9 ft. per sec., he found that with an orifice whose edges are in the plane of the side of the channel and passage normal thereto, the piezometer column will stand neither above nor below the surface of the stream, but will indicate the true height of the water surface in an open channel or the pressure in a closed channel; but if the passage inclines either upstream or downstream, or the edges of the orifice project

* Chief Engr. Essex Co., Lawrence, Mass. *Trans*. Am. Academy of Science, 1878.

beyond the plane of the side, the true height of the surface or the true pressure will not be indicated."*

641. Example of use of pitometer. The following diagram (Fig. 61) and computations illustrate the usual method of computing discharge.

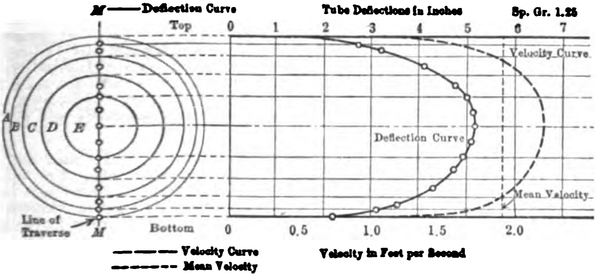


FIG. 61.—Velocity curve as determined by pitometer readings.

Deflection and velocity curves from 24-in. supply main

Ring	Ring areas (sq. ft.)	Ring velocity (ft. per sec.)	Ring volumes of flow (cu. ft. per sec.)
A	0.502	1.57	0.788
B	0.873	1.87	1.632
C	0.698	2.05	1.431
D	0.720	2.18	1.570
E	0.349	2.24	0.781
Total discharge of pipe	3.142		6.202

$$\frac{\text{Discharge of pipe}}{\text{Area of pipe}} = \frac{6.202}{3.142} = 1.97 \text{ ft. per sec., mean velocity.}$$

$$\frac{\text{Mean velocity}}{\text{Centre velocity}} = \frac{V}{V_c} \frac{1.97}{2.24} = 0.879 = \text{pipe coefficient.}$$

642. Floats. Under favorable circumstances one of the simplest methods of measuring the flow of water is by means of velocity determinations with floats. The different kinds of floats are surface, subsurface, or combinations of the two, and rod floats. **Surface floats,** even on a perfectly quiet day, give only the surface velocity and with any wind blowing the velocity cannot be measured with accuracy. **Subsurface floats** are but slightly heavier than water and are easily caught by eddies and cross currents which move them about in an undeterminable path and make the results unreliable. **Twin floats** have been used, but their place is better filled by rod floats.

643. Rod floats are cylinders usually made of metal tubing loaded with lead at the bottom so that they will float vertically with about 6 in. extending above the surface of the water. They are best adapted for use in power canals with straight, smooth sides and level bottom so that rods may be used reaching nearly to the bottom without danger of bumping. Under such conditions rod floats have been used continuously on a large scale for a great many years. The method of measurement is direct. The

* Hughes & Safford, "Hydraulics," New York, MacMillan Co., 1911, page 104.

following paragraphs are quoted from Hughes and Safford's Hydraulics (MacMillan Company):

"Procedure in measuring velocity. A straight stretch of stream should be selected as a place for gaging, and two cross-sections selected to mark the beginning and the end of the area. The float should be placed quietly in the stream at such a distance upstream from the upper of the two cross-sections, that it will be running with the current before the first marker is reached. The time of passage between these two sections, of which the distance apart is known, should be noted with a stop watch; or the position of each float at successive intervals of time be located by engineers' transits or sextants by intersection, and the points plotted on a scale drawing, from which the distance traveled in the observed interval of time can be computed. The distance in feet divided by the time of each run in seconds will give the velocity of the float in ft. per sec."

644. "Application of rod float measurements (Hughes and Safford). The sphere of usefulness of rod-float measurements is somewhat limited, and the expense of making them is relatively great. Their regular use in the future will probably be limited to straight, deep canals or flumes where a high degree of accuracy is required, where a sufficient force of men is regularly employed for this and other purposes, and where it is very necessary to gage all the water used for power and other purposes, without interfering with the operation of the mills. Ordinarily, the difficulty of getting good results from the sum of individual measurements, or readings of water wheels, is due to the fact that the total discharge, which is simply the sum of the individual water wheels, often does not include the leakage or the water used for manufacturing purposes other than power; but the flume measurements of the total quantity passing to each mill will cover everything. There is very little opportunity to make such measurements in rivers or canals which do not have a regular cross-section; and for such conditions there is no question that measurements by current meter (Par. **662 to 665**) will take the place of those formerly made by rod floats. The most notable published gagings by rod floats are those by Humphreys and Abbott of the Mississippi River, those described by James B. Francis in the Lowell Hydraulic Experiments, Darcy and Bazin's gagings, and the gagings of certain rivers in India."

645. "Limits of accuracy in use of rod floats (Hughes and Safford). With a straight, smooth flume of great depth, and velocities ranging from 2 to 5 ft. per sec., quantities of water from a few hundred to 4,000 cu. ft. per sec. have been repeatedly measured with a probable error of 1 to 2 per cent. This form of measurement, which in its successive steps gives the product of the cross-section and the velocity of the water as indicated by the rod floats, is a perfectly natural one; and its simplicity appeals to the non-technical man."

Rod floats cannot be run with the lower end closer than 2 or more in. from the bottom. Some correction must be made to account for this slower layer of water which does not act on the float. The following formula was derived by James B. Francis by comparing rod float measurements with a weir:

$$C = 1 - 0.116\,(\sqrt{D} - 0.1) \qquad (130)$$

where C = a coefficient of correction which multiplied by the observed velocity will give the corrected velocity, and D = difference between the depth of water in the flume and length of immersed part of tube, divided by depth of water.

Values of the Coefficient C

D	0	1	2	3	4	5	6	7	8	9
0.0	.....	1.000	0.995	0.992	0.988	0.986	0.983	0.981	0.979	0.977
0.1	0.975	0.973	0.971	0.970	0.968	0.967	0.965	0.964	0.962	0.961
0.2	0.960	0.958	0.957	0.956	0.955	0.954	0.952	0.951	0.950	0.949
0.3	0.948	.....	.....	.....	.....	.....	.....	.....	.....	.....

Direct interpolation may be made for intermediate values.

STREAM FLOW

646. The local variation of the average annual rainfall in the United States is all the way from nothing in some years in the desert regions, to an

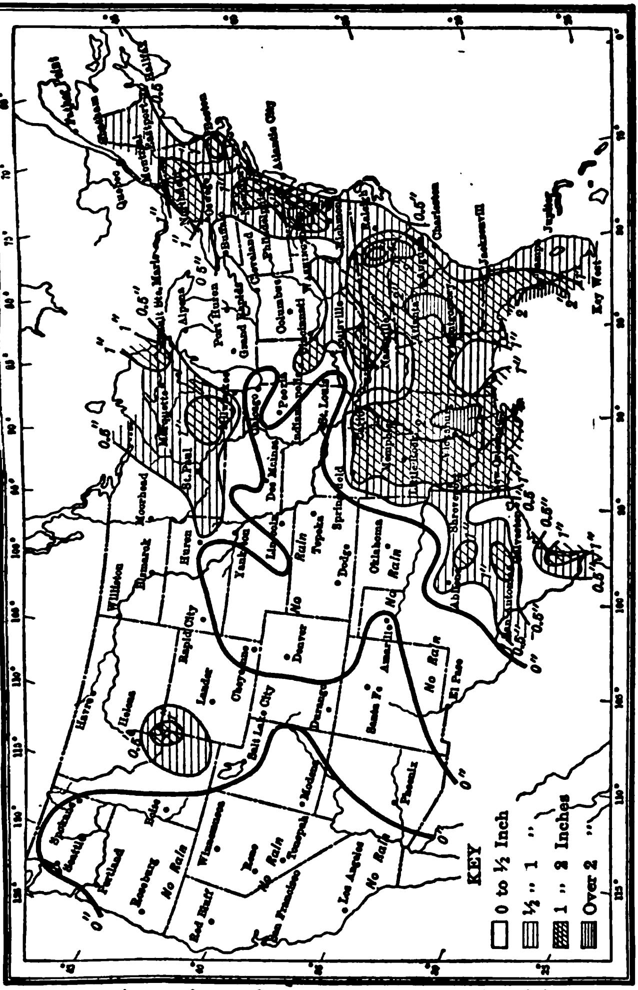


Fig. 62.—Map of United States showing distribution of rainfall.

occasional maximum of more than 100 in. in the mountains of the extreme northwest. An examination of the map in Fig. 62, will give an idea of the

geographical distribution of rainfall over the United States as affected by altitude, climate, proximity to the ocean, etc. In general mountain ranges receive a greater amount of precipitation than the surrounding valleys and yield a greater proportionate run-off.

647. Source of run-off. Rain or snow falling on the drainage areas of rivers is the immediate source of water power. The relation between the rainfall and the run-off is a direct one; rain falls on the ground and a part of it finds its way to the water courses, and yet there are so many physical factors affecting the disposal of rainfall that to establish the relation between it and run-off is baffling if not actually impossible. The cycle of rainfall and run-off is complete when we include the evaporation of moisture in the form of vapor from water and ground surfaces, to fall later as rain.

648. Rainfall records. The U. S. Weather Bureau has kept rainfall records at stations geographically widely distributed for a long period of time and it frequently occurs that good rainfall records are at hand when no stream gagings can be obtained. For this reason, any relations, even only approximately fixed, between rainfall and run-off are of considerable value to the water-power engineer.

649. The main factors affecting the disposal of rainfall are the topography, geology, evaporation and the amount taken up by vegetation. Rugged drainage areas with steep slopes discharge the water readily and quickly into the water courses. Rivers draining such areas, unless there is good storage in lakes and ponds, are more subject to sudden fluctuations in flow than rivers draining flat or rolling country where there are many swamps and where the water has chance to sink into the pervious soil. Evaporation, according to our best present knowledge, is essentially the same from year to year in any one locality and likewise the amount of moisture taken by the vegetation is about a constant.

650. Run-off is the result of rain falling on the contributing drainage area and is subject to the same conflicting influences, with an additional factor of great importance, which is the degree of water-storage development on the river. We can measure and know the rain at any one or a number ot points and form a more or less close estimate of the total rainfall over the whole area. We can measure and know the evaporation from water surfaces with fair precision. For the rest it is mainly conjecture, though we can count on vegetation to take a fairly constant amount of moisture from year to year and over large sections of the country. In a year of small precipitation, the evaporation will be at least normal, vegetation will require as much as usual and take all it can get, with the combined result that the run-off of the rivers will get a smaller proportion of the total rainfall than in years of average or excess precipitation. For these reasons, it is very difficult to use any percentage ratio between run-off and precipitation.

In the case of water powers already established where run-off records are kept, a knowledge of the local relation between rainfall on the contributing area and the flow may be very valuable from an operating point of view. Of course if there are gaging stations up river these give more direct and reliable information. It is only in the absence of gaging stations that estimates based on the amount of rainfall need be resorted to, and then must be used with the greatest care.

651. Distribution of run-off. For comparative purposes it is convenient and advantageous to express the flow of rivers not by total flow, but in cu. ft. per sec. per square mile of drainage area. The following is a list of the major factors influencing the distribution of run-off:

(*a*) Geology—is the soil pervious or impervious (Par. 652).

(*b*) Topography—is the drainage area flat or rolling, or has it steep precipitous slopes (Par. 653).

(*c*) Size of the contributing area (Par. 654).

(*d*) Climate—amount and distribution of rainfall and evaporation (Par. 655).

(*e*) Storage—whether natural or developed—the degree of development and the location of the storage basins (Par. 656).

These cannot be said to be of equal importance and the relative effect will differ on different areas. It will be seen that the fifth factor only can be altered by man, and looked at in this light it assumes an importance of greater moment than the rest. An even distribution of the run-off is a most desirable characteristic. Taking up in order the main factors listed above we shall see how each one affects the distribution.

652. Geology. Pervious soil will allow the water falling on it to percolate down into it, where it is held as ground water, a part to find its way into the streams when the general water table is lowered. If the soil is impervious water must run off quickly and find its way to the main water courses. Thus heavy storms of short duration falling on frozen or saturated ground will cause sudden rises in the stream and much water may be wasted.

653. Topography. Flat or rolling country combined with a pervious soil is admirably fitted to hold the rain in storage as ground water. The precipitous, rocky slopes are equally fitted to discharge the rain almost as it falls and do nothing to even up the distribution of run-off. But if complete or nearly complete water storage is provided, a precipitous drainage area may be better for water-power purposes than more level country. Between the two conditions are a multiplicity of possible combinations and effects.

654. Size of drainage area has an additional influence when there is little or no storage available. This is because the variation in the extent and intensity of rain storms is extreme. A local storm of sufficient intensity to cause a freshet on a small area, occurring on a drainage area of a thousand square miles or more would hardly be felt on the main river. It is for this reason that without storage small rivers show much greater divergence between maximum and minimum discharge. This would to some extent be offset by a complete forest cover, which on the small stream would undoubtedly delay the peak of the flood and might entirely prevent a sudden rise. It can never, however, hold the water in storage like a reservoir, to let it down at certain seasons of the year. Furthermore on drainage areas of considerable size sufficient areas usually cannot be deforested or grow up fast enough to have an effect more than local.

655. Climate. The climate prevailing on a drainage area will depend on its geographical location and on its topography. It is sufficient here to refer to but two aspects: (*a*) the total annual precipitation and its distribution; (*b*) the total evaporation (Figs. 65 and 68) and its distribution. There is such radical variation in different parts of the country that no general discussion will be attempted here. Every case must receive careful study to ascertain the local conditions and tendencies. A map of the United States is given in Fig. 62 showing the distribution of the average annual precipitation over the country.

656. Storage may exist on streams and rivers naturally in the form of swamps and lakes, or may have been developed by damming up streams at favorable points, or in raising lakes already in existence. The degree of development of the storage on a drainage area is important. If underdeveloped there will be a waste of water during the periods of high water which, if held in storage for future use, would greatly enhance the value of the reservoir. The storage on a drainage area may be said to be completely developed when the reservoir fills once in each normal year without much waste, and is of sufficient capacity to carry over a series of two or three dry years with undiminished yield, but without filling entirely; of course such cases are rare. Two examples in New England are the Winnipiseogee river which drains the lake of that name in New Hampshire, and the Presumpscott river flowing out of Sebago lake in Maine. Lake Winnipiseogee (Par. **657**) has an area of approximately 70 square miles with a drainage area exclusive of the lake surface of about 300 square miles. The steady yield of this lake with rare exceptions is from 1.5 to 2 cu. ft. per sec. per square mile. Sebago lake has a surface area of about 50 square miles and a contributing area of about 430 square miles. The flow at the outlet of the lake rarely falls below 1.6 cu. ft. per sec. per square mile on week days.

Perhaps the most **advantageous location** for storage reservoirs, if not too large for their contributing areas, is near the head waters of a river, for in that way all powers are benefited. The most economical **method of handling** the storage will vary in different cases; usually the water is let down quite uniformly throughout the year. There are cases, however, where the best way is to keep the storage gates closed most of the year and then draw heavily during the dry season. This method is the desirable one to follow when the total area of the river basin is large, the water storage great, and the area contributing to the reservoir a small part of the whole. The whole object of storage is to keep up the flow of the river as well as possible in order to make as high as may be the permanent dependable power. Every reservoir and mill pond on any stream must be operated subject to the legal rights of others on the stream. In any particular case the yield of a reservoir may be predicted from a study of the run-off of the contributing area, the precipitation on and the evaporation from the water surface. Trial drafts from the storage are assumed and the effect traced through a number of years. In this way very safe estimates can be made of the storage yield.

657. Example of a large storage basin. The following figures show by way of illustration the condition of Lake Winnipiseogee (Par. 656) on May 1, Aug. 1, Nov. 1, and Feb. 1, using 1911 and 1912 figures of run-off and precipitation, and average figures of evaporation. The yield of the contributing area is expressed in inches of depth on the lake area, rainfall and evaporation are given directly in inches and the draft, 600 cu. ft. per sec. throughout the year, is also reduced to in. of depth on the lake area for each month.

Date	Yield of the contributing area expressed in in. of depth on the lake area for the month	Rainfall in in. during the month	Evaporation in in. during the month	Draft 600 cu. ft. per sec. expressed in in. of depth on the lake area for the month	Net gain or loss in in. of depth on the lake area for the month	Elevation of the lake*
April 1, 1911 During April May 1, 1911	+38.35	+1.38	−1.6	−9.56	+28.57	27.57 Wasting
July 1, 1911 During July August 1, 1911	+ 1.83	+4.36	−4.32	−9.88	− 8.01	38.09 30.08
October 1, 1911 During October November 1, 1911	+ 9.44	+4.51	−2.20	−9.88	+ 1.87	15.49 17.36
January 1, 1912 During January February 1, 1912	+11.51	+3.12	−0.70	−9.88	+ 4.05	17.21 21.26

* 44 in. represents full lake.

658. River gaging stations are maintained by the U. S. Government and the State Governments on many rivers and streams throughout the country. This work of gaging the rivers is carried on by the U. S. Geological Survey, Dept. of the Interior, and the observations and results are published. These publications, which are invaluable in studying the possible water-power development of our streams, may be obtained at nominal expense from the Supt. of Documents, Government Printing Office, Washington, D. C.

659. Flow in open streams is subject to the same laws as the flow in any other channel (Par. 602), but because of the irregularity of section and the changing character of the bed from point to point the difficulties of finding a formula to fit all conditions are manifold. The only reliable data concerning discharge of a stream are based on actual measurements.

660. Measurement of stream flow. The method adopted will depend largely on the size of the stream, its cross-section and the variation between minimum and maximum flow. A weir can be successfully used in a small stream discharging a few cu. ft. per sec. and is largely employed in irrigation ditches. For rivers from medium to large size the most adaptable method is to employ a current meter and by making measurements at several stages of flow establish a **rating curve** by means of which it is only necessary to read a gage, compare the reading with the rating curve and find the discharge corresponding to the given stage. The same rating curve cannot be used for both winter and summer conditions.

661. Typical hydrographs showing the monthly average stream flow in sec-ft. per square mile of drainage area are shown in Figs. 63 and 66, for the Kansas (Kan.) and Columbia (Ore.) rivers respectively. Figs. 64 and 67 show the accompanying monthly rainfall in typical years. Figs. 65 and 68 show the accompanying monthly evaporation. These stream-flow records or hydrographs naturally exhibit different characteristics according to the local climatic and other conditions, as noted by comparing Fig. 63 with Fig. 66, and Fig. 64 with Fig. 67. Furthermore, the hydrographs of the same river vary materially as a rule from year to year, between rather wide limits; Figs. 63 and 66, besides showing the stream flow for typical years, also show the maximum (wet year) and minimum (dry year) flow observed during a series of years. It is also instructive to compare the records of rainfall with those of stream flow; compare Figs. 63 and 64, and Figs. 66 and 67. Similar records and charts should be obtained for any particular river or stream, if possible, in connection with consideration of its water-power possibilities.

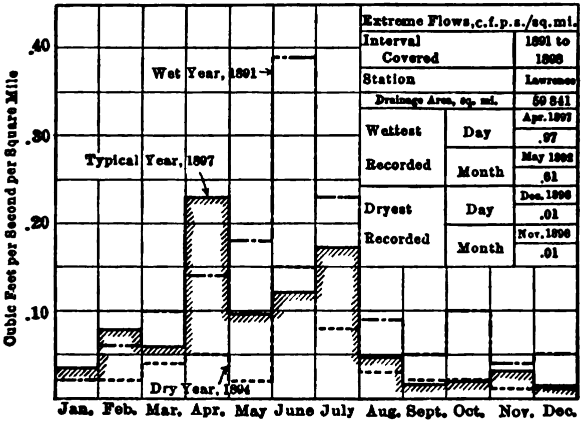


Fig. 63.—Hydrograph of Kansas River from records at Lawrence, Kansas.

662. Current meters may be roughly divided into two classes, those in which the wheel revolves about a vertical axis and those in which the axis is horizontal.

The Price-Gurley meter (Fig. 69) belongs to the first class and is the type adopted by the government in its stream gaging work. It is fitted with a vane to keep it headed into the current and with an electric sounder to enable the operator to record the revolutions without taking the meter from the water. This meter can be slung from a cable and operated from the shore or from a bridge, or from a car suspended from a cable. In shallow water the meter is attached to a rod and operated directly by hand. The disadvantage inherent in this meter is that it always records the maximum velocity, whether that velocity is in a forward direction or is merely caused by cross currents and eddies; all alike are recorded as forward. Consequently this meter has a tendency to give results which are too high.

The Haskell meter (Fig. 70) is of the screw-propeller type and operated in the same manner as the Price-Gurley meter. It is subject to the same criticism in that it records the maximum velocity at the point of immersion regardless of its direction.

The Fteley-Stearns meter (Fig. 71) was designed for use in the Sudbury Aqueduct of the Boston Water Works and is especially adapted for use in flumes or any channels where it is desired to get the velocity close to the sides and bottom. It is ordinarily fitted for use on a rod and is equipped with recording dials thrown in and out of mesh by a cord. The meter can also be fitted up with vane and electric sounder. It then loses its peculiar value in recording only the forward component of the velocity of the water, which makes it a true integrating instrument. It has been successfully used in large rivers and in velocities from 0.4 to 10 ft. per sec.

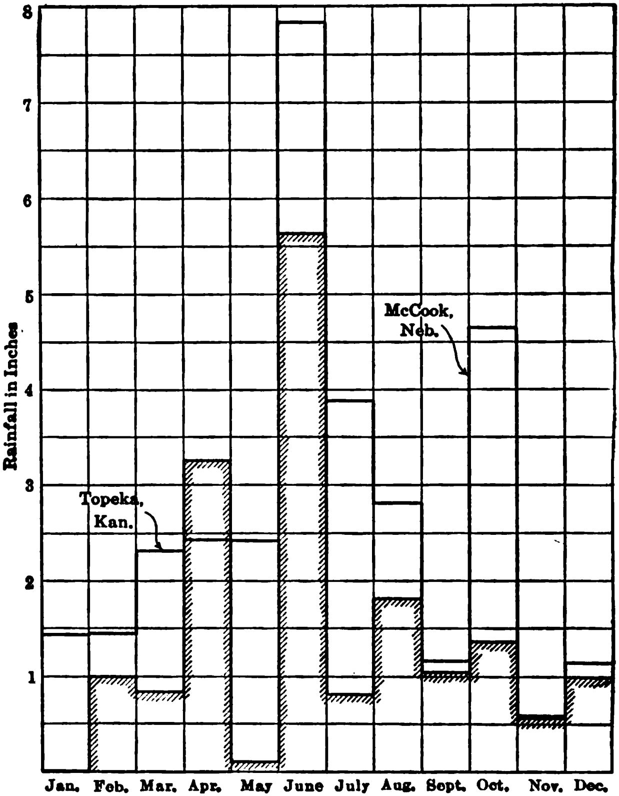


FIG. 64.—Monthly rainfall in Kansas River valley, 1897.

663. Water wheels as current meters. Water wheels if rated to determine their discharge with given head, gate opening, and speed, are in common use as water meters in power plants. If occasionally checked by rod float or current meter measurements they are quite accurate enough to base the use or sale of water on the quantities so determined. The Holyoke test (Par. 706) of a wheel gives the necessary information from which a discharge rating curve may be constructed, but it is more satisfactory if in addition to this, careful measurements are made with the wheels in place.

664. Methods of using current meters are as follows:
(*a*) Single point at 0.6 depth.
(*b*) Two points at 0.2 and 0.8 the depth.
(*c*) Multiple point.
(*d*) Integrating: (1) vertically; (2) diagonally.

The single point method at 0.6 depth (*a*) is supposed to give the average velocity of the vertical section in which it is held. Except in special cases such as natural streams uncontrolled by local conditions this can rarely be relied upon.

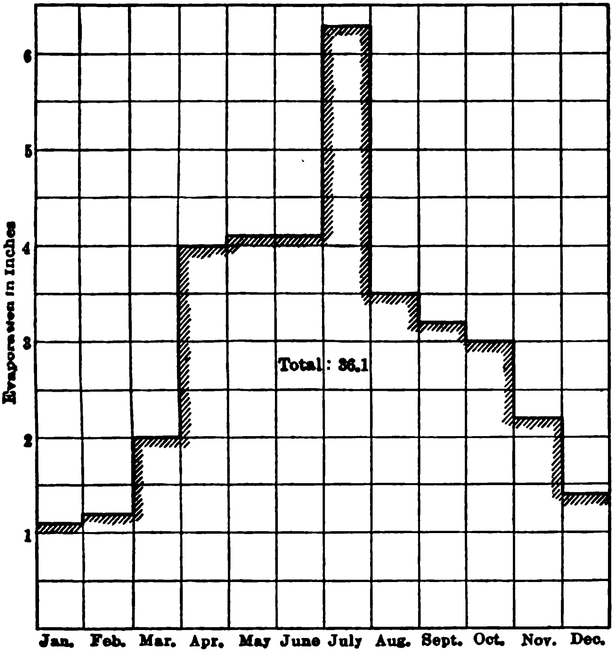


FIG. 65.—Monthly evaporation of Topeka, Kan., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

The average of the two velocities at 0.2 and 0.8 depth (*b*) is supposed to give the mean velocity of the vertical section in which it is held. The same comment applies.

These two methods have been advocated by the government service for quick measurements but are not recommended for accurate work, without actual determinations of velocity distribution in the stream cross-section.

By dividing the cross-section into several imaginary vertical strips of width depending on the total width of the stream and the uniformity of flow, and measuring the velocity at several points in each vertical strip the true mean velocity can be closely approximated. This method (*c*) is recommended for use in power canals where the flow is fairly steady so that during the time consumed in making the measurement there is no material change. It is

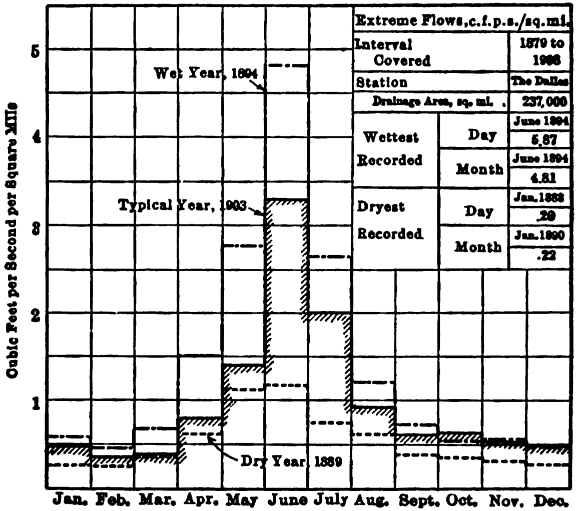


FIG. 66.—Hydrograph of Columbia River from records of The Dalles, Oregon.

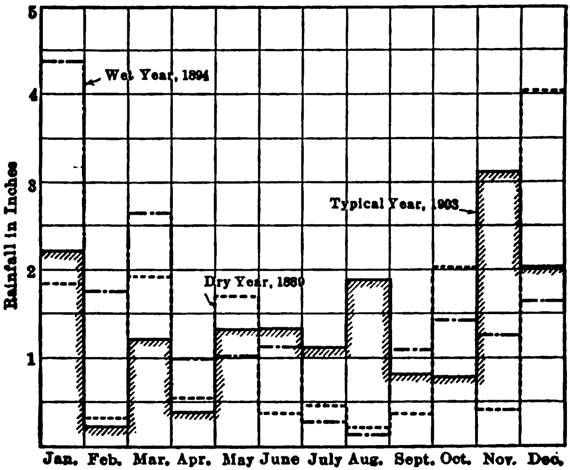


FIG. 67.—Monthly rainfall at Spokane, Wash.

especially useful in showing the distribution of the velocity over the cross-section.

Vertical integrating measurements (*d*) (1) are made by slowly lowering the meter from top to bottom and raising it again along the same vertical path. In this way the average velocity for the strips in order is obtained mechanic-

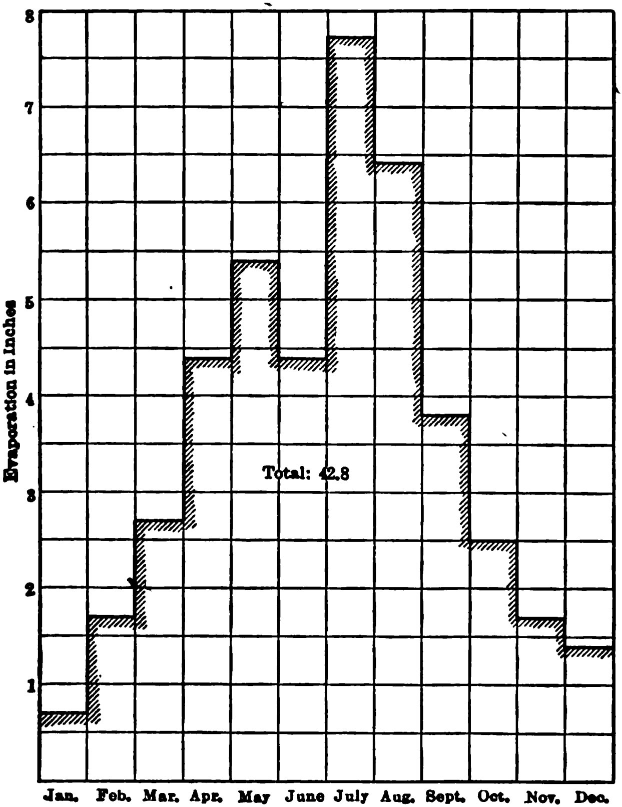


Fig. 68.—Monthly evaporation at Spokane, Wash., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

ally. In diagonal integration (*d*) (2) the meter is moved slowly across the stream at the same time it is being lowered and raised. By this method the mean velocity for the entire cross-section of the stream is obtained in one continuous operation.

665. Choice of method. The width of the channel, the conditions of flow and the degree of accuracy desired are important considerations in selecting the method to be used. By dividing the stream cross-section by verticals into areas of equal width, through the centre line of which the meter is lowered and raised with uniform speed, the mean velocity in ft. per sec.

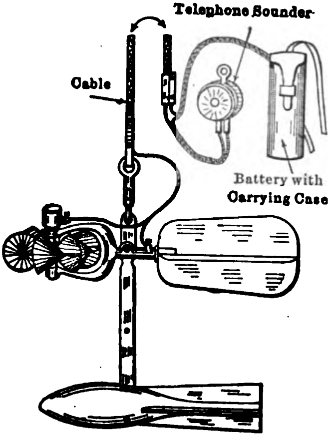


FIG. 69.—Price-Gurley electric current meter.

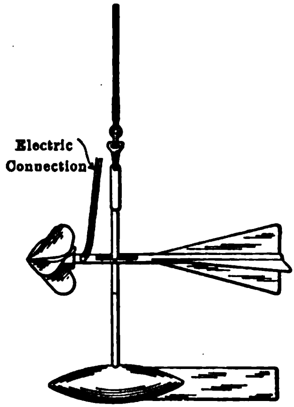


FIG. 70.—Haskell current meter.

for each section is obtained in one operation. This method is on the whole to be preferred for determinations of discharge. The multiple-point method is of great value in determining the distribution of velocity in any cross-section, which is often necessary for at least one gaging; but for determination of discharge this method is tedious and if the stream is subject to fluctuation in stage it is too slow.

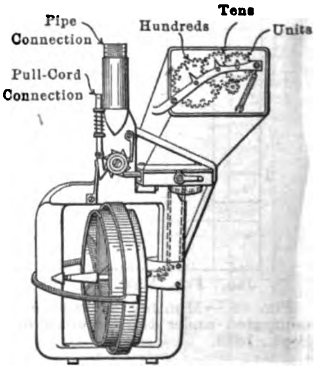


FIG. 71.—Improved Fteley-Stearns current meter.

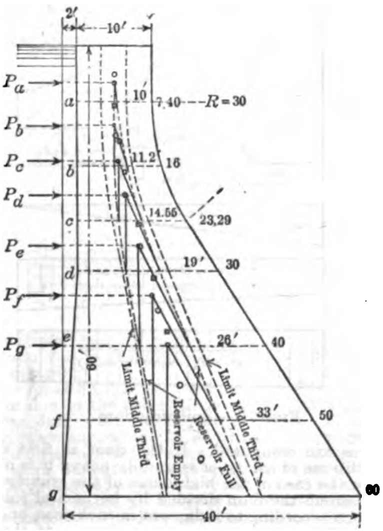
If the channel is not too wide or deep the diagonal integration which covers the whole stream in one operation is a very satisfactory form of measurement because it permits a great many measurements under different conditions and avoids many disturbing conditions. Its use is limited by the endurance of the operator. The double-point and single-point methods are only rough approximations, but serve a useful purpose in securing information of stream flow at low cost.

666. Effect of ice. Ice cover on a stream or canal decreases the cross-section, and increases the wetted perimeter or rubbing surface. Both of these result in additional loss of head, the first through increasing the velocity, the second through increasing the frictional resistance to flow. In power canals the formation of an ice cover of sufficient thickness to last through the cold season is a protection against troubles from anchor ice and frazil ice. Neither anchor ice nor frazil ice will form under an already existing ice cover; the latter is therefore desirable and canals should be designed with this in mind, and the velocities should be kept down (2 to 3 ft. per sec.) by making the cross-section ample for extreme conditions. Anchor ice is ice which forms on the bottom of the stream or canal and may seriously obstruct the flow. Frasil or needle ice forms, as the name implies, in small needles where the current is too rapid for the formation of surface ice. It may either attach itself to the bottom or to anchor ice already formed or it may be carried against and effectually clog the racks of a power house.

DAMS AND HEADWORKS

667. Water storage has already been referred to in Par. **656** and a method outlined for testing out the dependable constant yield. The value of a storage reservoir increases rapidly as the capacity per square mile of contributing area increases up to 15,000,000 cu. ft.; beyond that point there is likely to be a slower rate of increased yield for a given increase in capacity per square mile of drainage area. 75,000,000 cu. ft. per square mile might be an overdevelopment of storage.

668. Pondage, as the term is used here, means the water impounded directly by the power dam and is therefore almost always formed by backing up the river itself. The study of pondage and its proper handling is complicated in the general case, but as a rule comparatively simple of solution for any actual power plant. The reason is that it is involved with the load curve, the natural and legal restrictions of the flowage permissible, and flow detained, and the variation in head economically advisable. Granting the possibility and rights of pondage, the problem reduces to a consideration of fitting the use of water to the demands for power made on the station. If the station carries a typical combined power and lighting load, pondage is essential to satisfactory operation since the great demand for power is during the day-time and the early evening hours. If the head may be drawn down during the day so that the pond will be just filled up by the night flow, the most that is possible is being obtained from the river.



For effect of upward pressure see Spillway Dam

FIG. 72.—Reservoir dam.

In some cases of low-head and medium-head developments the advisable reduction in head is the controlling or limiting factor. As the head falls the power and efficiency of the water wheels fall if the speed is kept up, as it must be in hydro-electric stations. Foresight and study of the probable range of head variation make it possible to have wheels designed with characteristic curves specially suited to the case and a greater variation of head may be permitted.

669. Dams, regardless of the material composing them, may be roughly classified into two main divisions: (*a*) Impounding dams for holding water back, as in a reservoir, but which are not designed to have any water pass over them; (*b*) spillway dams or sections.

670. Impounding dams (Fig. 72) are almost invariably of the gravity type depending on their own weight to resist the forces of the water except in the rare cases where curved dams have been built depending wholly or in part on arch action. The present practice is tending toward heavy earth dams.

671. Spillway dams (Fig. 73) may be further subdivided into gravity types and those depending, through their design, on the hydrostatic pressure of the impounded water to hold them against the river bed, and arch dams. The arch dam is very economical of material but requires that the abutments be founded in strong solid material capable of taking up the thrust.

672. Coffer dams according to their height, the nature of the bottom and the exposure of the location to current or wave action are constructed in a great number of ways. Some of the more common methods are mentioned. Interlocking sheet steel piling, and single or double rows of wooden sheet piling with a puddled filling between the two rows, are forms frequently used. For low cofferdams the A-frame covered with gravel; or bags half filled with sand piled in careful rows have been successfully employed. The design of cofferdams is based on the same principles of hydrostatics governing the design of any other dam.

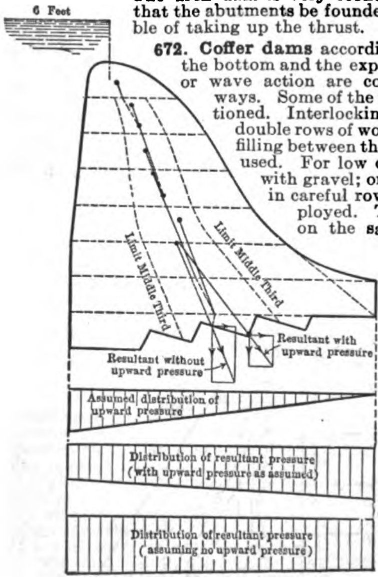


Fig. 73.—Spillway dam.

673. Design of dams. The conditions which should be safely met by all dams are stated briefly as follows: (*a*) the dam must not slide; (*b*) the dam must not overturn; (*c*) the dam must not crush. The external forces acting are the water pressure, the weight of the material composing the dam, the reaction of the foundation, ice pressure near the top, and wind and wave pressure. The pressure usually figured is that of the greatest known freshet, on the toe of the deepest section, without backwater. The cross-section of the dam is determined by trial. A tentative section is assumed and then all the forces are computed. If the dam as first designed cannot satisfy all the conditions of safety or is unduly heavy it is modified accordingly.

In the case of the high dams of the gravity type (Fig. 72) it is customary to assume the dam divided by horizontal joints, the depth of each section chosen according to judgment in each case, and to treat the sections arbitrarily so selected progressively beginning at the top, testing each for sliding, overturning, and crushing. In this way a resultant line of pressure may be traced. In the design of masonry dams it is customary so to proportion the section that the resultant pressure at all horizontal joints shall fall within the middle third whether the reservoir be full or empty. This gives a factor of safety of two against overturning, and there will be no danger from tensile stresses on the face of the dam.

There is rarely any trouble experienced, when proper construction methods are used, from sliding within the body of the dam itself. The joint between the dam and its foundation is the critical point at which to guard against sliding. It is in this connection that the amount of upward pressure becomes of vital importance. On ledge foundations, steps or trenches should be cut to ensure a sufficient bond. On poorer foundations the dam must be made massive enough to safeguard against sliding by keeping the angle between the resultant pressure on the base and a vertical line, less than the angle of sliding of the foundation material. There is no danger from crushing in dams otherwise stable, except in very high dams which are not treated here.

Dams which depend on the hydrostatic pressure of the water to hold them in place (Fig. 74) may be made much lighter than the solid masonry dams. The principal calculations for strength involve the deck treated as a reinforced slab and of the buttresses as walls subjected to simple compression. Fig. 74 illustrates the action of the resultant pressure. If a floor is used weep holes are provided to allow any seepage to escape unobstructed.

For a more thorough and comprehensive treatment of dams reference should be made to chapter XXIX. "Principles of Construction of Dams" in "Water Power Engineering," D. W. Mead (McGraw-Hill Book Co.) and to "The Design and Construction of Dams," Edward Wegmann (Wiley & Son).

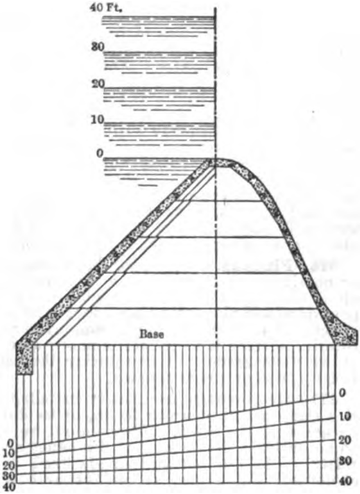


FIG. 74.—Concrete-steel dam.

674. Upward pressure on the base of a gravity-type dam (Fig. 73) should receive most careful study. The limiting conditions are, on the one side, a tight impervious bottom with the dam so set and keyed into it that no leakage can occur under the dam. This in effect assumes an unbroken, water-tight wall extending from below the bed of the river up to the crest of the dam. The other extreme would be a dam founded on loose gravel or porous rock which freely admitted the water under the entire base of the dam, but at the downstream toe a cut-off wall would prevent the water from escaping.

In the first case the assumption is no upward pressure whatever, in the second there would be pressure due to the full hydrostatic head uniformly distributed over the base of the dam. Rarely, if ever, can either of these cases be found in the extreme form suggested. The truth in every case is doubtless between the two. In other words there is probably no dam existing without some upward pressure, its extent to be determined only by a most careful examination of the geological formation of the river bed at the dam site and the thoroughness with which the seepage is cut off by cut-off walls, grouting or other preventive measures. Except in those cases where the dam is founded on ledge rock which gives undoubted evidence of soundness and extent, borings are the essential preliminary to the study and design of a dam. No rule can be given as to the number of borings necessary but in a general way there should be enough to cover the area not only of the spillway section in the river bed, but also of the abutments and wing walls; and other structures near the river; undermining here may prove quite as disastrous as under the spillway section.

In the case of pervious foundations it is desirable to carry a cut-off wall or piling at the upstream toe down to an impervious stratum. Where such does not exist the wall should be carried to such a depth that the friction opposing the flow of water will render the seepage under the dam inappreciable. It is good practice in designing and building dams to eliminate so far as is possible the leakage which causes upward pressure, but to assume in the computations for stability the existence of full upward pressure at the upstream side diminishing uniformly to zero at the downstream toe.

675. The design of canals for power purposes should be made from an economic viewpoint. Canals are employed to utilize a greater head than is obtainable directly at the dam and must be built to give the greatest benefit at the least cost. Head, the very object of the canal, is often unnecessarily lost through poor design of the cross-section and alignment, or through permitting unnecessary roughness of the bottom and sides. Some slope will be required to carry the water through the canal. This should be provided by the canal bottom itself unless the drainage must be in a contrary direction, otherwise an extra loss of head will result, for the slope of the water will reduce the stream cross-section and necessitate a higher velocity to pass a given quantity of water. The form of the cross-section must be determined by its requirements and the character of the material. The form should be such that it will remain as first built and not wash or slide. In general the relatively wide and shallow canals should be avoided because with any drawing down of the head, or with an ice cover the net area suffers a greater proportionate reduction than in the case of deeper, narrower canals. The advantage of the deep canal can also be shown from a consideration of the formulas for flow, which show that for a given area the section with the smallest wetted perimeter will give the best results. The velocity should be kept low and as uniform as possible. If there are changes they should be made gradually and in general a velocity once gotten up should be held. The same statements apply to ditches whether for irrigation or power.

676. Flumes. The word flume implies a narrow waterway with vertical or nearly vertical sides. It was formerly used to designate the canal or penstock conveying water to the wheels at its end. In modern practice a flume is understood to mean an aqueduct of relatively small dimensions constructed usually of timber or concrete employed to carry water long distances. The interior surface is in general smooth and water is carried at a high velocity on an even grade. In computing the carrying capacity of such structures loss by friction predominates.

677. Head-gates are usually installed at the entrance to a canal to control the amount of water let in, or to shut it off entirely in case repairs are necessary in the canal. They should be strong enough to permit the water to be entirely drawn out of the canal and to protect the plant during high water. The number and size is fixed by the quantity of water and such structural limitations as weight and strength may impose. Head-gates are either hand or power operated according to local circumstances; but modern requirements are demanding motor hoists. In designing the piers it is usually well to provide for stop logs for occasional repairs to the gates. Whenever possible the gates should be so set that the water from the river enters at low velocity without sharp contraction or change in direction.

678. Booms either floating or fixed are usual to prevent floating débris from reaching the head-gates, and in northern rivers ice is also diverted over the dam or through special iceways by this means.

679. Penstocks are frequently used instead of canals or in conjunction with them, the choice depending on cost in the case of low-head to medium-head plants. In high-head plants penstocks and pressure tunnels become the only way for conveying water from high elevations down to the power house. Penstocks are usually built of riveted steel plates, wooden staves, or reinforced concrete, depending on local conditions. They must be designed for strength and carrying capacity. Structurally they must be able to withstand the pressure due the head plus the effect of water hammer and also, when empty or partly filled, be strong against collapsing. In long penstocks great care must be taken to provide against **water hammer.** In the first place, the thickness of the shell should be selected with this in mind and, secondly, provision should be made to take care of the surges when they occur. Where the head permits, the most satisfactory protection is given by **stand-pipes** or **surge tanks.** Further protection is given by **relief valves** and **blow-out plates**, usually placed just outside the power house.

The thickness of riveted steel penstocks necessary to withstand water hammer may be computed as follows:

$$t = \frac{(p + p')r}{15000\,e} \quad \text{(in.)} \qquad (131)$$

where t = thickness of the shell in inches (should never be less than 0.25 inch), p = intensity of internal pressure in pounds per square inch, p' = additional pressure in pounds per square inch allowed for water hammer, r = radius of the penstock in inches, and e = efficiency of the riveted joints which varies from 0.5 to 1.

Values of p' to be used in above formula (Eq. 131)

Nominal diameter of pipe (in.)	p' (lb. per sq. in.)	Nominal diameter of pipe (in.)	p' (lb. per sq. in.)
16 and 18	100	30	80
20	90	36	75
24	85	42 to 60	70

In designing penstocks for carrying capacity, the velocity to be allowed will depend, as in the case of canals, on the value of the head saved by additional expenditure in the original construction. The problem must be studied in the light of this consideration and the size of penstock selected accordingly.

680. Cost data. The cost per developed kilowatt of different hydraulic structures varies very much with the type and character of the development; and is relatively less where the power can be generated near the dam or the output is large by reason of a high head or a large dependable flow. A typical development representing fairly average conditions for a built up fall is:

Item	Per cent. of total cost	Cost per kilowatt on 25,000 kw. equipped
Property	19.3	$24.00
Dam	11.6	14.50
Canal	42.3	52.60
Power house and foundations	9.6	12.00
Equipment	17.2	21.40
Total	100.0	$124.50

Note that the cost of the canal in this case is two-fifths of the entire cost; but this is usually the case unless a portion of the fall is left undeveloped.

Steam relay, to supplement dry-weather flow, will add 30 per cent. more to the total cost.

681. Forebay and racks. The forebay, where water wheels do not draw directly from the canal or penstock, is an enlargement of the canal leading directly to the racks of the power house which is built across the lower end. The power house should be set so that the water flows from the canal and passes through the racks with slight if any change in direction. There is necessarily some loss of head in getting the water through the racks and this should be minimised by setting them so that they draw the water directly, as mentioned. Provision must be made by a waste weir and channel so placed that when open a strong surface current will be created making it easy to float accumulated débris and ice away from the racks and discharge them into the river.

Racks are customarily built up of flat iron bars from 1/4 to 1/2 in. thick and 2 to 3 in. wide, spaced an inch and a half or more apart in the clear, with the flat side parallel to the flow. The spacing will depend on the size of the water wheels and the fineness of the material to be excluded. The rack should be sectionalised into panels which can readily be lifted out for repairs. They should be set at an angle of approximately 30 deg. from the vertical in order to facilitate cleaning with a rake from a platform extending the length of the intakes to the power house. They should be designed of sufficient strength to withstand the water pressure as a dam in case they become completely clogged or frozen up. In cases where every effort is made to save loss of head, rack bars are made with rounded edges or of lenticular shape. There is inevitably some contraction of the streams of water in passing through the racks, which should be allowed for in computing the net area to be procured. The velocity through the racks should be kept low, even when partially clogged. Three feet per second should be the maximum allowed under the very worst conditions.

WATER-WHEELS

682. Hydraulics of water-wheels. Force is required to change the velocity and direction of any moving body. In the case of hydraulic turbine motors water is the moving body and the water-wheel (whether impulse or reaction, or combined) is the agent by which the velocity and direction are changed and useful work derived from the process. The portion of the reduction in velocity not chargeable to friction or other losses occurring during the passage of the water through the buckets is a measure of the efficiency of the wheel as a prime-mover. If a jet of water impinges on a moving vane or bucket, assuming a condition of no friction, the bucket will acquire a velocity equal to that of the jet, *i.e.*, the theoretical velocity due the head acting. The velocity of the wheel must be considered that of the centre of application of all the filaments of water. Under this condition, where the velocity of the bucket and of the jet are the same, the jet can exert no pressure on the bucket and no work is done. Actually the bucket velocity must in any case be decreased by friction from that supposed above, and the water must exert at least a corresponding amount of pressure. If now the velocity of the bucket be further decreased until it is blocked, the water is exerting its maximum pressure but again no work is being done. There is some speed of rotation between these two extremes at which the maximum amount of work will be done; that is, the maximum portion of the velocity of the moving water will be converted into useful work. At this point the motor is running at maximum efficiency. Although the buckets and vanes may be simple or complicated, the above fundamental conception holds true and the performance of the wheel may be analysed by a study of the velocity diagrams at the entrance and the exit of the buckets or vanes. This analysis is indicated in Fig. 75.

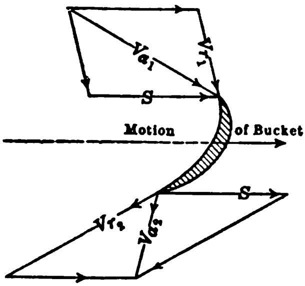


Fig. 75.—Velocity diagram of a water-wheel bucket.

In this diagram S is the peripheral velocity of the bucket, Va_1 is the absolute velocity of the water at entrance, Vr_1 is the resultant of these two and is the relative velocity of the water at entrance. Va_2 and Vr_2 are the absolute and relative velocities at exit. It is the object of good design to make Vr_2 such that Va_2 shall be as small as practicable. But this can be so fixed for only one condition of speed and gate opening. It is this which makes it important to know in advance the conditions under which the wheel is to operate.

683. Types of water-wheels. Modern water-wheels may be classified either as reaction or impulse wheels. While the same fundamental theories hold for each, as pointed out in Par. **682**, the outward form and the method of utilizing the water are radically different in the two types. The **reaction wheel** (turbine) utilizes in the main the pressure of the water and the reactive force on the curved buckets which tend to change its direction. An **impulse wheel** utilizes the velocity and impact of a jet of water directed against buckets on the rim of a wheel. The two types are primarily adapted to widely different conditions: the reaction wheels are best adapted to relatively low heads and large quantities of water; the impulse wheel to high heads and small quantities of water. In recent years reaction wheels have been used for all ranges of head up to 600 or 700 ft., where the units are large. But for heads upwards of 200 ft., with small flow, the impulse wheel of the Pelton type is the natural selection.

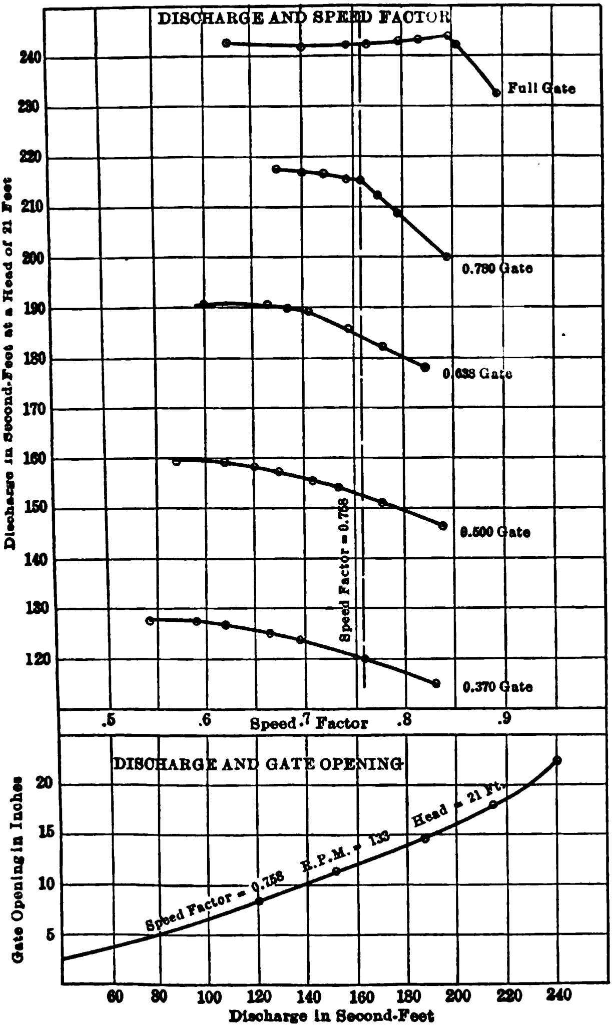


FIG. 76.—Characteristic curves—48-in. turbine.

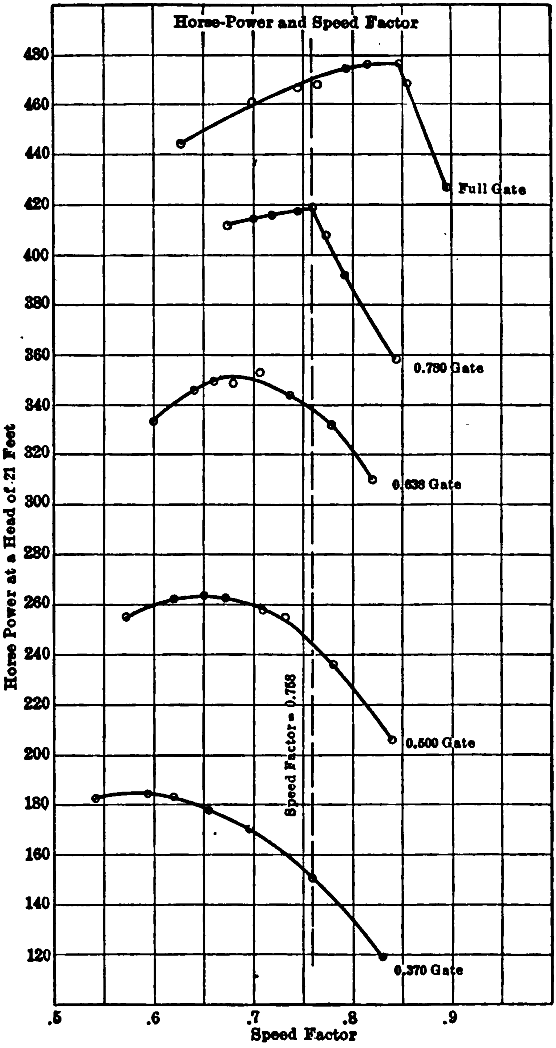


FIG. 77.—Characteristic curves—48-in. turbine.

684. The speed of turbines for a given output and head is confined within quite narrow limits. As noted in Par. 682 there is for any given set of conditions a best speed. This for modern reaction wheels is such that the peripheral velocity is from 0.60 to 0.85 of the theoretical spouting velocity of the water due the head. The best speed may be, and is, varied by design, the recent tendency being toward the development of wheels with high relative velocity; this is easily overdone and is oftentimes secured at the expense of part-gate efficiencies. The best relative bucket velocity in the case of impulse wheels can be shown analytically to be 0.5 and this has been verified by actual tests. Characteristic curves for a modern reaction wheel are given in Figs. 76 to 78 inclusive.

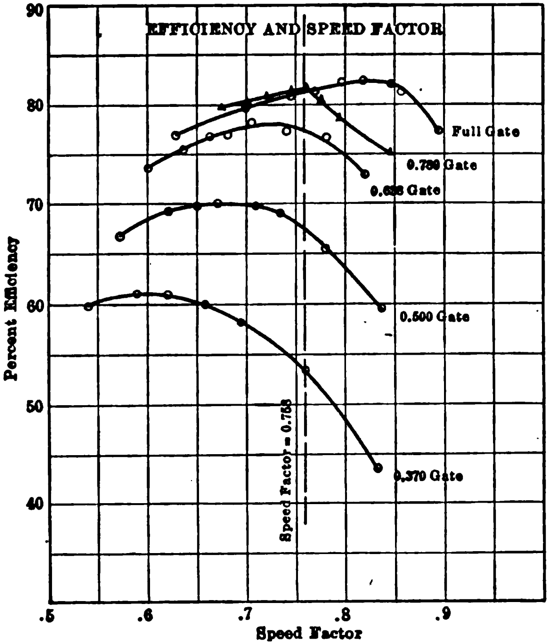


FIG. 78.—Characteristic curves—48-in. turbine.

685. The efficiency of modern water-wheels has been steadily improved by experiment and design until the makers can now guarantee test results of from 80 per cent. to 90 per cent. at the Holyoke Testing Flume (Par. 707). To get the same result in place requires the best design of the setting and waterways. Many wheels which came up to specification in the Holyoke test have failed signally in place to show the power and efficiency of which they were capable. In most of these cases the fault was not in the wheel but in the setting. A wheel improperly installed is not given a fair chance. By carefully tracing the velocity through the penstocks, wheel case, discharge case and draft tube, using net areas throughout, it is possible to design settings which avoid high velocities and undue changes of velocities and direction, and results in place equal to the Holyoke test results may be expected. Efficiency curves for a modern reaction wheel are given in Fig. 78.

686. Water velocity through guide chutes. Mention has already been made of the importance of keeping the velocity of the water through head-gates, canal and racks low. It also should be kept low, not over 3 ft. per sec., as it approaches the guide chutes of the runner itself. There is an exception to this in the case of single runners set in the so-called scroll case. In these, wheel makers are now requiring a velocity of about 15 per cent. of that due to the head acting on the wheel.

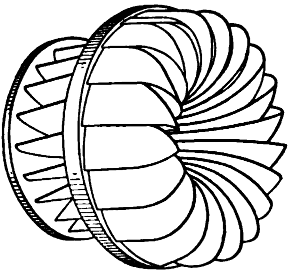


FIG. 79.—Cylinder gate runner.

687. Mechanical details. A cylinder-gate runner is shown in Fig. 79, and a special runner in Fig. 80. The general appearance of a vertical turbine with cylinder gate is shown in Fig. 81, with the usual form of setting in a concrete wheel pit. The same type of wheel with a horizontal setting in a steel flume is indicated in Fig. 82.

688. Settings. There must be equal chance for the water to feed to all parts of the guide circumference. When one or more pairs of wheels on the same shaft are set horizontally, extra care must be taken to insure that the last wheel in the line can draw its share of the water under as favorable conditions as the first wheel. A pair of centre-discharge wheels should be set in the case so that the clear distance between the discharge lips of the two runners shall be at least from 3 to 4 times the diameter of the runners. The greater distance should be used with higher heads; rough limits of heads and corresponding distances are given: 12 ft., 2.5 diam.; 18 ft., 3.0 diam.; 30 ft., 3.5 diam.; 50 ft., 4.0 diam.

Single, large, vertical units have recently received special attention from designers and builders, and it has been demonstrated possible to obtain efficiencies with them about 4 per cent. higher than have been obtained with horizontal settings of equal output. In comparing different settings it is important to know exactly where the head is measured; it is here assumed that the net effective head is taken. See also Par. **711**.

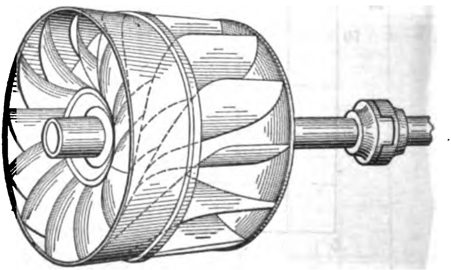


FIG. 80.—Special runner.

689. Ratings. Water-wheels are rated in horse-power, the rating given being usually the maximum output under the head stipulated. It is important to keep in mind three things: (*a*) that a horse-power is a smaller unit than the kilowatt (1 horse-power = 0.746 kw.); (*b*) that water-wheels driving generators must carry the normal load at from 0.75 to 0.80 gate in order to take care of overload on the generators; (*c*) when once under a given head the wheel is discharging its maximum quantity of water no further output can be wrung from it. The attempt to impose a heavier load can only result in reduced speed and output. Simplification would result if water-wheel ratings for hydro-electric plants were stated in kilowatts and generator ratings were stated in terms of the maximum output instead of normal rated output. This would remove the sources of confusion brought about by rating each half of an integral unit by a separate standard.

690. Draft tubes make it possible to set reaction wheels well above tail-water. This is a distinct and important advantage. It makes the wheels accessible for inspection and repair in spite of backwater conditions, and permits the use of horizontal wheels direct-connected to generator or shafting without sacrificing head. In a plant subject to severe backwater, if the machinery floor can be set 20 ft. above low tail-water elevation, draft tubes frequently save great expense in heavy construction and waterproofing of the power house.

A reaction wheel discharging freely into the air would be acted on by a head equal to the distance from headwater elevation to the elevation of the centre of the discharge orifices, minus such losses as occur. The pressure against the discharge is full atmospheric. If now we attach an air-tight pipe of suitable diameter to the runner case and conduct the water down from the wheel and discharge it under the surface of the water in the tailrace we have increased the head acting on the wheel, because now the pressure against the discharge from the wheel buckets is less than atmospheric by an amount corresponding to the vertical distance from buckets to tailrace, where the full atmospheric pressure acting on the water in the tailrace is holding up the column of water in the pipe or draft tube so-called (Fig. 84). A further gain is effected by gradually enlarging the cross-section of the draft tube. This reduces the velocity of discharge and some of the energy present as velocity is transformed into pressure within the draft tube. This increases the column held up by atmospheric pressure acting on the tailwater and correspondingly decreases the pressure against the discharge from the wheel. With good design this may amount to a foot of head. The flare should not be greater than approximately 1 in 10.

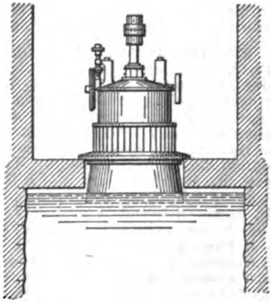


FIG. 81.—General arrangement of vertical turbine with cylinder gate.

The normal atmospheric pressure will support a column of water 34 ft. in height. Draft tubes are seldom used longer than 25 ft. There are

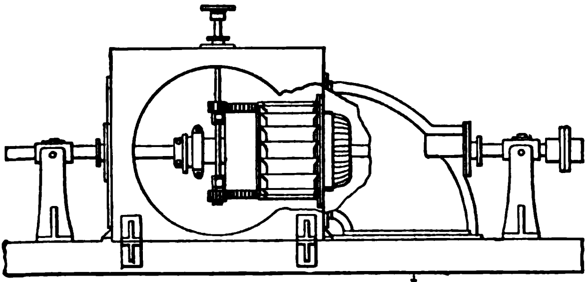


FIG. 82.—Cylinder gate turbine, horizontal type in steel flume.

structural limitations, inevitable losses and some leakage of air which makes it difficult to maintain to any greater height an unbroken column of solid water, essential to the success of the tube. It has been noted that the pressure within the draft tube is less than atmospheric. This necessitates an air-tight design suited to withstand collapsing pressure.

The velocity through the upper portion of the draft tube is necessarily high. For this reason, the interior surface should be smooth to minimise friction and eddy losses; and in the case of horizontal wheels the obstruction caused by the shaft should be made as slight as possible. If draft tubes are set on an angle it should never be more than 45 deg. from the vertical. The elevation of the outlet should be fixed so that the draft tube shall be sealed during lowest tailwater conditions. The velocity of discharge from the tube should in general be a little greater than that of the water into which it discharges, but ordinarily not more than 3.5 or 4 ft. per sec. at full discharge.

691. The tailrace should be designed to carry the water away with a minimum sacrifice of head. It should therefore receive the same care in design and construction as the feeding canal.

692. In selecting the type of wheel to be installed in any power plant the natural conditions of head and flow, with their variations, and the power demand on the plant must be clearly and definitely understood. Stock wheels can be purchased which fit a wide range of conditions; special wheels may be designed to fit a far wider range. The following points should be covered in any wheel selection: (*a*) head, and its variation; (*b*) flow, and its variation; (*c*) speed, and the importance of close regulation; (*d*) power demand, and its variation. These may best be studied in connection with the characteristic curves of different types of turbines; it is in fact the only way of making an intelligent selection from stock designs. The fluctuation in power demand is probably the most troublesome point and the wheel which shows the best efficiency over the desired range may be readily picked out from a comparison of the curves. In the same way the effect of the variations of head on each type of wheel may be seen and allowance made in the choice. A set of common characteristic curves are shown in Figs. 76 to 78; these are drawn from Holyoke test results, reduced to the head under which the wheel is to operate.

Three examples are given below to illustrate three typical but variant requirements which water-wheels have met successfully. The number of units should be based upon the fluctuations in stream flow and power demand; but each unit should be ready to take care of momentary fluctuations.

(1) Ground-wood pulp mill. Here the wheels are run at full gate as long as there is water to run them. High speed is important, but moderate variations in head are of small concern.

(2) Textile mill. There is only moderate variation in load during working hours. Uniform speed is vital; therefore wheels which hold their efficiency for constant speed under variations of head are desired.

(3) Hydroelectric plant carrying a railway and lighting load. Here fluctuations in power demand are extreme and close regulation is essential. Such a plant frequently requires a specially designed runner; the requirements are obvious.

693. Speed regulation. The control of **reaction wheels** is effected by governors which act directly on the wheel gates. There are two general types of governors, mechanical and hydraulic. Either to be most effective should be of the relay type in which* "the energy is transmitted from a source independent—as to quantity—of the centrifugal governor balls but controlled by them in its application." In all cases in which the fluctuations in load may be large and sudden some form of relief must be provided. For open canals the spillway already described for getting rid of débris will answer. For long penstock lines standpipes or relief valves or both should be provided and careful study as needed to ensure the best results.

Impulse wheels may be governed by deflecting the stream away from the buckets or by throttling the stream. The throttling may be accomplished in the case of a multiple orifice nozzle by closing some of the orifices. The usual nozzle is known as the Doble needle nozzle. It is usually the case in impulse wheel installations that the head is great and the velocity of the water high. For this reason the inertia of the column of water contained in the penstock is such as to prohibit, on the grounds of safety, governing by throttling alone. In such cases the first action of the governor is to deflect the stream, the second and slower action is to throttle the flow. This combined control is the most economical of water.

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* Mead, D. W., "Water Power Engineering;" New York, McGraw-Hill Book Co., Inc., 1908.

694. Governors have been developed and improved rapidly in recent years. The increasing demand for close regulation of power plants has stimulated this improvement until now there is a new type fitted to every new requirement. In general it can be said that for small units and for cases of which the textile plant is representative the mechanical governor is admirably suited. For large units such as are becoming common in hydroelectric practice the hydraulic governor is better fitted to develop the great force necessary to operate the turbine gates. According to Mead* governor specifications should call for a guarantee of the following: (*a*) sensitiveness or per cent. load change which will actuate the governor; (*b*) power which the governor can develop and force which it can exert to move the gates; (*c*) rapidity with which it will move the gates; (*d*) anti-racing qualities, such as number of gate movements required to adjust for a given load change; (*e*) general requirements of material, strength, durability, etc. The hydraulic engineer can simplify governing to a marked degree by good design of the penstocks, draft tubes, etc.

695. Operation. The cost of operating a hydroelectric plant is from 10 to 15 per cent. of the first cost.

696. Cost data. A sub-division of costs for a typical case is as follows:

Item	Per kw. year
Interest 6 per cent. on $124.5 (Items 1-5, Par. 680)..........	$7.47
Depreciation 10 per cent. on 21.4 (Item 5, Par. 680)..........	2.14
2 per cent. on 26.5 (Items 2 and 4, Par. 680).............	0.53
1 per cent. on 52.6 (Item 3, Par. 680).................	0.53
Ordinary repairs and maintenance $2⅔ per kw. year..........	2.67
Administration 1.00 per kw. year.........................	1.00
Taxes 2 per cent. on 75.0 (60 per cent. of total cost).........	1.50
Insurance ½ of 1 per cent. on 33.4 (Items 4 and 5, Par. 680)..	0.17
	$16.01

Note that interest at 6 per cent. and depreciation are two-thirds of the total. Steam relay to supplement dry-weather flow will add 25 per cent. to operating cost *without coal*, if charged against the water power.

PLANT DESIGN

697. General ensemble. The location and relative position of the dam, head-works, power house, tailrace, and all other necessary structures must be governed to a large extent by the topography and the geological conditions at the site. The choice between various possible schemes will be based in the main upon the relative cost considered in connection with the efficiency of the proposed plant as an energy producer, or as an income producer. The height to which the dam may be built is usually limited by the extent of flowage damage. In a hydroelectric plant pondage may have great value, making fully warranted the purchase of extensive flowage rights. The spillway section of the dam should be designed to pass safely the maximum amount of water that can be expected. Likewise the abutments and other shore structures must be built to withstand successfully the greatest freshet conceivable on the river. In this connection it is important to realize that under extraordinary flood conditions the channel above and below the dam, and not the dam itself, may frequently control the height to which the water rises. This is especially likely to be the case when the dam is built at the head of rocky tortuous rapids or in a bend of the river.

The intake should draw water from the stream with as little change in direction as feasible and must be protected by some form of boom which shall direct ice and floating débris away from the head-gates and over the dam, or through a waste channel designed for that purpose. Additional head may be obtained over that at the dam itself by carrying the water downstream in canals or penstocks. The advisability of such procedure is determined by a study of the fixed charges on the structure and the value of the increased energy so obtained.

The whole system of waterways from head-gates through the canal or penstock, racks, wheelpit and tailrace to the river should be designed to

* Mead, D. W., "Water Power Engineering;" New York, McGraw-Hill Book Co., Inc., 1908; Chap. XVIII, p. 467.

keep the velocities low enough to avoid excessive loss of head. Fluctuations in velocity are bad, and if unavoidable the changes should be made gradually. It is better to gradually speed the water up from say 1 ft. per sec. at the head-gates to not more than 3 ft. per sec. at the wheel gates, in the case of the ordinary vertical or horizontal setting; the exception in the

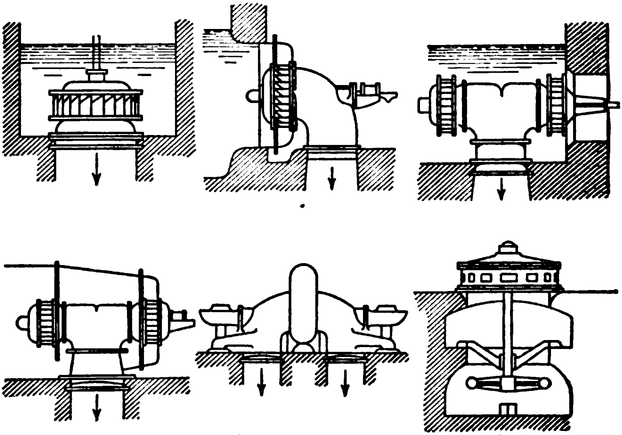

FIG. 83.—Miscellaneous settings of water-wheels.

case of scroll case settings has been noted in Par. 686. Where more than one wheel is mounted on a shaft it is important to provide for equal distribution of the water among the units, and to provide against interference in the draft chest as mentioned in Par. 688. The velocity at the top of the draft tube is necessarily high and should be gradually reduced by enlarging the cross-section of the tube until it is discharged at about 3 ft. per sec.

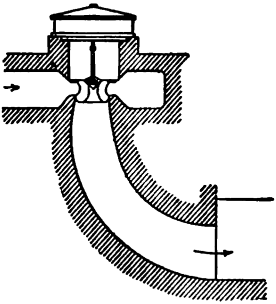

FIG. 84.—Single vertical turbine in a spiral flume direct connected to a vertical electric generator.

698. Typical settings of water wheels are shown in Fig. 83. A modern form of setting known as the spiral or scroll casing is illustrated in Fig. 84, which shows a longitudinal vertical cross-section. The latter type of setting is employed at the Keokuk plant of the Mississippi River Power Co.

699. The economical development of a water-power proposition must depend upon the available power in the river, the market, and the degree to which auxiliary power is to be employed. Two things must be determined as exactly as possible: (*a*) the hydrograph of the river (Par. 658); (*b*) the load curve.

A thorough and exhaustive study of all run-off data should be made where these are available; otherwise study must be made by comparison with similar drainage areas by means of rainfall data. Existing and possible storage should receive careful attention. It should be remembered that on streams with incomplete storage *averages are dangerous*, leading to overdevelopment. Two or 3 days of flood discharge in a month much above the capacity of any possible equipment can raise the monthly average to give a totally erroneous impression of the kilowatt hours available. For this reason, daily records of flow should be used in preference to monthly records, since the daily records bring out the maximum and minimum flows and the final estimate can be much nearer the truth.

The probable load curve is of prime importance, and taken together with the available pondage it will determine the number and size of units to be installed to give flexibility and economy in operating.

700. Auxiliary power. If a relay station, steam, gas or oil, be used, it should be placed as near the market or sources of fuel as economic conditions warrant. Its capacity must be determined by the daily and yearly hydrograph and the load curve. So many combinations of conditions of pondage, storage and load occur that every case must have special and detailed study. There are very few developments where a relay station owned either by the seller or the buyer of hydroelectric energy is not almost essential.

701. Choice of units. With varying load, efficiency requires two or more units so that during the hours of minimum demand the machine or machines on the line can carry the load at good efficiency. Then as the load comes on additional machines are cut in as needed.

702. Provisions for handling floods include: (*a*) **flashboards**; (*b*) **Tainter gates**; (*c*) **sluice gates**. It has been noted that the height to which a power dam can be built is usually limited by the extent of the flowage permissible (Par. **697**). This necessarily applies to the high-water stages which may be expected every year, and settlements for the necessary rights are usually made once for all. During most of the months in each year increased pondage or head, or both, can advantageously be procured by raising the dam without creating greater flowage than occurs during high water from the dam at its permanent elevation. This is accomplished in a number of ways, but most commonly on power dams by the use of flashboards which are designed to bend over or go off during floods. In this way provision is made for handling floods at the moderate cost of replacing the flashboards.

In order to provide for the occasional summer freshet and to give greater discharging capacity in cases of great freshets **flood gates** are incorporated in many modern dams. When warned of a freshet, probably of short duration, it is frequently possible by opening the gates in the dam to pass the extra water without straining or losing the flashboards. Flashboards are ordinarily held in place by either wrought-iron pins which will bend over, or light wooden figure-fours which will break when the water rises too high. The development of water power on navigable streams also leads to the use of Tainter gates, Chanoine wickets, Bear traps and other forms of movable dams ordinarily suited to their purpose, but which in northern rivers carrying much ice must be designed with great care.

703. Log sluices and fish ladders are necessary appendages to most power dams. A log sluice is an inclined chute on the downstream side of the dam with a gate at the crest which is opened whenever a log drive must be run past the dam. These are usually required by law where log driving has ever existed on the river. Fishways are required by federal law on most rivers and must be kept open during certain portions of the year. There are various forms, two of which are mentioned. One is constructed to form a flight of pools, the water spilling into each successively. The other is a chute set at a moderately flat slope with baffles built alternately from the right and left sides, about three-quarters of the way across.

704. Buildings and foundations. The conditions controlling plant design are discussed in detail in Par. **697**, **700** and **701**. Foundations are usually subject to water pressures due to head or backwater or variations from drought to flood conditions. These conditions usually require foundations much in excess of ordinary building requirements.

The size, height and arrangement of buildings usually follow these hydraulic conditions and the type of unit selected.

705. Summary of unit costs. Unit costs common to most water-power developments with some idea of the range of prices which depends upon the amount of each contract, distance from markets, difficulties of handling, etc., are:

Rock excavation under water	$5.00 to $10.00 per cu. yd.
Earth excavation under water	0.50 to 2.00 per cu. yd.
Rock excavation in the open or behind tight coffer dams	1.25 to 2.00 per cu. yd.
Earth excavation behind tight coffer dams	0.25 to 0.50 per cu. yd.
Coffer dams	5.00 to 10.00 per lin. ft.
Reinforced concrete	8.00 to 12.00 per cu. yd.
Ordinary concrete	6.00 to 8.00 per cu. yd.
Reinforcing material	0.03 to 0.05 per lb.
Penstock and draft tubes of steel plate, erected	0.03 to 0.05 per lb.

TESTING

706. Water-wheel testing has played a vital part in the improvements which have been accomplished in the design and construction of turbines. Every water-wheel should be tested if possible before it is installed. That a similar wheel of the same make, diameter and pattern has been tested and shown satisfactory results is no guarantee that a wheel which has not been tested will give similar results. The expense of the test should never be allowed to militate against it, for a gain of only 1 per cent. in efficiency will pay for the test in a relatively short time. Specifications and guarantee requirements should be drawn with care and include where feasible provision for final acceptance tests in place, in addition to the preliminary tests at the Holyoke Testing Flume. In addition to finding out whether the wheel has met the specification requirements, the tests furnish data by means of which the use of the wheel as a water meter is possible (Par. 663).

707. The Holyoke Testing Flume furnishes the only place in this country where systematic testing is carried on. The maximum head is 17 ft. and the maximum discharge possible is between 250 and 300 cu. ft. per sec., at which discharge the head is reduced nearly one-third. In spite of these limitations the tests are invaluable to the water-power engineer and form a common basis of comparison for designers.

708. The quantities to be measured in a water-wheel test are speed, head, discharge and power output. At the Holyoke flume these are observed by a revolution counter, head and tail water gages, weir and Prony brake, respectively. Various gate openings are selected and for each opening the wheel is run at many speeds in order to determine the most efficient speed for each gate.

709. For making the final acceptance test of water wheels a test in place is becoming more frequent. Such a test furnishes direct evidence of the performance of the wheels under service conditions.

710. The general problem is that of any test of power machinery: namely, to measure the input and the output. To measure the input requires the measurement of the head and the quantity of water used by the unit under test.

711. The points of measurement of the head should be selected to show the net head actually acting on the wheel. Friction losses in canal or penstock and tailrace are not properly charged against the performance of the turbines, however much they may affect the overall efficiency of the plant. The point therefore at which to measure the headwater is just before the water is drawn to the guide chutes, and the tail-water should be observed at the nearest feasible point to the discharge of the draft tube. In open flume settings the head water is observed in the flume. In the ordinary pressure-case setting a gage should be tapped into the side of the penstock (Par. 640, *piezometers*) just clear of the case in order to avoid disturbances due to eddies and uneven flow in the case. In a scroll-case setting, the scroll, like the draft tube, must be considered an integral part of the wheel and the head should be measured between the entrance to one and the discharge of the other.

712. Measurement of the quantity of water used presents some difficulties unless special provision was made in the design of the plant. It has been usual practice to install a weir in the tailrace. Unless the conditions are exceptional the results are subject to serious but undeterminable error due to the relatively high velocity of approach to the weir (Par. 609 *et seq.*). The attempt is made by building the crest high enough from the bottom to cut down the velocity, the head acting on the wheel is thereby reduced and at once the actual service conditions are only approximated and the peculiar value of the test in place is partially vitiated. It is difficult to make the conditions of the channel of approach to the weir suitable for good measurements and the expense of installation is relatively great. Whatever method of measurement is used, there should be an agreement in advance by the buyer and seller of the wheels to accept the results. Where conditions for their use are right, rod floats (Par. 643) afford an excellent means for measuring the flow either in the headrace or tailrace.

The easiest measurements to make properly are probably those with a current meter (Par. 662). The expense is slight and in the hands of careful and experienced operators simultaneous measurements in head race and tailrace will give excellent results without interfering in any way with the normal service conditions of operation. Suitable measuring stations may be easily included in the original design of the plant at little or no extra expense.

For relatively small units fed by penstocks, the most accurate measurement without question can be made by a venturi meter(Par. 636) incorporated in the penstock when the plant is installed. When properly rated it has the great advantage of giving a continuous record of flow.

713. For measuring the output two general methods are available for a hydroelectric station. They are (1) to measure the energy generated electrically, or (2) with some form of absorption dynamometer. The electrical measurement requires that the driven dynamo shall have been carefully tested and the efficiency determined for all loads. Electrical measurements can be made with great accuracy but the determination of the turbine output by this means is somewhat indirect. With the development of the **Alden dynamometer** direct and accurate measurement is possible. This apparatus is described as follows by Prof. C. M. Allen:

"It is a form of Prony brake, and usually consists of several smooth circular revolvable cast-iron discs keyed to the shaft which transmits the power; a non-revolvable housing having its bearings upon the hubs of the revolving discs; and a pair of thin copper plates in contact with each cast-iron disc, the plates being integral with the housing. Through a system of piping, water under pressure is circulated through chambers between the units, each consisting of a disc and its copper plates, and between the outer plate at either end and the wall of the housing. The water pressure is regulated by hand or by an automatic valve. Another system of piping circulates oil for lubricating the surface of the copper plates next to the revolving discs."

714. Advantages of the test in place. The test in place, if made complete enough to cover all gate openings under normal conditions of head at the plant, will serve two purposes: it will tell whether the wheels tested are up to specification; and it will provide a means of measuring the daily or hourly amount of water drawn by the plant so long as the wheels are kept clean and in good repair, and the operating conditions are essentially those obtaining during the test. These records if carefully kept become of great value to the owner and operator of the plant.

ELECTRICAL EQUIPMENT OF POWER PLANTS

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ELECTRIC GENERATORS

715. Types of generators are covered in Sec. 7 and Sec. 8.

716. Generator characteristics required for a given power plant are largely determined by the size, overload capacity, speed, speed variations, and possibilities of over speed of the prime mover; the size of the plant, the number of units, the load factor, fluctuations and power-factor of the load; the voltage and type of the distribution system.

717. Sizes of generators. The ratio between the adjacent sizes of generators varies from 1.25 to 1.50. The size limitations seem to have been reached only for direct-current generation, where 2,700 kw. is the largest obtained commercially. Engine-driven alternators are in operation which will carry from 8,000 to 10,000 kv-a. continuously without overheating. Water-wheel alternators are built up to 20,000 kv-a. and there is little doubt that larger sizes can be built if required. Steam-turbo-driven alternators are being built up to 30,000 kv-a.

718. Overload capacity in generators is necessary only when the prime mover has ability to deliver loads greater than rating, or in special cases where it is desirable to install a generator smaller than the maximum output of the prime mover. Gas engines which will stop when their rated capacity is much exceeded, require generators which will reach their maximum safe temperature when continuously operated at rated load. This same condition is required of steam turbines when rated at the maximum capacity, and by water-wheels except in very unusual circumstances. Steam engines which are rated at their most economical load, or steam turbines having overload valves, require generators with considerable overload capacity. Generators of the first class are usually designed to carry their rated load continuously with a temperature rise of about 50 deg. Cent. Generators of the second class are designed to carry rated loads continuously with 40 deg. Cent. temperature rise, and 25 per cent. overload with a 55 deg. rise. It is doubtful if this latter temperature is safe except for temporary operation.

719. Speeds of standard designs range from 75 r.p.m. upward, the ratios between adjacent speeds being from 1.1 to 1.2. Low speeds are confined to large machines. Several speeds for the same size are usually available, particularly in small and moderate sizes. The speed of direct-current machinery is limited by commutation. High-speed direct-current generators, even of relatively small size, are not recommended. The speed of alternating-current generators is controlled by frequency and by number of poles. At the high speeds, ventilation becomes one of the principal problems, but the manufacturers have solved it to such an extent that machines are offered in sizes up to 5,000 kv-a. at 3,600 r.p.m. and up to 30,000 kv-a. at 1.500 r.p.m.

High-speed generators deliver short-circuit currents of enormous instantaneous value, even though the sustained short-circuit currents are limited. This characteristic is of greatest importance in large systems, particularly in reference to switching methods (Par. **799**).

720. Speed variations or fluctuations in the driving torque have a tendency to accentuate the difficulties of commutation. In alternating-current machines the speed variations are of great importance to parallel operation, particularly when the speed is low and the number of poles is large. The driving impulse in gas engines and low-speed steam engines being non-uniform, flywheels of large moment of inertia are required to keep down the speed fluctuations so that satisfactory parallel operation may be obtained. It is usually necessary to have alternators for this service designed with large armature reaction and reactance, so that the angular variations will produce a minimum of surging in the electrical circuits. With gas engines it is necessary to use short-circuited pole-face windings.

721. Runaway speeds. In engines and turbines it is easily possible to provide emergency governors so that generators need be specified to stand only about 30 per cent. overspeed. In water-wheel units, however, the difficulty in caring for the inertia of the water in long pipe lines makes it necessary to have generators safe at 90 per cent. to 100 per cent. over-speed.

722. Inherent regulation. In very small plants good regulation is to be sought for, particularly on account of the lack of skilled attendance, and also on account of the large number of other uncontrollable influences affecting the uniformity of voltage. In the larger plants the question of regulation is of less importance because of better attendance and the feasibility of automatic regulating devices.

In very large plants the importance of keeping down short-circuit currents, both instantaneous and sustained, looms up in such large proportions that regulation is completely neglected except as may be necessary to secure proper conditions of parallel operation. In these large plants it is usual to go to considerable expense to secure automatic regulation of voltage allowing generators of exceedingly low inherent regulation. Induction generators and current-limiting reactances (Sec. 6), are also used in some large plants to limit short-circuit currents.

723. The number of units has relatively small influence except as affecting parallel operation, the conditions of which are more exacting in a plant of many units. (Also see Par. 724.)

724. The load factor, or the form of the load curve has particular influence in determining the number of units to be installed and the overload capacities of the same. With a steady load for 10 hr. per day, generators should be installed to carry the load with one unit shut-down, without exceeding the overload capacity. With large short peaks for a few months in the year, and much smaller loads during the other months, the peaks can safely be carried at overloads even in excess of 25 per cent. for which generators are frequently specified.

725. Load fluctuations. If the load is widely fluctuating, such as on electric railways of few cars, the commutation limit of direct-current machines determines the size to be installed. Interpole generators with ability to commutate loads far above the usual rating are frequently used so that the average load may approach the heating limit. In alternating-current machines this question is of less importance, as they are stable at very considerable momentary overloads. In single-phase railway systems where violent short-circuits are frequent the windings need to be specially braced. Fluctuating loads will cause considerable voltage variation and may determine the requirements of regulation, particularly in small and medium size plants. Compounding is almost invariably resorted to in direct-current plants and sometimes in small alternating-current plants; even then there is considerable variation in voltage, especially on rapidly varying loads.

726. The power-factor determines not only the kilovolt-ampere rating of the generators to be installed, but also the size and resistance of the field windings. Machines required to carry lagging loads need larger fields than machines to carry leading loads of the same magnitude. Generators are usually supplied with field windings suitable to care for full inductive loads at 80 per cent. power-factor. This is usually sufficient to take care of any condition which may be expected.

727. The voltage. Direct-current machines are available at 125 volts, 250 volts, two-wire and three-wire, and 600 volts, with 1,200 volts as a possibility, alternating-current machines at the above voltages and in addition 2,300 volts, 2,300/4,000 volts, four-wire, three-phase, 6,600 volts, 11,000 volts and 13,200 volts. Higher than 2,300 volts, without the use of compensators or transformers, is not recommended in small high-speed machines. 11,000 volts and above in turbo-generators, except of largest size, should be avoided, but is entirely safe in slow-speed machines. Other voltages are used at times but the machines are special. Occasionally it is desirable to use generators connected in delta at 2,300 or 6,600 volts but insulated for 4,000 or 11,000 volts, making it possible later to increase the voltage of the system. High-voltage machines are usually star connected, because of the possibility of larger conductors and more rigid windings.

728. Foundations for electric generators are usually parts of those of the prime movers. The type and form is largely dictated by the requirements of the prime mover. It is becoming the practice to support turbo-generators on skeleton foundations and even directly on the floor with a basement underneath. For the cost and detailed design see Sec. 10.

729. The erection of generators covers a considerable range of work depending upon the method of shipment. Small machines are shipped completely assembled and the erection consists merely of placing in position and leveling. With larger units the facilities for transportation and hauling limit the sizes for separate parts and in extreme cases the machines are shipped almost completely dismantled, requiring the most careful work in erecting them and preparing them for preliminary operation by drying and voltage tests.

730. Preliminary operation requires a determination of the polarity or phases, before actual connection to the lines, as well as careful watching and testing during operation necessary to determine whether or not the machine is perfect and ready for regular and continuous service. Phases as marked in the factory should not be depended upon unless testing is impossible, Phases and synchronising equipment may be checked by connecting to a spare machine and bus, bringing up to speed with the spare machine and synchronizing by the use of the apparatus on the spare machine. If no spares are available, lamps, alone or with shunt transformers, connected across the open switch may be used. Simultaneous dark lamps indicate correct phases; when lamps do not darken and brighten together crossed phases are indicated.

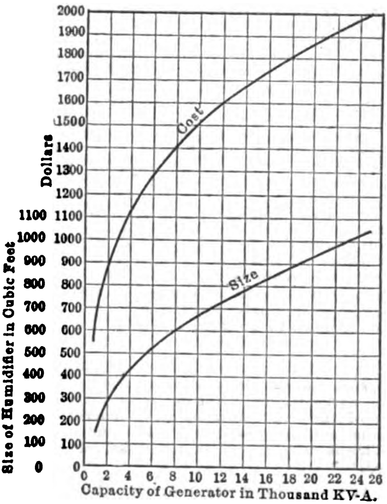

Fig. 85.—Size and cost of humidifiers (*G.E. Rev.*, Sept., 1913, p. 634).

731. The volume of air required for cooling is generally about 5 cu. ft. per min. per kv-a. of generator capacity.

732. Cleaning the air is a matter of great importance but frequently neglected. Dirt which clogs up the air passages and coats the cooling surfaces prevents proper cooling and shortens the life of the machine. Reasonable cleanness may be secured by having the intake above the roof, thus keeping out all but the finest dust. If the air must be taken from near the ground, it should be filtered by passing at low velocity through one or more thicknesses of cheese cloth or Canton flannel. Complete cleaning requires large areas, amounting to about 1 sq. ft. per kw. of generator capacity. Means must be provided for the ready cleaning

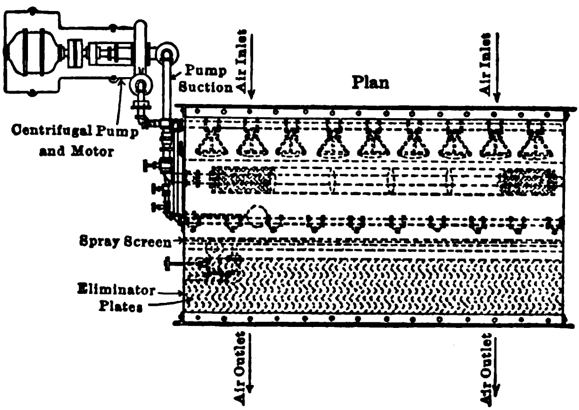

Fig. 86.—Air washer, Spray Eng. Co.

and replacement of screens. Water screens or humidifiers are coming into favor, the air being passed through falling water which takes out the dust, and then freed from mist by baffles (Fig. 86). This method has the added advantage of cooling the air several degrees. The value of this may be seen in Fig. 87.

733. The cost of erection and preliminary operation of generators ranges between wide limits depending upon local conditions. Smaller machines which are shipped assembled may cost for erection and preparation for regular service, in reasonably equipped stations, from 4 per cent. to 5 per cent. of the cost of the machine at the factory. If the machine is shipped dismantled, the cost of erection will be about 1 per cent. to 2 per cent. higher. The cost of erecting large machines is from 4 per cent. to 5 per cent., and in a few cases where conditions allow shipment assembled, about 1 per cent. can be saved. An average cost, for machines from 500 kw. to 6,000 kw., can be obtained from the formula $C = \$400 + \$0.32$ kw., where C is expressed in dollars. Freight and haulage is dependent absolutely on location and local conditions, and may vary from 1 per cent. to 15 per cent. of the cost of the machine.

734. Ventilation. The continued success of ventilation methods has a most important influence in determining the life of the insulation. The requirements call for a plentiful supply of cool air free from dust, oil and excessive moisture. Except in turbo-generators, no special means are taken to fulfill these conditions other than those provided in the machine. In high-speed turbo-generators, however, large volumes of air at enormous speeds are passed through the windings, and the utmost pains should be taken to maintain the best possible conditions. In most stations it is customary to take the cooling air directly from, and discharge it into the turbine room, but in cases where the room cannot be well ventilated, this arrangement may overheat the room and the machines. In some stations it has been found possible greatly to increase the capacity of the generators by installing specially designed vanes on the rotors, thus passing much larger volumes of air. With a machine thus ventilated, the coils quickly become dirty and much care has to be exercised to keep out the oil that permeates the atmosphere. In the larger stations it has been found important to install ventilating ducts taking cool air directly from outside the building. The ducts should be of liberal size to keep down air velocities to about 1,000 ft per min. Dampers should be provided to enable shutting off the air supply in case of burn-outs. Ventilation by separately driven blowers is being used and is strongly recommended by some engineers.

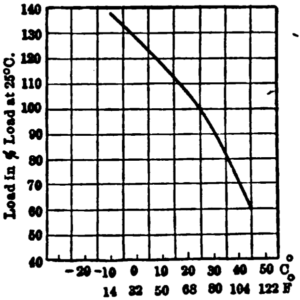

Fig. 87.—Safe load and temperature of cooling air (*G. E. Rev.*, Sept., 1913, p. 633).

735. The cost of ventilating ducts arranged for cleaning the air should not be more than 25 cents per kw. of generator capacity.

736. The operating temperature, combined with the kind of insulation, determines absolutely whether or not the machine is overloaded. Temperatures are difficult of measurement, particularly in respect to finding the hottest parts. It is the maximum temperatures which are of importance, and it is probable that these are never found in tests. Resistance temperature tests are difficult to make, and in large machines take considerable time after shut-down; such tests give only average copper temperatures, which are certainly less than the maximum. Ordinary thermometer tests give the temperature of the outside of the insulation, and by means of refinements it is possible that maximum temperatures can be measured to within 10 deg. to 20 deg. Cent., but this method is not recommended. Resistance thermometers and thermo-couples, inserted between the coils and the iron, have been used with considerable success. The actual indicator may be located anywhere convenient, even on the switchboard, where continuous record of the temperature may be kept. This method gives more consistent and precise results than the others and probably shows more nearly the maximum temperatures.* Indicating electric thermometers, several for each machine, can be installed for $100 to $200 per machine.

737. Safe temperatures of insulation are given by C. P. Steinmetz and B. G. Lamme in the February, 1913, *Proceedings* of the A. I. E. E. as 90 deg. Cent. for fibrous insulation such as is commonly used, and 125 deg. Cent. for mica and other fire-resisting materials. These temperatures are the measurable temperatures rather than the absolute maximum that may be expected in local spots. H. G. Stott recommends 20 deg. lower temperatures especially on high voltage work.

EXCITATION

738. Excitation equipment should be designed with a view to the maximum possible **continuity of service.** Simplicity, ruggedness, "foolproofness" and reserve apparatus are important requirements. The methods in use for securing these results are greatly varied and much difference of opinion exists as to the best method. Each plant must be considered as a separate problem.

739. Exciters directly connected to the main generators were the earliest form in use. They are now seldom used in steam or gas engine plants, but are used in some of the largest and most recent hydroelectric stations with satisfactory results. Each exciter is frequently made large enough to handle two generators, in emergencies. The chief arguments in favor of this method are simplicity, high efficiency and the absence of large field rheostats. The most important objections are the possible crippling of a large unit due to trouble with its exciter, and the fact that voltage fluctuations in per cent. are twice as great as the speed fluctuations.

740. Exciters driven by separate prime movers are necessary in all stations except those above mentioned (Par. 739). They may be obtained for service with any kind of prime mover. On account of their small size the efficiency of the unit is very poor, this constituting the chief objection to their use. Where steam at atmospheric pressure is necessary for feed-water heating, the inefficiency is of no importance. Their use is determined principally by questions of convenience and economy, it being absolutely necessary to install them for starting purposes.

741. Motor-driven exciters are in use in almost all stations. They are cheap, economical, efficient and reliable, but cannot be used for the complete equipment. They should not be driven by synchronous motors, because short-circuits on the outside system not in themselves sufficient to cause a shut-down of the station, are likely to throw the motors out of step, thus shutting down the plant. Induction motors are almost invariably used. A well-balanced exciter plant consists of units driven both by motors and by prime movers. In some cases, motor-driven units are considered as auxiliary to the prime-mover units, and in other cases the motor-driven plant is considered of first importance; the first plan is probably most in favor.

742. The importance of continuous excitation points strongly to **storage batteries** which are frequently installed of sufficient capacity to excite the entire plant for an hour. Danger of a shut-down of the entire plant by failure of the exciters is not considered great enough in all cases to warrant the great expense of a battery. When used, it may either be floated on the excitation busses, or allowed to stand by fully charged.

743. A new method of securing continuous service is being introduced with great promise. The exciter generator is arranged to be driven both by motor and prime mover. The motor is provided with a relay which shuts it down if the voltage becomes low. The governor is arranged practically to shut off the steam at normal speed, but after cutting off the motor, the prime mover continues to drive the unit at but slightly reduced speed.

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* Reist, H. G. and Eden, T. S. "Method of Determining Temperature of Alternating-current Generators and Motors, and Room Temperature;" *Trans.* A. I. E. E., 1913.

744. The size of the exciter plant depends upon the size of the power plant and the types of generators used. Small, low-speed generators require up to 3 per cent. of their capacity for excitation. Large, high-speed turbo-alternators may require as little as 0.75 per cent. The exact requirements may be obtained from the manufacturer. The total capacity should be ample to carry the whole excitation load with the spare apparatus out of commission. The amount of spare apparatus required is not very definite; practice ranges all the way from depending on the overload capacity to having two to three times the total capacity required.

745. The number and relative size of the exciter units should be chosen for the greatest simplicity and the required flexibility. The minimum size of any unit is in general dictated by the requirements of the largest generator. It is doubtful if the largest exciter should be large enough to excite the entire plant. Except in very large plants a size sufficient for half the equipment, with a total of three units, will give very satisfactory results.

746. The exciter voltages in common use are 125 volts for all except the very largest plants where 250 volts are used. The generators are usually flat compounded. With standard exciters it is possible to run at not more than 15 per cent. over standard voltage, which is quite sufficient to take care of the excitation of ordinary alternators at full-load. Where overload capacities are to be used, it is frequently desirable to raise the excitation voltage as much as 25 per cent. during the peaks. Exciters can usually be arranged for this voltage with very little deviation from standard design.

747. The cost of exciter sets installed, ready to run, exclusive of wiring, piping, etc., correct to plus or minus 10 per cent., (covering ordinary differences in speed and other commercial differences in design), may be expressed as follows:

High-speed compound-engine drive,	$1,000 plus $35 per kw.
High-speed simple-engine drive,	$750 plus $26 per kw.
Steam-turbine drive,	$425 plus $31 per kw.
Induction-motor drive,	$625 plus $15 per kw.

The cost of exciters attached to the shafts of the main generators can best be expressed as a percentage of the cost of these generators; this will vary from 3 per cent. to 5 per cent., depending somewhat on the speed.

748. Exciter wiring systems are in use covering practically all the direct-current types of switchboards. On account of the low voltage no complications need be entered into except as may be necessary to make available the various sources of excitation. Occasionally a double exciter bus is desirable, but in most cases it adds complications without any adequate gain to the service. Alternating-current wiring for motor-driven exciters should be worked out on the basis of the exciters being most important feeders, unless, however, the presence of a storage battery makes this treatment unnecessary. In stations above 2,300 volts, it is recommended to use transformers in connection with the exciter motors, as small machines wound for high voltage are not of sufficient reliability.

749. Excitation switching appliances. The current must not be broken without at the same time short-circuiting the field windings, otherwise punctured insulation will result. This requirement calls for special field-discharge switches. It also limits the use of circuit-breakers to those operating on reverse current, thus serving to cut out damaged exciters. Fuses of very large overload capacity, which will blow only during most severe trouble, are used for the protection of the exciters.

750. Field rheostats for small generators are usually mounted on the back of the switchboard, but for large machines some more conveneint location involving remote control is necessary. Electrically controlled rheostats are frequently necessary in large stations and are operated either by solenoid and ratchets or by motor; the latter is necessary where the field current exceeds 300 amp.

VOLTAGE CONTROL

751. Hand regulation. Voltage is controlled in all systems by hand regulation, whether or not there are automatic means. Hand regulation alone is suitable only where the load is steady and the generators inherently regulate well.

752. Automatic regulation may be secured by two methods; first, the automatic adjustment of the field resistance by motors or solenoids controlled by a relay; second, the alternate short-circuiting and insertion of resistance in the field circuits. The first method is used in the **Thury regulator** the second method in the **Tirrill regulator.** The first method makes the adjustment more or less gradually; the second changes the resistance much more than necessary, alternately one way and then the other, while the time lag of the field windings produces a practically steady voltage of a value depending upon the proportionate time the resistance is in and out of circuit. The latter method is inherently more sensitive than the first and is practically the only one in use in America.

753. The Tirrill regulator for small direct-current machines operates as follows (see Fig. 88). The regulation depends on the rapid make and break of contacts *A* which short-circuit the resistance in the shunt field circuit of the generator. The closure of these contacts depends upon the machine voltage across the relay *B*. The contacts closed by this relay serve only to close or open one of the two differential windings on the magnet *C*, which in turn operates contacts *A* cutting in or out the field resistance. When the voltage is high, relay *B* opens one winding in *C* which in turn causes the latter to open contact *A*, inserting the resistance, and *vice versa*. The final result of operation is that the contacts vibrate continuously and remain open or closed a longer or shorter portion of the time as may be required to keep the voltage steady. A regulator of this type with multiple contacts at *A* can control machines up to 125 kw.

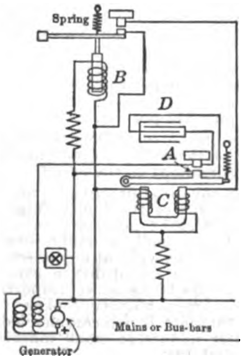

Fig. 88.—Tirrill regulator for small direct-current machines.

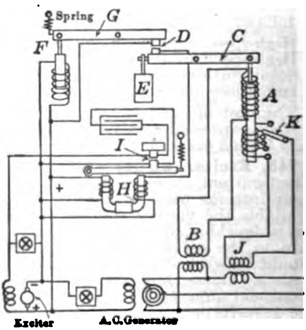

Fig. 89.—Tirrill regulator for large machines.

754. Tirrill regulators for large direct-current machines and alternators operate as follows (Fig. 89): The solenoid *A* is connected across the bus bars, usually through a potential transformer. The core, which is lifted by the solenoid, is attached to the lever *C* on the other end of which is a contact *D* and a balancing weight *E*. Across the exciter terminals is connected a solenoid *F* whose core is attached to the lever *G* with contact *D* on the other end. This lever is pulled in a direction to close the contacts by a spring so designed that the plunger *F* is pulled downward in direct proportion to the voltage. This arrangement gives greater sensitiveness than the simple arrangement at *B*, Fig. 88.

When the alternating voltage is low the weight of the plunger *A* overcomes that of the balancing weight *E* and closes contact *D*, causing relay *H* to close contact *I*, thus short-circuiting the field resistance and raising the exciter voltage and the alternating voltage. As the exciter voltage rises, solenoid *F* pulls down its plunger and lifts contact *D*, but as long as the alternating voltage is low, the lower contact follows. When the alternating voltage rises above the correct value the contact *D* is opened, which causes the resistance to be inserted again in the field circuit. The winding *K* on the solenoid *A* allows compounding with the load, which may compensate for the average line drop. In stations where there are several exciters, the relay *H* operates a number of contacts *I*, one or more for each exciter. In very large stations a separate regulator is used for each exciter.

755. Regulators with exciter batteries are possible by the use of boosters in the exciter bus under control of the regulator, bucking or boosting the voltage supplied to the field windings.

756. Manual regulation with regulators is secured by varying the resistance in the circuit of solenoid *A*, Fig. 91.

757. Protection against regulator failures or abnormal conditions should be provided whereby excessively high or low voltage results in the operation of a relay, thereby making the regulator non-operative.

758. Exciters for Tirrill regulators require careful adjustment for parallel operation. Field circuits should permit voltages from 40 per cent. to 140 per cent. normal. They must respond rapidly and equally to change of resistance. Unequal response causes the quicker machine to take all the load and it may flash over.

759. The cost of Tirrill regulators installed is from \$500 to \$1,000 each, exclusive of instrument transformers.

760. Feeder regulators for alternating-current circuits consist essentially of compensators, the secondary winding of which is in series with the outgoing circuit. They are fully described in Sec. 6. There are two types, the contact type and the induction type, the latter being preferable. These regulators may be either single phase or polyphase as necessary. They are usually wound for ± 10 per cent. regulation. They may either be hand operated, or automatically operated through a relay and motor to compensate for line drop thus maintaining constant voltage at a distant point. The **cost** of 2,200 volt automatic feeder regulators for ± 10 per cent. regulation is about as follows: Single phase, \$300+\$350 per 100 amp. Three phase, \$600+\$600 per 100 amp. If motor-operated but non-automatic, about \$80 is saved. Hand-operated regulators cost about \$150 less than automatic.

LOW-TENSION DIRECT-CURRENT SWITCHING

761. Direct-current switching may conveniently be grouped in the following **general classes**: (*a*) Single polarity; (*b*) Double polarity with equalizer on pedestal; (*c*) Double polarity with equalizer on panel; (*d*) Three wire; (*e*) Multiple voltage.

Obviously a great number of subdivisions could be made, the number of busses being the most important. Fig. 90 shows the elementary wiring of these various classes, leaving out all auxiliary wiring and all instruments.

762. Parallel operation of compound generators is secured by the equalizer connections which are usually of one-half to one-third the rated capacity. They parallel both terminals of all series fields, making the direction of current in all of them necessarily the same. Parallel operation is fully discussed in Sec. 8.

763. Single-polarity switchboards find their greatest use in railway work where the negative bus is at approximately ground potential, and is usually located in the basement beneath the machines; it should be insulated, however. The circuit breakers and instruments are in the positive side of the board and the equalizer and negative switches are on small panels or pedestals near the machines. The feeders are frequently without negative switches.

764. Three-wire switchboards are used for combined lighting and power systems. The generators require an equalizer on each side. If both these equalizers are thrown in, the machines are paralleled as shunt machines, so that some means must be taken to make it possible to close the equalizer switches only at the same time as the main switches. This usually calls for four-pole switches on small boards and two double-pole switches on the large, each double-pole switch consisting of one line and one equalizer switch. It is obvious that a circuit breaker and instruments are needed in each side. In the case of two-wire full voltage feeders, a double-pole circuit breaker is necessary when the neutral is grounded.

765. The instruments required to measure completely the output of the machines or of a feeder, comprise an ammeter or a wattmeter, or both, for each circuit-breaker shown in the diagram (Fig. 90), together with a voltmeter on the main bus. For purposes of connecting incoming generators

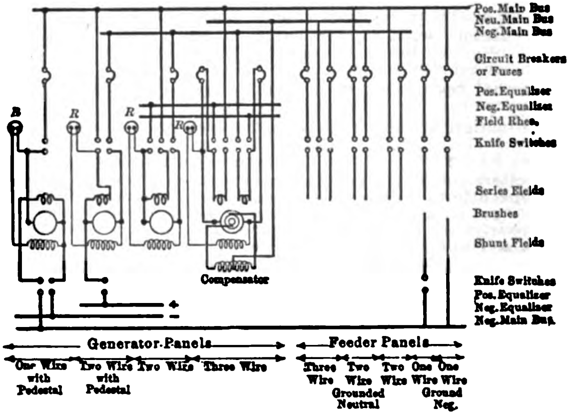

Fig. 90.—Elements of direct-current wiring.

provision must be made for a voltmeter on each machine, or a socket and plug which will enable its voltage to be measured by a common machine voltmeter. (Fig. 93.)

766. Double-polarity switchboards find their greatest use in power work, particularly at 250 volts. They are desirable where both bus bars must be insulated. Except for large stations there is no disadvantage in having both polarities on the same board. Except on small boards, it is desirable to have the equalizer switches on pedestals near the machines (Fig. 91).

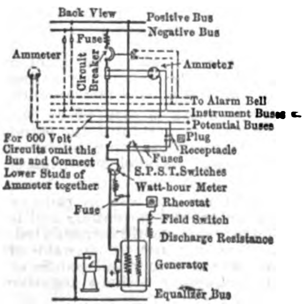

Fig. 91.—Detail wiring diagram of generator panel.

767. Multiple-voltage switchboards are in use where three-wire distribution is extensive. The extra busses are operated at a voltage higher than the main busses to take care of the drop in long feeders. Their voltage is usually maintained by boosters, although in some cases provision is made for connecting the generators to either set of busses.

768. Double bus bars are seldom warranted except for operating at two voltages. However, when there are two distinct classes of service which should be kept independent, double bus bars are desirable (Fig. 92).

769. Spare circuit breakers are almost necessary in heavy railway work and provision should be made for inserting them in a simple manner (Fig. 93).

770. Auxiliary circuits are frequently installed to accomplish many different purposes. Some of the more commonly used are as follows:

) Voltmeter bus and receptacles to enable the use of one instrument for machines; (b) Current supply for instrument excitation and the opera-on of circuit breakers; (c) Signals indicating open breakers; (d) Remote

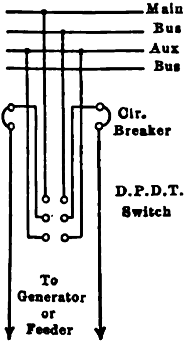

FIG. 92.

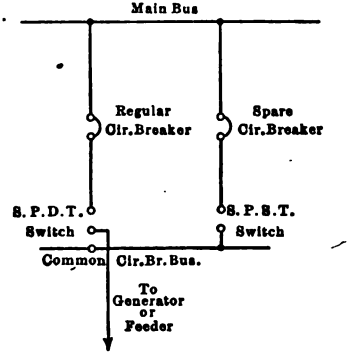

FIG. 93.

FIGS. 92 AND 93.—Wiring for spare busses and for spare circuit breakers.

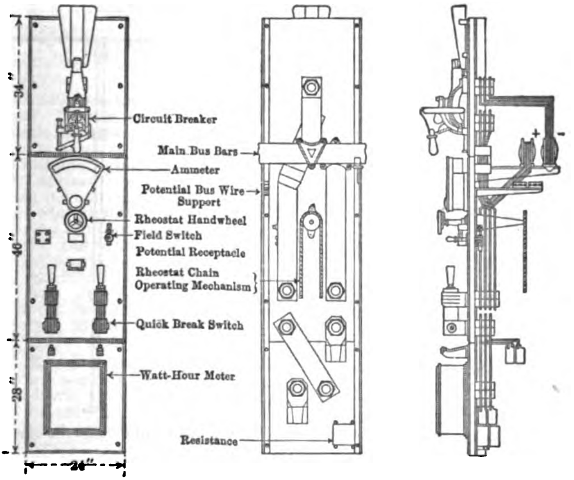

FIG. 94.—Two-pole generator panel 2500A, 250 v.

control of circuit breakers and switches; (e) Interlocking circuits between circuit breakers; (f) Reverse-current relay wring (Fig. 91).

771. Types of switchboard panels. The accompanying illustrations, Figs. 94 and 95, serve to indicate general types of panels. In very small installations, the generator and feeder switches may be located on the same panel. In moderate sized plants there may be several feeders per panel, although generally each generator has its own. In large systems there is sometimes a separate panel for each feeder, but this is necessary only in very special cases, usually two being grouped on each panel. The require-

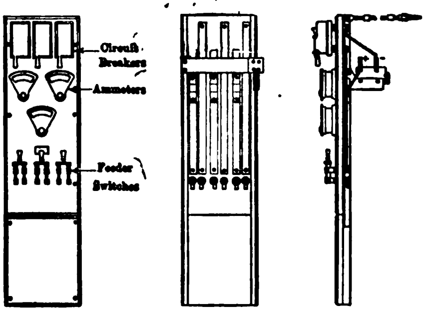

Fig. 95.—Two-wire feeder panels; three small feeders.

ments of ammeters and circuit breakers are the same both for generator and feeder panels except that occasionally two feeders running to the same point are protected with a single set of circuit breakers.

772. Station panels are usually provided containing a totalizing ammeter and watt-hour meter, bus voltmeter (or voltmeters if a three-wire

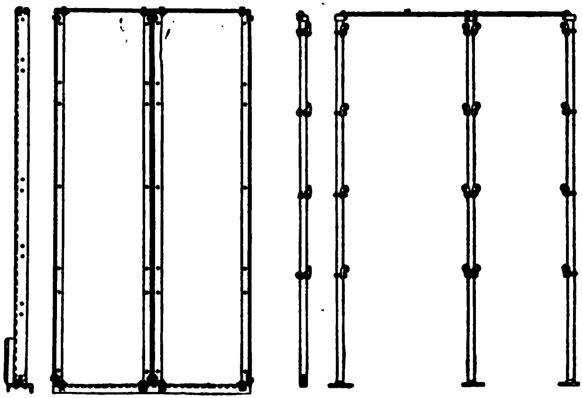

Fig. 96.—Switchboard supports; angle iron and pipe (*Elec. Jour.*, Feb., 1913, p. 168).

system), machine voltmeter and switches for auxiliary circuits and power-station lighting.

773. Switchboard supports are usually in the form of angle-iron framework although lately iron pipe is coming largely into use (Fig. 96). An inverted channel iron, or sill of hard wood is sunk into the floor to which the upright supports are bolted. There is an upright for each joint between panels consisting of two angles back to back, or of a single iron pipe. Along the top is another angle or pipe. The entire board is braced in an upright position by numerous wall braces. The iron used varies in size from 2 in. × 1.5 in. × 0.25 in. to 3 in. × 2 in. × 0.25 in. One and one-fourth inch pipe is generally used. At least 3 ft. of clearance should be left between the board and the wall to allow for cleaning and repairs. In direct-current practice it is customary to insulate the iron framework from ground.

774. Complete lines of detailed fittings are on the market, facilitating almost any conceivable arrangement of framework for supporting the panels and bus bars. (Fig. 97.) Brackets with special insulators are used for the bus bars and longitudinal wires. Vertical small wiring is fastened to the back of the board with small straps. Vertical conductors made of copper bars or heavy wires are usually supported by the studs of the switches and the main bus bars to which they are connected.

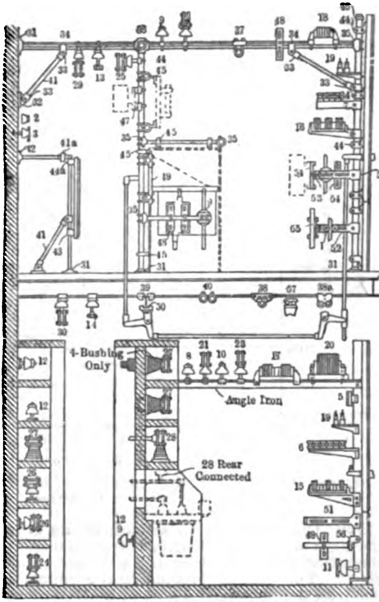

Fig. 97.—**Standard switchboard details** (Elec. Jour., May, 1913, p. 82).

775. In laying out the wiring for the switchboard panels care should be exercised to have sufficient **clearance** around all live parts (1 in. or more) and to avoid all unnecessary complications. It is important that all panels be as nearly alike as possible.

776. The materials for panels. Marble is used in the more important switchboards on account of its better insulating qualities and better appearance if unpainted; it is advisable if the voltage exceeds 600. Slate is likely to contain conducting veins, but when clear is a perfectly satisfactory material, considerably cheaper than marble and somewhat stronger. Panel from 1.5 in. to 2.5 in. thick are used, depending on the size of the switches and circuit breakers. In some cases even thicker reinforced panels are necessary. Marble panels complete with framework cost from $2.50 to $3 per sq. ft.; slate panels from $1.75 to $2.50.

777. Bus-bar connections. Bolted joints are preferable in light work, largely on account of the awkwardness of the clamps, but on heavy work, clamps have many advantages. Lap joints or butt joints with covers should be used with a uniform pressure of from 100 to 200 lb. per sq. in. The copper surfaces should be well cleaned. The **current density** in these connections should be from 100 to 200 amp. per sq. in. Under these conditions, the drop in the joint will but slightly exceed that in an equal length of bar.

778. Bus bars are usually made of 0.25-in. or 0.125-in. copper of various widths, seldom more than 10 in. The bars are grouped together with 0.25-in. spaces between them when using 0.25-in. copper and 0.375-in. when using 0.375-in. copper. Aluminium bars 0.25 in. and 0.375 in. thick are sometimes used. Fig. 98 shows approximately the relation between the number of bars, the width of the bars, and the **current-carrying capacity** based on a temperature rise of 25 deg. to 30 deg. Cent. Free circulation of air is important and the bars should be supported on edge. Smaller spaces between the bars would greatly reduce their carrying capacity. In general, **current densities** of from 800 to 1,000 amp. per sq. in. are not excessive. Where aluminium is used, densities 25 per cent. less should be figured. The **cost** of copper bus bars installed will be covered in general by adding 10 cents per lb. to the cost of the copper.

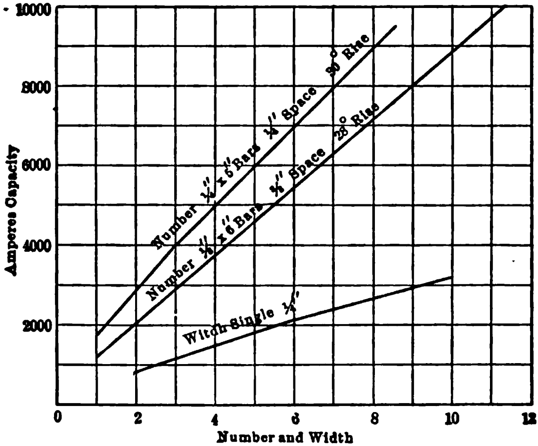

FIG. 98.—Current-carrying capacity of bus bars taken from manufacturer's bulletins.

779. Connections to switch studs between nuts should be figured on the basis of a current density of from 100 to 200 amp. per sq. in. Connections should be carefully fitted and the burr carefully removed from the edges of holes. The cost of making heavy connections between switch studs and bus bars can be covered approximately by adding the cost of 1 ft. of bar for each connection and 6 in. for each joint. For usual panels this work will cost about $10 per panel plus $1.50 per 100 amp.

780. Switches should carry the maximum overload at a temperature rise of not greater than 25 deg. Cent. Current density in the blades and studs ranges from 700 to 1,000 amp. per sq. in. and in the jaws and hinges from 40 amp. to 50 amp. per sq. in. The switches must be carefully made and lined up so that the full contact area is available. If the switch overheats, the contact resistance will be greatly increased by oxidation. A 6,000-amp. single-pole switch is about the **limit of hand operation**. Very large switches with laminated brush contacts closed by toggle joints are sometimes used.

781. Cost per pole of single-throw switches complete with nuts, etc., ready for mounting on switchboards is $1.80 per 100 amp. of capacity; 40 per cent. should be added if the switches are double-throw; 10 per cent. should be added if they are 600-volt switches, to cover added length of blade and quick-break feature, which should always be used.

782. Fuses are the simplest means of automatically opening a circuit under short-circuit or overload conditions. Enclosed fuses are on the market and are approved by the fire underwriters, having capacity up to 600 amp. at 250 volts, or 400 amp. at 600 volts. Up to 30 amp., the contacts are simply ferrules on the end of the tube. On the larger fuses, contact is made by blades fitting into jaws similar to those on knife switches. The tube is filled with heat-resisting powder which confines the arc and puts it out quickly. All fuses are supplied with indicators to show when they are blown. They will usually carry full rated load continuously, but will blow in from one to five minutes if the current exceeds 15 per cent. overload.

783. The cost of fuses complete with the clips is about $1 per 100 amp. capacity. The cost of the fuses alone is about 50 cents per 100 amp. capacity, and the cost of refilling the fuses is about 20 cents per 100 amp. capacity.

784. Automatic circuit breakers are required on all circuits larger than 400 to 600 amp. and even on the lighter circuits where overloads and short-circuits are likely to be frequent. There are two methods in use for preventing burning of the contacts, namely —the **carbon break** and the **magnetic blowout**. In the carbon-break method, three contacts are successively broken on the opening of a circuit. First the main current-carrying contacts open; then an auxiliary copper contact opens, and lastly a contact opens between the carbon plates and breaks the entire current, thus protecting the current-carrying contacts. In the magnetic blow-out breakers (Fig. 100) the carbon contact is replaced by a contact located between the poles of an electric magnet energized by the passage of current through these contacts. The directions of magnetic flux and current are arranged to blow the arc upward. Magnetic blow-out breakers are used in cases of extremely difficult service. In both types provision is made for the easy replacement of the auxiliary contacts.

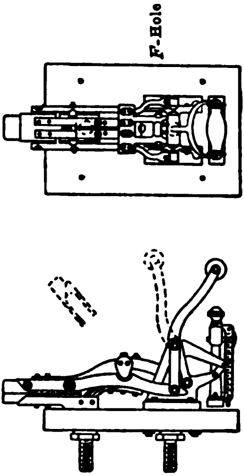

FIG. 99.—Carbon-break circuit breaker.

The main contacts in circuit breakers consist almost invariably of laminated copper brush bearing on flat copper blocks, and pressed down by a toggle joint exerting considerable pressure. Several types of breakers are shown in Figs. 99 to 102. The current densities used in the laminated contacts are from 400 to 500 amp. per sq. in. The entire breaker is designed for a temperature rise not to exceed 25 deg. to 30 deg. Cent. in any part.

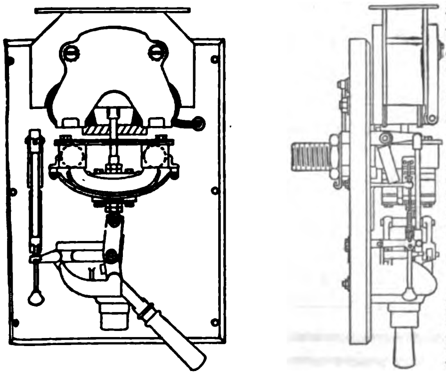

FIG. 100.—Magnetic blowout circuit breaker.

785. Circuit breakers are ordinarily hand operated by a lever, which is of sufficient power even for the largest sizes (Fig. 99). Frequently, however, **remote control** is desirable and electric or compressed-air operation is used. The breakers are usually arranged to reopen immediately without damage when closed on a short circuit. Motor-operated breakers are usually in pairs, one closing before the other, so that the second is practically a switch. All breakers are supplied with an overload **tripping mechanism** which is adjustable to open the circuit at currents from 50 per cent. to 250 per cent. of rating. Other tripping arrangements may be operated by low voltage, excess voltage, reverse current of a tripping switch located at any convenient point.

786. Multiple-pole circuit breakers are commonly used in the smaller capacities. For many purposes they are specially arranged so that if closed on overload or short-circuit, the tripping coil will release the closing mechanism and the breaker will open before the main contacts are closed. Such breakers may be used on feeder panels, avoiding entirely the use of knife switches.

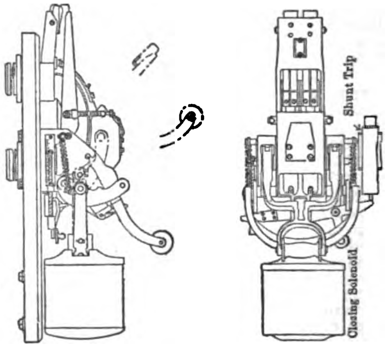

FIG. 101.—Solenoid-operated circuit breaker.

787. The cost of carbon-break circuit breakers is about $6.00 per 100 amp. of rated capacity per pole; magnetic blow-out circuit-breakers cost about $7.50 per 100 amp. of capacity.

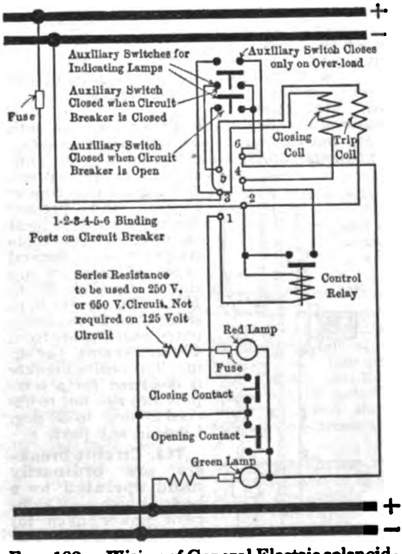

FIG. 102.—Wiring of General Electric solenoid-operated switches and circuit breakers.

788. Switchboard instruments in direct-current work should be carefully protected from stray fields. Wherever the bus-bar currents exceed 2,000 amp., all except the very best protected instruments will be affected, and to secure accurate readings they should be calibrated in place. It is customary to provide instruments with scales such that at the rated load of the machines, the needles will be at approximately mid-point.

789. The cost of switchboard instruments varies between wide limits. Ammeters may cost all the way from $15 plus $1 per 100 amp. of capacity, to $75 plus $1.20 per 100 amp. of capacity. Voltmeters may cost from $20 to $80 depending largely on the type. Watt-hour meters will vary in cost from $35 plus $1.50 per 100 amp. to $100 plus $7.50 per 100 amp.

790. Standard switchboard panels embodying the various devices described above and suitable for all classes of work have been developed and catalogued by the various manufacturers, so that it is now possible to buy complete, almost out of stock, panels suitable for almost any kind of work; Fig. 96, is taken from one of these catalogues. These panels can be purchased for a lower price than it is possible to make up special panels and should be used whenever possible. The particular panels shown in this figure would cost approximately $100 plus $12 per 100 amp. without watt-hour meter, and $220 plus $16 per 100 amp. with watt-hour meter, equipped for 250 volts.

CONSTANT-CURRENT SERIES SWITCHING

791. Series systems are now used in America solely for street lighting. It is probable that they will continue in use for this purpose indefinitely. The earlier installations used **series-wound generators** operating on the drooping part of the characteristic (Sec. 8). When the total pressure exceeded 2,500 volts, multiple independent armature windings and commutators were used, connected in series externally to the machine. The regulation of these machines is accomplished in two ways, by shunting the series fields or by moving the brushes, or both. Since these machines operate on the drooping part of the characteristic curve, they have considerable inherent regulation in themselves. The adjustments are made automatically by a series-connected relay or operating magnet which actuates

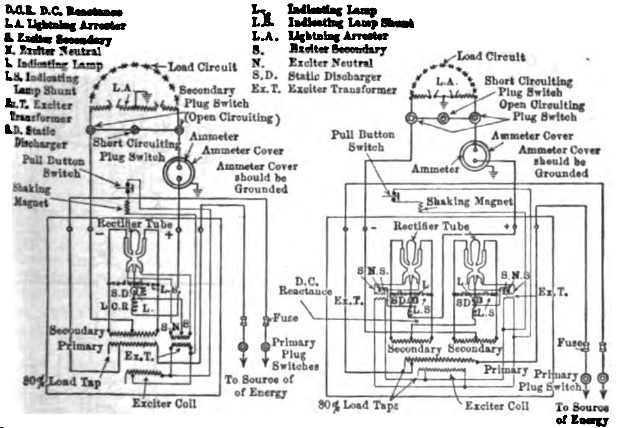

Fig. 103.—Series lighting circuits with constant-current transformers and mercury rectifiers.

the field rheostat or rocks the brushes. **Constant-current transformers** are employed very extensively for this class of service (Sec. 6) and regulate themselves almost perfectly. Each transformer is supplied with a terminal panel, etc., which forms part of the unit. Series-wound generators are installed, however, to a limited extent.

792. Mercury-arc rectifiers are also employed in this class of service, in connection with constant-current transformers, for series direct-curent lighting. The equipment itself is described in Sec. 6. The connections are illustrated in Fig. 103.

793. Switching practice is practically the same whether generators or transformers are used. Since the opening of a series circuit causes full voltage across the break, and short-circuiting causes only a relatively small increase in current, all transfers of circuits are accomplished after short-circuiting the same. Apparatus will run on short-circuit for a short time without damage. The switching is accomplished very simply by means of a transfer or carrier-bus panel as shown in Fig. 104. This arrangement is relatively inexpensive and will allow almost any conceivable switching.

794. Ammeters may be connected into any circuit by inserting the proper plug in the sockets in rows 1 or 11. When the plug is inserted the circuit is opened and simultaneously completed through the ammeter. In direct-

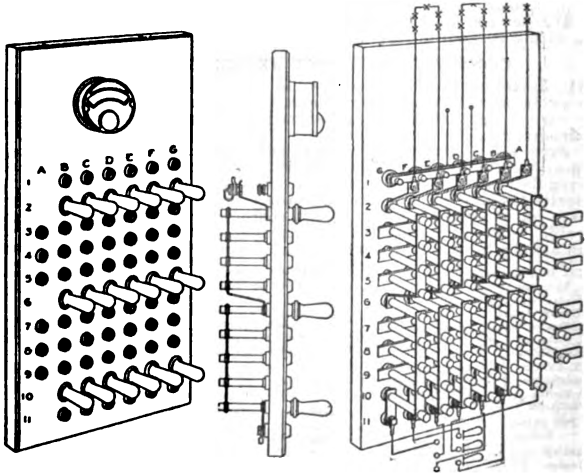

Fig. 104.—Transfer panel-series switching.

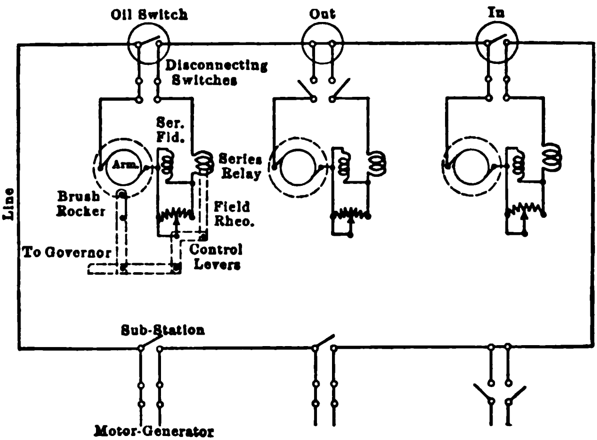

Fig. 105.—Elements of Thury system of transmission.

current work it is necessary to have the instruments in the line circuit. They must be insulated for high voltage and the cases protected with the grounded covers to protect the operator. In alternating-current work a current (series) transformer may be used in connection with a standard instrument.

795. The Thury system of direct-current series transmission (Fig. 105) is not unlike the series lighting systems in use in this country. Series-wound generators are employed, developing up to 4,000 and 5,000 volts each, a sufficient number being connected in series to secure the desired transmission voltage. Currents of various magnitudes are used, approaching 200 amp. maximum. The Thury system, like our lighting systems, is essentially constant-current and is regulated to produce this condition, the voltage varying directly with the load. The system is not planned for the general distribution of energy in small quantities, but rather for transmission to substations where it is transformed to constant-potential energy. These substations are in series and each has one or more motor-generators with series-wound motors. This system has not been received with favor in this country.

796. The insulation of the machine windings. (Thury system) need not be for the full voltage. If a small number of machines is contemplated, this insulation could probably be advantageously used, but in large systems of high voltage and numerous machines, the most economical results may be expected by insulating each machine from the ground and from other machines. The difficulty lies largely in securing an insulating coupling combining mechanical with dielectric strength. The machines must each be surrounded by a highly insulated platform so constructed as to allow easy access without danger to the operators.

797. The switching (Thury system) may be exceedingly simple, as no automatic circuit-interrupting devices are required or even desired. Since the characteristics of series generators permit short-circuit currents but slightly in excess of the operating currents, no devices for protecting against excessive currents are necessary. It is probable that satisfactory switching can be secured by hand-operated non-automatic single-pole switches, one to short-circuit the terminals of the machines and two others to disconnect it from the line (Fig. 105). None of the complications usual in constant-potential systems need be considered. The short-circuiting switch should have a rupturing capacity equal to the rating of a single generator. The disconnecting switches may be of the ordinary air-break type, but insulated for the total voltage of the system. This insulation is necessary so that the machines may be disconnected from the lines and grounded for repairs.

798. The regulation (Thury system) consists in maintaining constant current and can be secured in three ways, any combination of which may be used: (*a*) shunting the series fields by an adjustable rheostat; (*b*) rocking the brushes from the neutral point; (*c*) controlling the speed. The difficulties of commutation prevent any very considerable adjustment by the first two methods, but the generators themselves are self-regulating in a large degree. The automatic regulation is secured by a series relay which operates the field rheostat or other controlling means through direct connection or by electric control. Large adjustments are taken care of by the starting up or shutting down of machines. Motors are regulated to give constant speed by centrifugal governors which actuate the field rheostat and rock the brushes. Protective devices are required for short-circuiting the terminals when the voltage exceeds rating.

ALTERNATING-CURRENT SWITCHING

799. The principles of alternating-current switching are not necessarily different from those of direct-current (Par. 761 to 790). The same equipment and apparatus may be used for low-voltage work, except for slight modifications to avoid eddy currents. The elements of alternating-current switching arrangements are shown somewhat progressively in Fig. 106. The symbols indicate **oil switches,** (*O*) capable of being opened under load and **disconnecting switches** (*X*) incapable of interrupting any except the smallest currents.

The simplest arrangement is that shown in sketch *A* (Fig. 106), where the generators and feeders are grouped at either end of a single bus. Sketches *B* to *E* indicate arrangements for **sectionalizing the bus** by disconnecting switches, which permit the division of the plant at any desired point; some sectionalization by oil switches is frequently desirable. The

ring bus shown at *E* probably has the greatest advantage. **Double busses** are shown at *F*, *G* and *H*, which have the added advantage that any group of feeders may be supplied from any group of machines; double-throw disconnecting switches, and double-throw oil switches are shown, but the latter are not recommended. The **relay bus** system shown at *L* and *M* gives some control of the sectionalising under load.

The need for increased reliability of switching, as well as increased flexibility has led to the arrangements shown at *I* to *R* inclusive; sketch *I* shows spare oil switches arranged to replace any of the others, through disconnecting switches. In the other layouts, there is usually a spare switch for each generator or feeder group, so that no equipment need be kept out of service on account of switch trouble alone. Obviously, switching arrangements without limit can be devised to allow almost any conceivable switching operation.

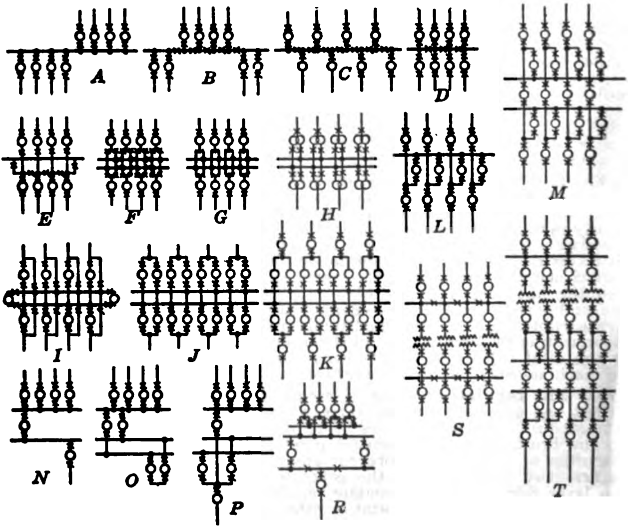

Fig. 106.—Elements of alternating-current switching.

800. Group switching is usually resorted to (Figs. 106*N* and 106*R*) in very large stations of moderate voltage, where the number of feeders is relatively large. It facilitates starting after a shut-down, and simplifies the sectionalisation of the loads for any purpose. It also provides the maximum of flexibility with a minimum of expensive oil switches.

801. High-tension power stations using transformers require both high-tension and low-tension bus systems. The great expense of high-tension switches and the large space necessary for their enclosure has led to very simple high-tension layouts. For example, the Ontario Power Company employs the complicated low-tension layout *M* and the simple high-tension layout *D* (T Fig. 106).

802. The grounded neutral has proved advantageous principally in systems having extensive underground distribution, the object being to open the circuit breaker of a grounded feeder before a short-circuit between phases can occur. A resistance is usually inserted between the neutral bus and the ground, of such magnitude that the current flowing to a grounded feeder will comfortably operate its overload relays. When three-phase star-connected generators have a third harmonic in the e.m.f. wave, it will appear as a voltage between neutral and ground. Where dissimilar machines are operated in parallel, a considerable voltage may develop between their neutrals which will make their interconnection dangerous. In such cases it is necessary to introduce resistance in these connections. It is common practice, however, to operate with but a single machine grounded, which prevents interchange of neutral current and still protects the system.

803. Current-limiting reactances are coming into use on large systems to limit short-circuit currents, thus protecting generators and limiting the duty of the oil switches. These reactances are of the air-core type (6). They are used in two ways: those permanently inserted in the circuits, and those inserted only during switching operations. The ordinary turbo-generator will deliver instantaneously on short-circuit, from 30 to 50 times rated full-load current; a reactance sufficient to reduce this to 15 times full-load is apparently all that is necessary in present installations. This reactance may be introduced in the machine leads, in the bus bars, or in the feeders. The first method is commonly used for permanent insertion in very large stations; these reactances are quite large and expensive. The second method is recommended for use between sections of the bus in stations where the switches would otherwise be inadequate. The third method is used for insertion of reactance only during the opening of a short-circuit; there are two switches in series, the first inserting the reactance (normally short-circuited), thus limiting the current to be broken by the second which is mechanically interlocked to open immediately afterward. These reactances are small and may even be included in the oil pots of large switches.

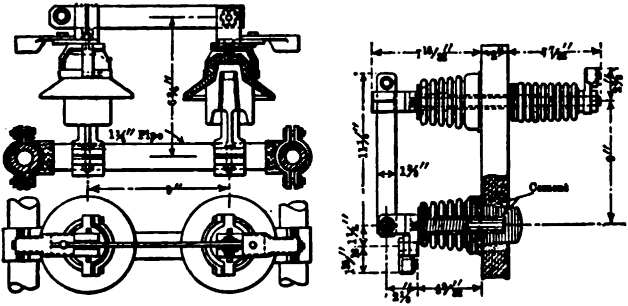

FIG. 107.—Disconnecting switches.

804. Disconnecting switches (Fig. 107) are ordinarily used for sectionalizing bus bars or circuits, or for isolating apparatus for grounding or repair, but not for switching under load. They are used sometimes, however, in place of oil switches on one side of parallel transformer banks. Disconnecting switches should not be located to open downward unless locks are provided to keep them from jarring out. In very heavy work care should be used to avoid loops in the wiring which on short-circuits will produce magnetic forces sufficient to open the switch. The cost of 300-amp. disconnecting switches is about $5+$0.50 per 1,000 volts. The cost of 600-amp. disconnecting switches is about $10+$0.60 per 1,000 volts.

805. Expulsion fuses (Fig. 108) are used for connecting potential or small auxiliary transformers to the bus. They are usually arranged also as disconnecting switches. They consist essentially of fine fuse wire confined in strong insulating tubes closed at the lower ends. The blowing of the fuse and the resulting confined arc suffice to blow the conducting vapors out of the open end, thus putting out the arc. The tubes are arranged for con-

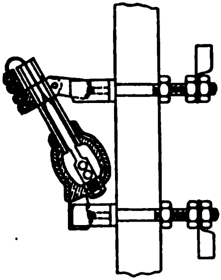

FIG. 108.—Expulsion fuse.

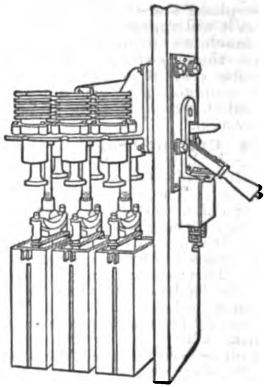

FIG. 109.—Westinghouse type E oil switch.

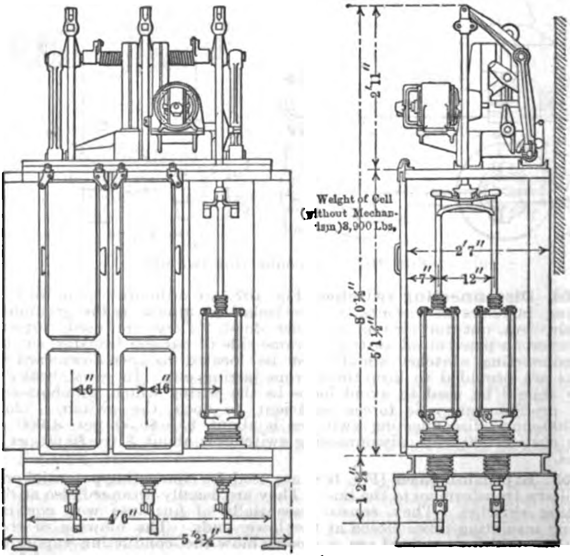

FIG. 110.—General Electric type H-3 oil switch.

venient removal and refilling. They are recommended only in small capacities and moderate voltages, although they are offered up to 60,000 volts, 20 amp. They cost about $20 plus $0.30 per 1,000 volts.

806. Oil circuit breakers are used for interrupting current at all voltages above 600. Three of the numerous types of oil switches are shown in Figs. 109 to 111. The contacts open under oil and the arc is put out by the cooling action, and the pressure of the oil. When a circuit is opened the resulting

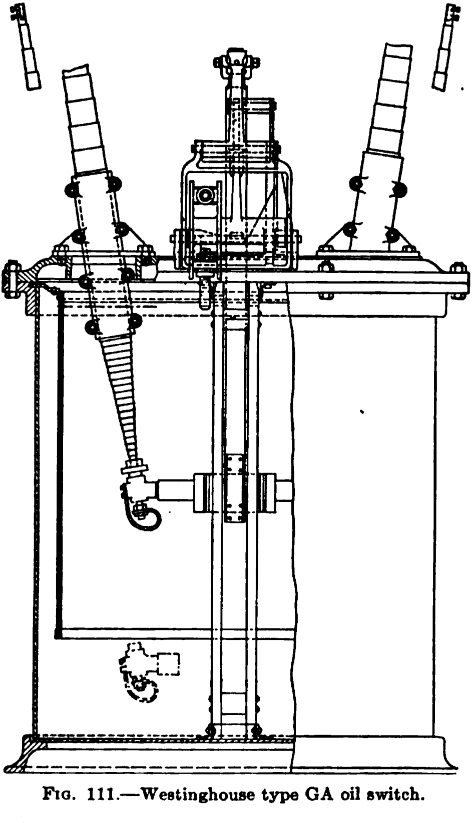

Fig. 111.—Westinghouse type GA oil switch.

arc tends to impart a more or less violent motion to the oil, away from the contacts, but its inertia and pressure due to depth resist the action and quickly quench the arc. This pressure becomes very great in violent short-circuit interruptions, and has been observed as high as 150 lb. per sq. in. a few in. away from the arc. Contacts of various types are used and all have certain advantages; many are arranged with auxiliary contact for the final breaking of the circuit. Most of the breakers are arranged to open by gravity.

A special **circuit-breaker oil** is used which is fluid at low temperatures and is free from moisture. The oil level must be carefully maintained in operation, and the oil must be changed when burned by short circuits.

807. The temperature rise should never exceed 25 deg. to 30 deg. Cent. in the hottest part at continuous full-load. The **voltage rating** is determined by the insulation distance to the grounded parts and by the breaking distance of the contacts. The Westinghouse Company designs its high-capacity high-voltage breakers, with a ground distance of about 5 in. plus 0.25 in. per 1,000 volts, and with a total breaking distance per pole of about 10 in. plus 0.33 in. per 1,000 volts. Breakers are available up to 150,000 volts.

The **current rating** is determined largely by the size of the current-carrying parts and may even be in excess of the safe rupturing capacity. Breakers for very high voltage are usually from 100 to 300 amp. capacity, while for 2,500-volt or even 11,000-volt work they are available up to 2,000 amp.

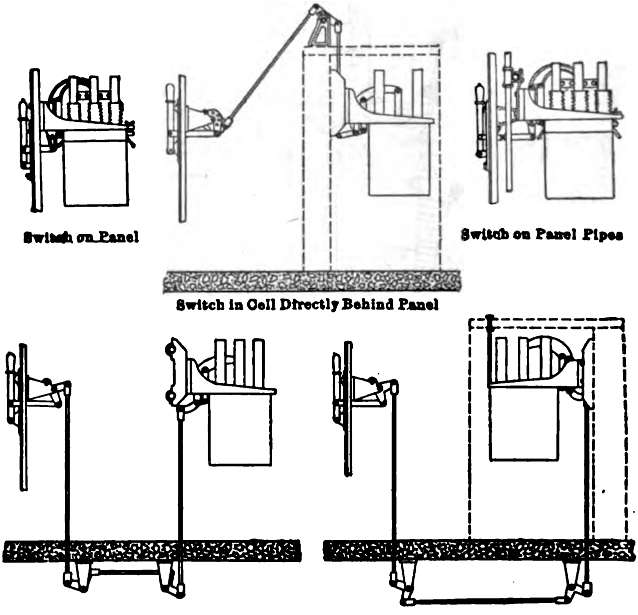

FIG. 112.—Mountings for small oil switches.

808. Oil switches for panel mounting (Fig. 112) usually have their poles enclosed in a common grounded rectangular steel oil-filled tank which is removable by dropping it away from the contacts. This type, when mounted on panels, is not desirable above 2,500 volts and 3,000 kw. station capacity.

809. Wall and framework mounting (Fig. 112) with remote control using this same type of switch (Par. 810), extends its capacity to about 12,000 kw. at 2,500 volts, or to 6,000 kw. at 15,000 volts.

810. Three-phase Ratings of More Important Types of Oil Switches

Type	Current ratings, amperes	Voltage ratings, volts	Station capacity ½ sec. relay	Means of operation	Mounting, max. poles and throws per tank
G. E. Switch					
P	100– 200	4,500– 15,000	4,000	Manual	Wall 4 double
K_5	100– 500	2,500– 4,500	6,000–5,000	Man. or Elec.	Wall 4 double
K_2	300–1,000	2,500– 15,000	8,000–2,000	Man. or Elec.	Wall 4 single
K_4	300– 800	2,500– 15,000	12,000–6,500	Man. or Elec.	Wall 4 single
K_{12}	300–2,000	2,500– 15,000	12,000–6,500	Man. or Elec.	Wall 4 single
K_6	100– 300	22,000– 45,000	6,000–4,500	Electric	Cell 1 single
K_{10}	100– 300	22,000–110,000	20,000	Man. Elec. or Air	Floor 1 single
K_{15}	100– 140	70,000–110,000	50,000	Man. Elec. or Air	Floor 1 single
H_3	Any	2,500– 66,000	Any	Electric	Cell two tanks per pole
Westinghouse Switches					
P	100–1,000	3,300– 6,600	3,500	Manual	Wall 4 single
F	10– 200	3,300– 6,600	2,600	Manual	Wall 4 single
B	100–2,000	600– 22,000	8,500	Man. or Elec.	Wall 4 single
E	100–1,200	3,500– 25,000	10,400	Man. or Elec.	Cell 1 single
L	50– 200	60,000– 88,000	20,000	Man. or Elec.	Floor 1 single
G	100– 200	60,000–120,000	200,000	Man. or Elec.	Floor 1 single
GA	300	44,000–110,000	60,000–200,000	Man. or Elec.	Floor 1 single

811. Remote control. In most cases **electrical control** is used where hand control is undesirable. The operation in most types is secured by solenoids, a powerful one closing the switch, and a lighter one releasing a latch which permits the switch to open by gravity. In the General Electric type *H* switch (Fig. 110) a motor is employed for the purpose of winding a spring which on the release of a stop by a solenoid closes or opens the switch, depending on its position. Following the operation of the switch the motor again winds up the spring. **Pneumatic control** is used in some cases in very high-voltage work. For wiring see Figs. 102 and 113.

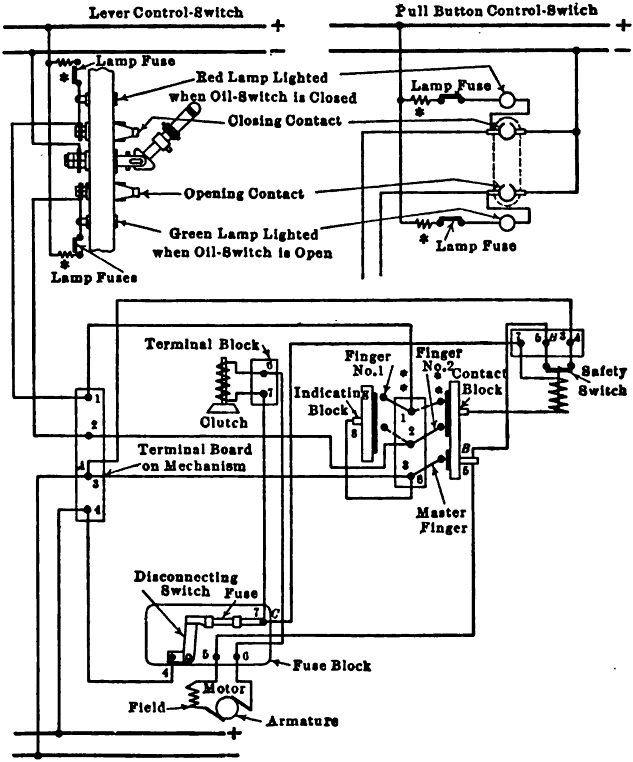

FIG. 113.—Wiring of General Electric type H oil switch.

812. The ultimate breaking capacity of oil circuit-breakers is determined by a great number of variables and the term itself is not very definite. The manufacturers use for this term the maximum size of station in which they recommend the breaker. Obviously this is not the ultimate breaking capacity. A breaker would be safe in a station of low speed units giving low instantaneous short-circuit current, while it might be destroyed in a turbo-generator station of the same size. Important factors determining this rating are voltage, length of break, size and strength of oil tank control of the oil, etc. Generally breakers with a separate tank per pole, or with a separate tank for each contact have larger breaking capacity than those where all the poles and contacts are grouped in one tank. A breaker operated at less than standard voltage will have its ultimate breaking capacity somewhat increased.

813. Hand control of oil switches is used for panel-mounted switches and for remotely mounted switches, in the smaller stations. The remote control is secured through bell cranks and rods (Fig. 112). Where the switches become numerous and are too far away, or the station is of too large capacity, hand operation is undesirable.

814. Oil switches for floor mounting (Fig. 111) have each pole enclosed in a heavy grounded tank and may be supplied with weather-proof entrance bushings and cast-iron covers for the operating mechanism, allowing use out of doors. They are available for voltages from 25,000 to 150,000 and are suitable for stations of almost any size.

815. Methods of Operating Oil Switches*

(All of the following: Without electric trip or with electric trip)

- **Manual**
  - On panel
  - On wall
  - Remote
    - On flat surface
    - In cell
    - On pipe framework
- **Electrical**
  - D. c. motor
  - Solenoid
    - Std. sw. op. mechanisms
    - H 3 forms
    - D. c. standard mechanisms
    - A. c. special switches
- **Mechanical**
  - Pneumatic
  - Float
  - Pressure reg.
    - Air
    - Liquid

Automatic Control

- **Without series transformers**
  - Series trip
    - Direct relay
    - D. c. trip
      - With or without time
        - Constant
        - Inverse
          - Overload
  - Auxiliary trip
    - Push button
    - Low voltage
      - With or without shunt transformers or series resistance
- **With series transformers**
  - Depending on load in secondaries
    - Without relay
      - Direct trip a.c.
        - On panel
        - On shaft
          - Short-circuit, Overload: A. c. trip; D. c. trip
          - Reverse power, D. c. trip
  - Without time element
    - Instantaneous
      - Reverse phase: A. c. trip; D. c. trip
      - Differential low voltage under load: D. c. trip
  - Depending on time element
    - With relay
      - With time element
        - Constant or inverse
          - Overload: A. c. trip; D. c. trip
          - Reverse power, D. c. trip

Attachments:
- Auxiliary switches (Circuit opening).
- Indicating switches (Circuit closing).
- Interlocks
  - Electrical
  - Mechanical

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* Rushmore, D. B. "Electrical Connections for Power Stations," *Trans.*, A. I. E. E., May 28, 1906.

816. Switches for cell mounting cover: (*a*) the above type where such mounting increases the safe rupturing capacity about 15 per cent. (*b*) a modification of this type with individual and stronger tanks for each pole, sometimes with separate cells for each pole, which is suitable to 40,000 kw. and 2,500 volts, or even higher with special design; (*c*) switches having two separate round pots per pole each containing a separate contact, and each pole in a separate cell, which are suitable for all capacities, particularly up to 25,000 volts.

817. The source of energy for operating switches should be of utmost reliability. Storage batteries are almost invariably used except in small stations where the exciter system is used. All switching mechanisms should be designed to operate satisfactorily on a range of voltage from 40 per cent. below to 20 per cent. above normal.

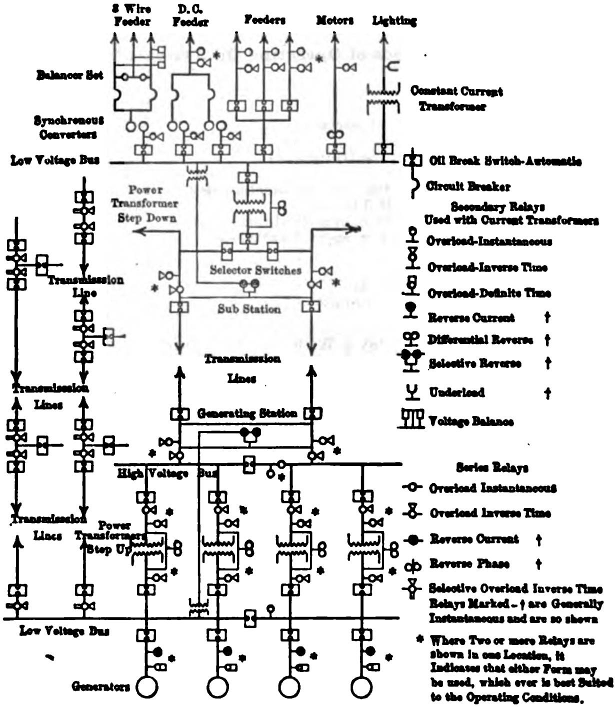

FIG. 114.—Use of relays (Hewlett, *Trans.* A. I. E. E., Mar., 1912).

818. Relays are used operating under all of the conditions outlined in, Par. 816. The most common arrangements are shown in Fig. 114 (E. M. Hewlett, *Trans.* A. I. E. E., March, 1912). The most common types are: the solenoid with plunger and the meter type very similar to the induction meter. Adjustment for current is made by position of plunger in first type and by strength of spring in second. Adjustment for time is made by bellows or oil pot resisting motion of plunger or disc and magnets resisting turning of armature of motor type. Definite time limit is secured by clockwork. Usual adjustments by bellows or magnet give a time in inversely as the actuating force.

It is important that under short circuit conditions relative settings remain unchanged. **The cost of three pole relays** varies from $25 for plain overload instantaneous to $60 for reverse current inverse time limit. Some types cost this amount per pole and special types are considerably more expensive.

819. The cost of oil switches varies between exceedingly wide limits, depending largely on rupturing capacity and voltage. Some idea of the costs may be obtained from the following three-phase non-automatic switches: For small systems up to about 5,000 kw. and 2,500 volts, about $20 plus $4 per 100 amp. capacity; for larger systems of say, 12,000 kw. and 2,500 volts, or 6,000 kw. and 15,000 volts, about $70 plus $10 per 100 amp.; for very large systems of 25,000 volts or lower, roughly $600 plus $20 per 100 amp. hand operation being unavailable. For very high voltage systems there is usually only one current rating for each voltage; such switches for 44,000 volts will cost from $400 for a 15,000-kw. rating, to $1,200 for a 50,000-kw. rating; for 110,000 volts, from $1,500 for a 15,000-kw. rating to $2,500 for a 50,000-kw. rating. The cost of electric operation is about $50 additional, exclusive of control wiring.

820. Mertz-Price System of relay protection depends on unequal currents at two ends of conductor in trouble. The series transformers at the two ends are interconnected so that, normally, no current flows through the relay. Unbalance due to trouble cuts out the apparatus (Fig. 115).

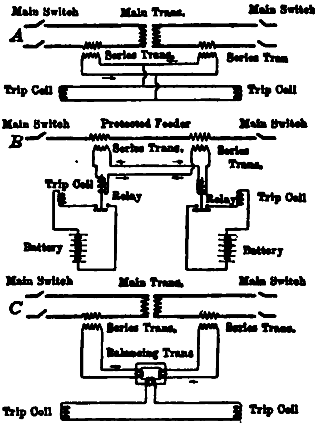

FIG. 115.—Mertz-Price systems of protecting transformers and cables.

821. Instrument equipment for generator panels includes:

(*a*) One alternating-current ammeter (where phases are likely to be unbalanced an ammeter is often supplied for each independent phase, or current transformers and transfer switches for connecting the single ammeter to any phase; (*b*) one alternating-current voltmenter (or voltmeter receptacle and plug to connect to common voltmeter); (*c*) one direct-current field ammeter (optional); (*d*) one indicating wattmeter (needed for parallel operation); (*e*) one power-factor meter (or wattless kv-a. indicator, optional); (*f*) one frequency meter (optional); (*g*) one ground detector (not common); (*h*) one watt-hour meter (optional but desirable); (*i*) one synchronizing outfit; (*j*) current (series) and potential (shunt) transformers; (*k*) one automatic relay (optional).

822. Instrument equipment for feeder panels includes:

(*a*) One alternating-current ammeter (ammeter transfer switches may be used if phases are unbalanced); (*b*) one indicating watt meter (optional); (*c*) one automatic relay; (*d*) current (series) transformers.

823. Instrument equipment for station panel includes:

(*a*) Synchronizer (extra one optional); (*b*) voltmeters for each phase of each bus (optional); (*c*) frequency meter; (*d*) voltage regulator (optional); (*e*) totalizing wattmeter (optional); (*f*) totalizing watt-hour meter (optional).

824. The cost of high-grade switchboard instruments mounted with panel wiring, but exclusive of instrument transformers, is about as follows: ammeters $40, voltmeter $45, single-phase wattmeters $50, polyphase wattmeters $70, single-phase watt-hour meters $70, polyphase watt-hour meters $125. Large variations in price however exist between various types and grades.

825. The synchronizing equipment in a station must be ample enough to prevent any possibility of failure, and should be in duplicate in all except small stations; there should also be synchronizing lamps in case of failure of the instruments. There should be more than one set of instrument transformers available for the bus voltage. Synchronizer wiring should preferably be as simple as possible (Fig. 116).

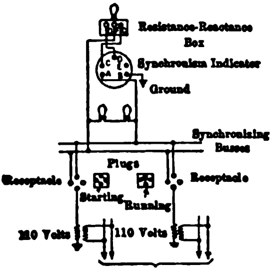

Fig. 116.—Synchronizer wiring using shunt transformers.

826. Instrument transformers (Sec. 6, and Sec. 3) are generally used whenever the currents exceed 100 amp. or the voltage 600. They are designed for 5 amp. and 110-volt secondary. Separate transformers of ample capacity should be provided for relays and for instruments. Potential (shunt) transformers are usually oil insulated for all voltages above 4,000 and current (series) transformers for voltages above 15,000. Instrument transformer wiring must be grounded thoroughly, both at the transformer and at the board, to prevent high potential on the panels in case of burnouts.

827. The cost of high-grade instrument transformers is about as follows:

Series type, 2,500 volts, $10 + $0.60 per 100 amp.; 11,000 volts, $30 + $2 per 100 amp.; 33,000 volts, $60 + $18.00 per 100 amp.; 66,000 volts, $175 + $35 per 100 amp.; shunt type, 200-watt size, $20 + $8 per 1,000 volts.

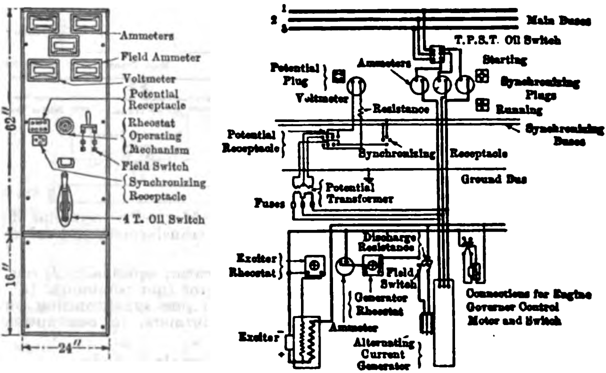

Fig. 117.—Three-phase generator panel.

828. Types of switchboards using the apparatus above described may b divided into three classes:

1. Self-contained panel type.
2. Remote mechanically operated: (*a*) panel boards; (*b*) bench boards.
3. Electrically operated: (*a*) panel boards; (*b*) bench boards.

The capacity and voltage of the station largely determine the typ as discussed under oil switches, type 1 being suitable for the smalle and type 3 for the largest systems. Space requirements for the differe types are not materially different. Typical panels are shown in Figs. 117 to 120.

829. Relative costs of switchboards are approximately 100 per cent. for type 1, 120 per cent. for type 2 and 140 per cent. for type 3 (Par. 828). These figures are approximate only for the same electrical layout, whereas different layouts would undoubtedly be used for the stations for which each type would be suitable. The following table gives the costs of typical panels shown in Figs. 121 to 123.

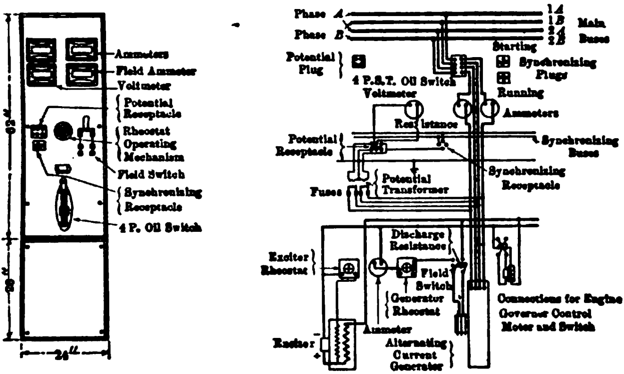

FIG. 118.—Quarter-phase generator panel.

830. Approximate Cost of Switchboard Panels
C. H. Sanderson, *Elec. Jour.*, 1913.

Kind of panel	Volts	Amps.	Fig.	Cost	U.B.C.*
Generator	2,200	"	121	440	9,200
	6,600	"		385	7,800
Feeder	2,200	"	121	345	9,200
	6,600	"		350	7,800
Generator	2,200	"	122	360	9,200
	6,600	"		310	7,800
Feeder	2,200	"	122	260	9,200
	6,600	"		265	7,800
Generator	11,000	"	123	1,240	12,500
	6,600	"		1,130	15,500
Feeder	11,000	"	123	1,045	12,500
	6,000	"		940	15,500

831. Cost of switchboards. Switchboards generally cost from $2 to $8 per kw. of capacity including all wiring and apparatus installed.

832. Mimic or miniature bus bars are invariably installed on the faces of the control boards in large stations. They represent by single bars exactly the electrical relation of the main switch controlled by each control switch and thus greatly simplify the operation.

833. Grouping of panels. It is customary to arrange the panels as follows, beginning at one end; voltage regulator, exciters, station auxiliaries, generators, feeders, with blank panels sufficient to care for any reasonable extension of the plant. With remote control, particularly electrical, this

* U. B. C. = Ultimate breaking capacity of circuit breakers set for instantaneous trip. Costs include all apparatus necessary and all structures shown but no wiring. Add 10 to 20 per cent. to cover installation.

arrangement of the switches themselves may be impossible on account of desired electrical layout, but the panels may be so arranged to advantage. Remote-control bus structures and switches should be located where there is room for considerable extension.

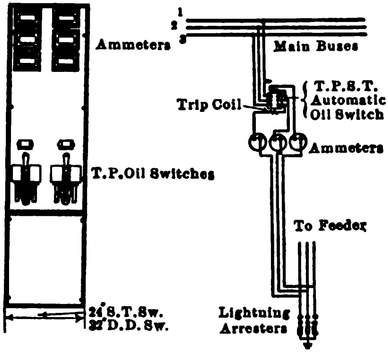

FIG. 119.—Three-phase feeder panel.

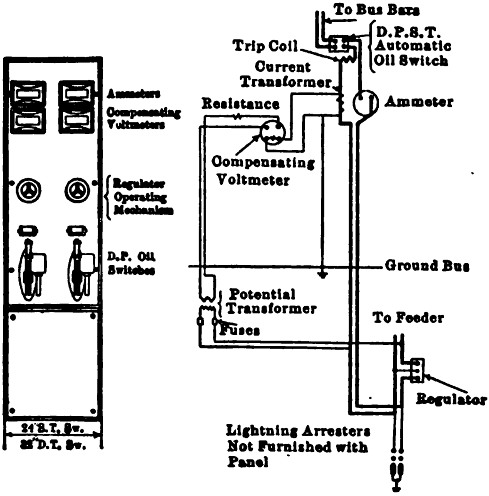

FIG. 120.—Single-phase feeder panel.

834. The operation and care of switchboards. Small stations up to say 5,000 kw. do not need any special operators for the switchboard. The engineer on watch has ample time to take care of any switching operations. With larger stations special operators become necessary; up to 10,000 kw. one operator on a watch is enough and, during the light load periods, if the arrangement of the board with respect to the turbine room is suitable, this operator may be unnecessary. Above 10,000 kw. an operator continuously on watch is necessary and frequently an additional man to take care of disconnecting switches and the cleaning and repair of oil switches. Above 20,000 kw. it is customary to have additional men until in the very large stations, there are never less than two men on the board at all times.

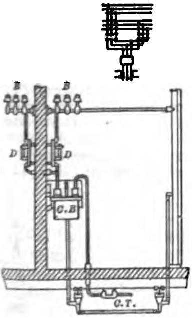

Fig. 121.

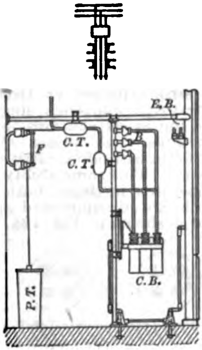

Fig. 122.

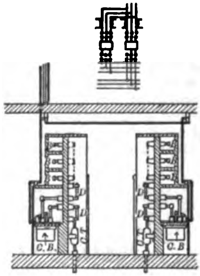

Fig. 123.

835. Bench boards are used only in large stations where the number of circuits is very large. A great saving in space is possible because the instruments do not crowd the control switches, thus allowing two or more generators to be handled on a single panel. Some of the types are shown in Fig. 124.

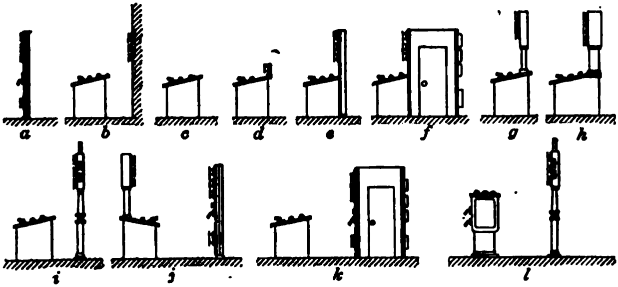

Fig. 124.—Types of bench boards.

836. Load dispatching in some form is necessary on complicated systems. The load dispatcher has full control over and knowledge at all times of the condition of the system. He usually has a map of the system indicating the condition of all electrical apparatus and issues all orders by telephone for the putting on or taking off of any machine or cable. Emergency conditions require a certain suspension of the direct control of the dispatcher, but in such cases a carefully worked out routine must be followed. Some very large systems have no man formally called a dispatcher but in such cases the senior operator in the largest station is given final authority and his orders must be obeyed.

STATION TRANSFORMER INSTALLATIONS

837. Transformers of practically all types are used for high-tension power-station work. On account of the size and voltage of most stations of this kind, the main power transformers are usually oil insulated, with or without water cooling, and of the shell type of construction. See Sec. 6.

838. Air-blast transformers are rarely used above 15,000 volts and in sizes above 1000 kv-a. They are available, however, up to 33,000 volts and 2,500 kv-a. These extremes should be avoided on account of insulation and cooling difficulty.

839. Self-cooled transformers are built in sizes up to about 2,000 kv-a. but the space required is large on account of the necessity of outside cooling tubes. Up to 1,000 kv-a. corrugated tanks give satisfactory results.

840. The question of single-phase vs three-phase transformers is not definitely settled. First cost, efficiency, simplicity of wiring and floor space, all point to the latter, but in installations of few units the desirability of flexibility frequently dictates single phase. When operated in delta, two units connected in open delta will safely carry about 60 per cent. of the load that a full bank will carry. This same ability also exists in shell type, three-phase transformers operated in delta, both primary and secondary, provided the damaged coils are disconnected and short-circuited. The relative floor space occupied is shown in Fig. 125.

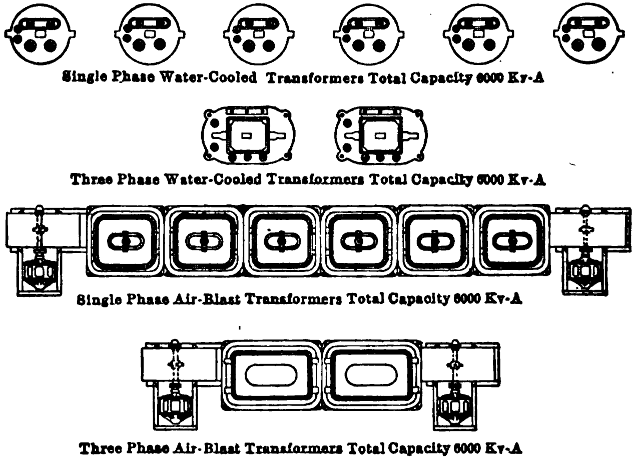

FIG. 125.—Relative floor space of single-phase and of three-phase transformers (G.E. Bulletins).

841. Water cooling is most generally used in large installations. The water supply must be continuous and pure. Where cooling water must be purchased cooling towers can be used to advantage. It is desirable to have negative pressure in the cooling pipes to prevent leakage into the oil.

842. The amount of water required is approximately 4 gal. per min. per 1,000 kv-a. capacity. This amount is not rigid. In winter considerably less is necessary, and in summer fully twice as much can be used to advantage.

843. The cost of water-cooling systems is from 10 cents to 25 cents per kv-a., depending on the source of supply.

844. Air-cooling requires blowers taking about 0.25 per cent. of the output. They are usually electrically driven and require from 3 cu. ft. per min. to 5 cu. ft. per min. per kv-a. at pressures from 1 oz. per sq. in. to 0.5 oz. per sq. in., depending on size. The first figures are for 100 kv-a. size and the latter for 1,000 kv-a. size.

845. Oil-insulated transformers are in reliable service up to 110,000 volts and 14,000 kv-a. and down to very small sizes at 25,000 volts. They are the most satisfactory in the average central station.

846. Forced oil cooling can be used for all sizes and gives satisfactory results. The transformers usually have plain boiler iron shells. The oil is pumped in at the bottom and overflows at the top, passing through a glass sight tubes to cooling coils located where good air circulation or cooling water is available. This method avoids the possibility of water leaking into the oil through defective tubes, as the oil may be kept under slight pressure. It also allows the convenient drawing of the shells without special piping. The chief objection is that a fire may put the entire equipment out of service. The cost is from 25 cents to 50 cents per kv-a. of capacity, which is considerably higher than water cooling, but there is a considerable saving in the cost of the transformers due to absence of cooling coils.

847. Fire danger from transformers, while not negligible, has been greatly exaggerated in the past. In some installations each bank has been placed in a well-drained fire-proof chamber, in addition to being equipped with a piping system to enable the rapid emptying of the shells into a buried tank. Some of the latest and very important installations have been constructed with simple barriers between banks opening into a common passage. The drainage system is still important but is used principally to facilitate repairs, inspection and the treating of the oil.

848. Convenient handling of the transformers should be provided for either by an overhead travelling crane, or by mounting on trucks on which they may be moved to an inspection pit.

849. Transformer oil must be kept particularly free from moisture; one part in 10,000 will reduce the dielectric strength 50 per cent. Drying outfits, which dry the oil by forcing it through successive sheets of blotting paper, are available at a cost of from $500 to $1,000 with capacities of from 5 to 20 gal. per min.

LIGHTNING ARRESTERS

850. Lightning protective apparatus is used in power stations to protect the apparatus therein from abnormal potentials on the system, whether caused by lightning disturbances or by switching operations. The ideal apparatus will immediately relieve the system of excess voltages, allowing no flow of the dynamic current of the system, and be ready for immediate service again.

851. The magnetic blow-out principle is frequently employed, particularly in low-voltage arresters. The spark gap is placed between the poles of an electromagnet (Fig. 126) excited by the flow of current which immediately bows out the arc. Series resistances are usually employed with this arrangement.

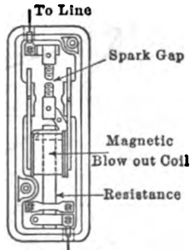

FIG. 126.—Magnetic blowout lightning arrester for low voltage.

852. Choke coils are simple open air core reactors inserted between the arresters and the apparatus to be protected to choke back the lightning disturbances, which are of very high frequency, thus allowing the arrester to discharge with a minimum strain on the station apparatus. To secure the full benefit of the choke coils, the connections to the arresters should be as straight as possible.

853. Spark gaps are used in practically all types of arresters, set at sufficient distance to prevent sparking over at ordinary voltages. Obviously something additional is needed to limit the flow of dynamic current after relieving the excess potential. Their most common use without considerable modification is to protect transformer secondaries, a single gap per bank of transformers being used.

854. Series resistances are usually inserted between simple spark gaps and ground for the purpose of arresting the current. This is accomplished, however, at a sacrifice in efficiency of the arrester in removing the disturbances which frequently have considerable current volume. This method is used, however, in many types from the lowest to the highest voltage.

855. Fuses inserted in series with a gap (Fig. 127) are not uncommon. They serve to relieve the system and interrupt the current, but they have the serious disadvantage of being able to handle only a single discharge. A simple circuit breaker is sometimes similarly used on low-voltage systems.

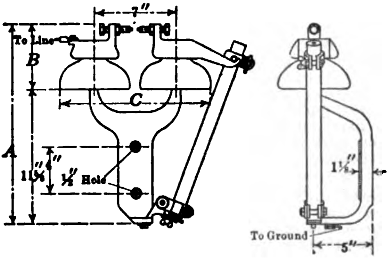

Fig. 127.—Air gap lightning arrester with fuse.

All of the above arrangements have their simplicity to recommend them but they are inadequate on all but very small or low-voltage systems.

856. Horn gaps are modified spark gaps which consist of conductors arranged in a "V" with a suitable gap at the bottom. The flaring sides are shaped so that the arc in rising by the heated air is lengthened and finally blown out. Careful proportioning is necessary, but even then the horns will fail to put out the arc from a heavy current.

857. Multigaps, which consist of a large number of gaps in series, between relatively large cylinders of non-arcing (composition) metal, have many advantages. When placed between line and ground the potential drop be-

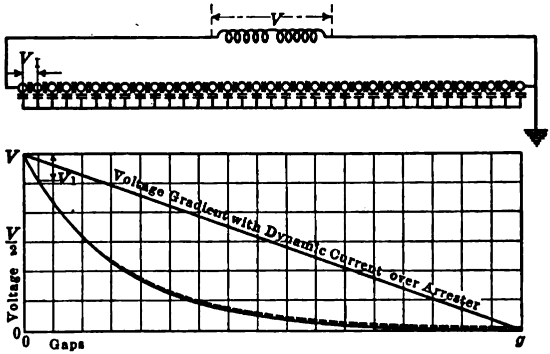

Fig. 128.—Voltage gradient across multigap arrester with and without dynamic current.

tween gaps is much greater near the line than near the ground, due to the electrostatic capacity of the cylinders (Fig. 128). This makes possible a much greater aggregate gap distance than with a single gap, which greatly aids the quenching of the dynamic arc. Lightning disturbances, being of high frequency, cause a still greater potential gradient, which will allow the disturbances to pass at a relatively low excess voltage. As soon as the gaps break down the flow of current causes an equal drop in all gaps.

The non-arcing metal has a low boiling point and acts as a rectifier, not allowing the dynamic arc to be resumed on reversal of current, if the voltage is kept low enough. The greater the number of gaps in series the more definite this action.

858. Multipath arresters allow high voltages to discharge along the surface of a very high resistance rod in numerous very fine sparks, the normal voltage being unable to continue the arc. This type is limited to small discharges.

859. Graded shunt resistance combined with multigaps, allows a greatly increased effective number. Referring to Fig. 129, which shows the arrangement used by the General Electric Co., the full line voltage is normally across the lower group of gaps, the resistance being low enough to accomplish this result. When breaking down, the flow of current through the high resistance causes a

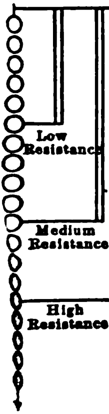

FIG. 129.—Elements of graded shunt multigap arrester.

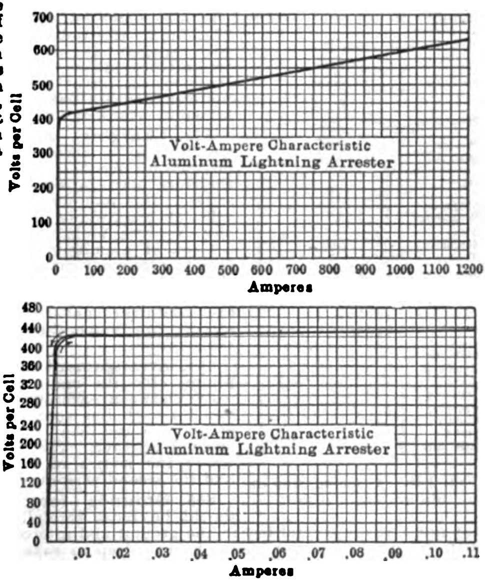

FIG. 130.—Characteristics of aluminum lightning arrester.

voltage across the second lower group of gaps which, if the lightning discharge is heavy enough, are broken down, thus inserting additional gaps to quench the arc. Similarly if the arc continues due to the discharge being too heavy, additional gaps are inserted until the entire group is in series. If this number will not rupture the arc the arrester may be destroyed, this being the limitation of the apparatus.

860. Series-resistance multigap arresters are built by the Westinghouse Company in recognition of this condition, called "Low-equivalent arresters." The series resistance is expected to limit the rate of discharge within safe limits. This type ordinarily uses but a single shunt resistance. There is considerable difference of opinion as to whether or not this series resistance is desirable. It sometimes saves the arrester, but at the expense of the apparatus by increasing the time necessary to relieve the system.

861. Care of multigap arresters requires the frequent removal of dust, best accomplished by blowing with compressed air. The arresters should be disconnected during this process.

862. Aluminum-cell lightning arresters depend for their action on the properties of aluminum when inserted in a suitable electrolyte, shown by Fig. 130. When an e.m.f. is applied between two electrodes, insulating films are formed which break down if the forming voltage is exceeded and reform immediately when the voltage becomes normal. This cell more nearly conforms to the ideal than any other arrester; it may be set for a very small increase in e.m.f.; its discharge rate is enormous and it immediately resumes normal condition after the discharge. Since the cells can be formed to withstand permanently only about 300 volts, a great number in series is required for high potential systems. Conical shaped aluminum electrodes are mounted on rods with spacers allowing a uniform space between (Fig. 131). Electrolyte is inserted in these spaces, great care being required to get uniform depth. The whole stack is then inserted in a tank of oil.

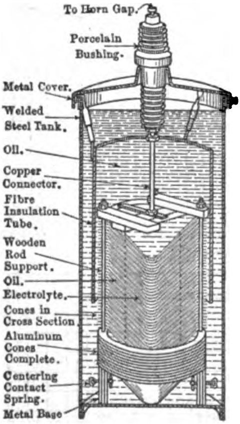

FIG. 131.—Construction of aluminum arrester.

863. Charging aluminum arresters. Continuous connection to the line is not possible on account of the loss of energy, and therefore horn gaps are usually connected in series. This requires frequent charging of the cells, at least daily, because the film gradually dissolves, more rapidly in warm weather.

Care of aluminum arresters requires not only this frequent charging, but also watching the charging current which is a guide to the condition of the electrolyte. Care should be exercised to prevent freezing of the electrolyte at very low temperatures, as it might destroy the arrester.

864. Arrangement of arresters on polyphase circuits may consist either of an arrester between each line and ground, or arresters for each line connected together on the ground side and then to ground through an additional arrester. The first method is used where the neutral of the system is grounded and the second where ungrounded.

865. Grounds for lighting arresters should be most carefully made. Numerous iron pipes driven several feet in the ground and interconnected by a copper strip are good. Copper plates buried deep in coke with earth filling are also used. In addition the arrester ground should be connected to the steel frame, piping, and other grounded materials in the building.

866. Summary of uses of various types of arresters.

(1) Spark gap—
- (a) Series resistance
- (b) Fuse
- (c) Magnetic blowout

  } D.C. systems, all voltages. A.C. trolleys, along the line.
- (d) Plain—Single point on transformer secondaries.

(2) Horn gap—
- (a) Series resistance
- (b) Fuse

  } A.C. systems, all voltages, located on poles. D.C. and A.C. series systems.

(3) Multipath—Frequent location along D.C. lines.

(4) Multigap—A.C. systems.
- (a) Plain—Frequent location along small distribution systems.
- (b) Series resistance—Frequent location along systems up 15,000 volts.
- (c) Shunt resistance
- (d) Shunt and series resistance,

  } Station use on systems of moderate size and length of line.

(5) Aluminum cell—

(a) In small jars or tanks,	D.C. systems along the line and D.C. stations.
(b) All stacks in one tank,	A.C. systems up to 7,500 volts.
(c) Separate tanks,	A.C. system up to 150,000 volts.

867. The cost of lightning arrester equipment is about as follows. Three-phase grounded-neutral systems: Aluminum cell, $70+$10 per 1,000 volts; multigap type, $13 per 1,000 volts. Three-phase ungrounded: Aluminum cell, $100+$15 per 1,000 volts; multigap type, $15 per 1,000 volts

868. The cost of 200-amp. choke coils of the "hour glass" type, is about: $20+$0.50 per 1,000 volts, up to 70,000 volts; $30+$0.80 per 1,000 volts, above 70,000 volts; the increased cost per 100 amp. is about $7. Pancake-type choke coils cost about $12+$20 per 100 amp. for 2,500-volt service and $40+$40 per 100 amp. for 25,000-volt service. The cost of installation of the above can usually be covered by a 15 per cent. increase, in addition to freight.

POWER STATION WIRING

869. Bus bars are made either of copper as discussed elsewhere in this section, or, in the case of high-potential stations or moderate potential in small sizes, of copper tubing, copper rods, and sometimes brass or iron pipe. Special bends and fittings are available for this pipe work. Where the current capacity is small, the physical stiffness required dictates the size of conductor. Bus bars are seldom continuously insulated. They are usually supported in the open in small low-voltage stations, and in all stations of very high voltage. Cell structures are used in stations of moderate voltage in all except relatively small stations.

870. Switch wiring on the board, or on the switch structure, should be stiff and well insulated for the full voltage, because the wires are particularly near together at this point. Stranded wires are seldom used except for simple layouts where accurate alignment is not necessary.

871. Main generator and exciter wiring should be run by the shortest possible route and provided with ample insulation, even above ordinary requirements. This wiring is not protected by automatic switches. Multi-conductor cables are not recommended and alternating-current and direct-current wiring must not occupy the same duct.

872. Instrument and control wiring form practically the nervous system of the power plant. Great care must be used to avoid trouble and only the highest grade of insulation should be used. Iron conduit should be used for all of the wires, terminating as closely as possible to the instrument panels and to the transformers. Terminals at oil switches and instrument transformers should be most carefully protected to prevent high-tension current from reaching them during switch troubles. All instrument wiring except that in main circuit must be thoroughly grounded both at the instrument transformer and at the panel. Terminal boards on the panels are of great assistance in calibrating instruments. Alternating-current and direct-current wires should not be run together any more than can be avoided.

873. Lightning-arrester connections should be as simple and direct as possible in order to secure maximum protection. Disconnecting switches should always be used.

874. The prevention of corona on wiring of very high tension requires special care. All sharp corners on the wiring and the switching apparatus must be avoided. Also see Sec. 11.

875. Bus and switch compartments (Fig. 132) are made of brick, soapstone and concrete, either plain or reinforced. Openings for switch inspection, etc., are usually covered with asbestos doors conveniently hung. When brick is used for the main walls, soapstone is used for horizontal walls and lesser barriers. Concrete is frequently used throughout. Whatever the materials of construction, their insulating qualities are not depended upon, and the conductors should be supported on insulators designed for full voltage with a wide margin of safety. Wide differences in design are possible, as is indicated in the cuts, and it is seldom that the same arrangement is ever used in two stations.

876. The cost of bus and switch structures varies widely, from $50 per switch in small sizes to $300 per switch in large capacity switches for 15,000 volts.

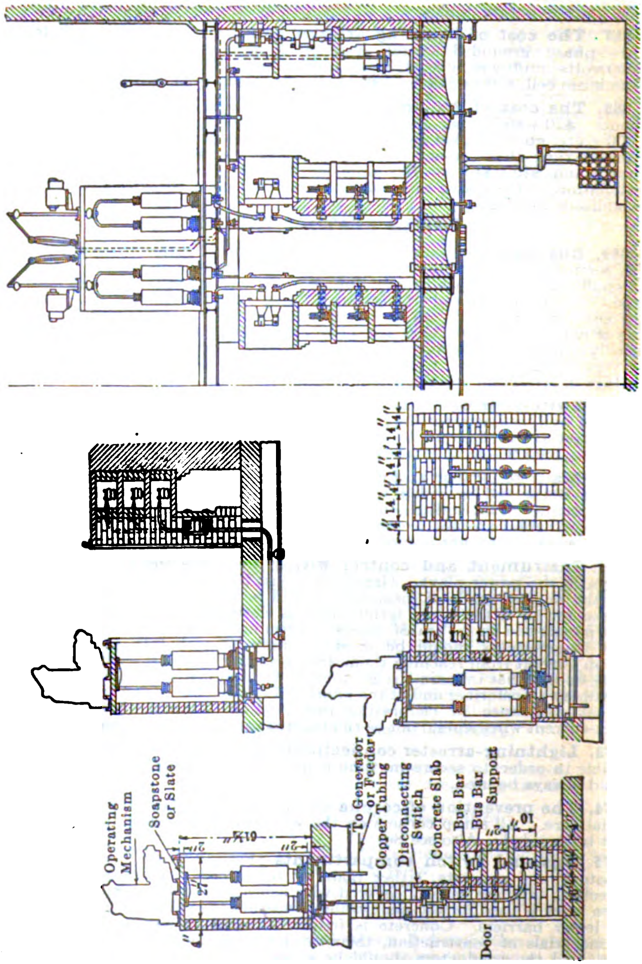

Fig. 190.—Typical bus and switch compartments.

877. Ducts and iron conduits are largely used in power station wiring but the latter should be avoided for alternating-current work of more tha very moderate current capacity. Clay or fibre ducts laid in concrete in the floor, or built into the ceiling cost, from 20 to 50 cents per duct ft. Iron conduit supported by clamps costs, in place, from 12 cents per ft. for the ½-in., to $1 per ft. for the 4-in. size. Brass pipe is sometimes used where large alternating currents must be carried in open conduit. The cost is about five times that of iron.

878. Bus-bar Compartment Dimensions

Max. e.m.f. kv.	Bus size inches	Dimensions, inches A	B	C
15	1–2 × ¼	13	12[illegible]	5¼
15	2–2 × ¼	13	12[illegible]	4[illegible]
15	1–3 × ¼	13	12[illegible]	5¼
15	2–3 × ¼	13	12[illegible]	4¼
22	wire	15	16¼	8[illegible]
33	wire	18	19[illegible]	9[illegible]
45	wire	25	26	13
66	wire	36	37	18
100	wire	56	56	28

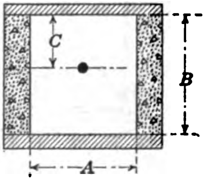

Fig. 133.

879. Spacing of High-tension Station Wiring

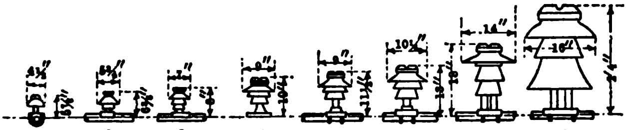

Fig. 134.

Number ref. to cut	E.m.f., volts	Spacing, inches	Ground distance, inches	Number ref. to cut	E.m.f., volts	Spacing, inches	Ground distance, inches
1	6,600	8	6	5	33,000	18	10 to 12
2	15,000	10	7	6	45,000	25	13
3	22,000	12	8 to 10	7	60,000	36	19
4	33,000	18	10	8	100,000	56	30

Note.—Ground distance (usually) $= \frac{\text{Wire spacing}}{2} + 1$ in.

Spacing of series transformers (self-cooled):

600 volts...........	1 in. clear	6,600 volts...............	3 clear
2,300 volts...........	1.5 in. clear	13,200 volts...............	5 clear

880. Terminals and entrances, particularly on high-tension overhead outlets, require the most careful design to prevent leakage during bad weather. Standard designs are on the market supplied by the various insulator companies. Wall outlets are usually relatively simple and cheap, but satisfactory roof bushings are available only at considerable expense. The latter are similar to the oil switch and transformer terminals used for outdoor work. Several types are shown in Figs. 136–138.

881. The cost of power-station wiring varies greatly and is exceedingly difficult to estimate. The cost of wire, supports, insulators, etc., can be obtained from manufacturers' lists, and usually an addition of from 25 per cent. to 50 per cent. will cover the cost of labor, the larger percentage being for the smaller wires. The cost of drawing into conduits varies from 1 cent to 5 cents per duct ft. The cost of joints and terminals varies

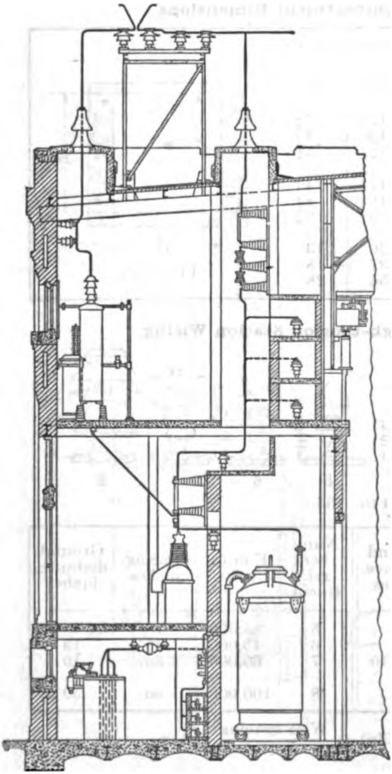

Fig. 135.—Cross section of transformer and switch galleries of high tension power station (*G.E. Rev.*, 1912, p. 598).

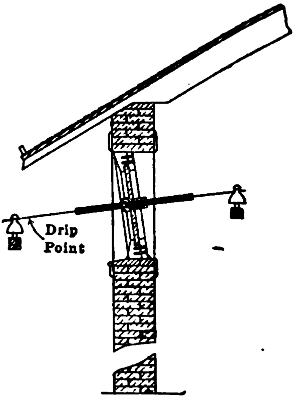

Fig. 136.—Wall outlet with slab and tube of insulating material.

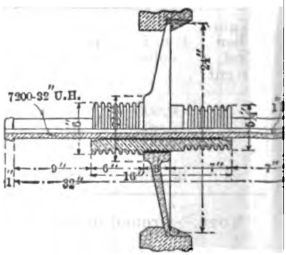

Fig. 137.—Thomas wall bushing for 66,000 volts.

between that of 5 ft. and 10 ft. of wire. The total cost of wiring varies from $0.50 to $3 per kw. of station capacity, in addition to the cost of switch gear, panels and compartments.

MISCELLANEOUS

882. Plant location. Electrical considerations seldom have preponderating influence on the location or general arrangement of a power station.

The location affects the cost of the distribution system, for moderate and low voltages, directly as the square of the average distance of the load; on high-potential systems, the variation is more nearly proportional to the distance. Other conditions being equal, however, it is obvious that the best location is as near as possible to the **load centre.**

883. Parallel operation. Large systems frequently require the parallel operation of power stations, and little difficulty is ordinarily experienced. In some cases where plants in close proximity are thus operated, the service conditions require that the stations shall not be automatically disconnected from each other except in case of trouble in the tie lines. In other cases provision is made for the immediate disconnection of the stations in case of trouble in either. The latter arrangement is used where there is no connection between the systems supplied by the stations, other than directly between the station bus bars. Where stations are widely separated, parallel operation is not satisfactory when the resistance drop in the connecting lines exceeds 15 per cent. on alternating-current systems and 50 per cent. on direct-current systems. The operation of such **interconnected systems** requires careful arrangement, frequently making it necessary to have a **load dispatcher** in full control of all switching operations.

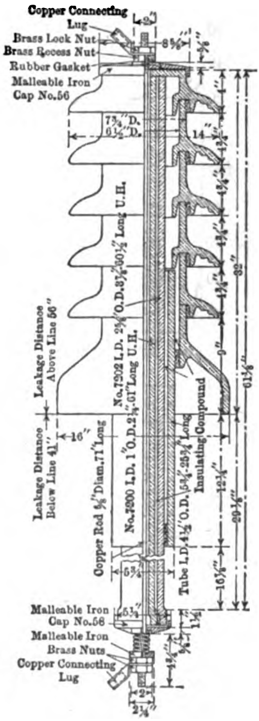

FIG. 138.—Thomas roof insulator for 66,000 volts.

POWER-PLANT ECONOMICS

BY GEORGE I. RHODES

884. Load fluctuations largely determine the desired overload capacity of units. Lighting systems have steady loads except for peaks shown by the usual load curve. Industrial loads are very steady except for certain kinds of applications to intermittent work using large units. Railway loads have considerable fluctuation even in the largest systems. Swings of five times the average are experienced when but a single car is running, twice, when about ten are running, and to 120 per cent. when a very large number are running.

885. Sudden peaks are always a possibility on a lighting system, and occur whenever a sudden storm appears. An increase in load of as much as 100 per cent. within a very few minutes is not uncommon.

886. The load factor of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a period such as a day, or a year, and the maximum is taken over a short interval of the maximum load within that period. In each case the interval of the maximum load should be definitely specified. The proper interval is usually dependent upon local conditions and upon the purpose for which the load factor is to be determined. The yearly average of daily load factors is frequently used. (See Sec. 25.)

887. Diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system, to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

888. The load to be carried is probably the most important factor to be considered in power-plant design. It determines the size of plant, the kind of plant, and the size and number of units. **Typical load curves** are shown in Figs. 139 and 140. These curves are such as would be obtained from 15-min. readings of watt-hour meters but do not show the exact load on

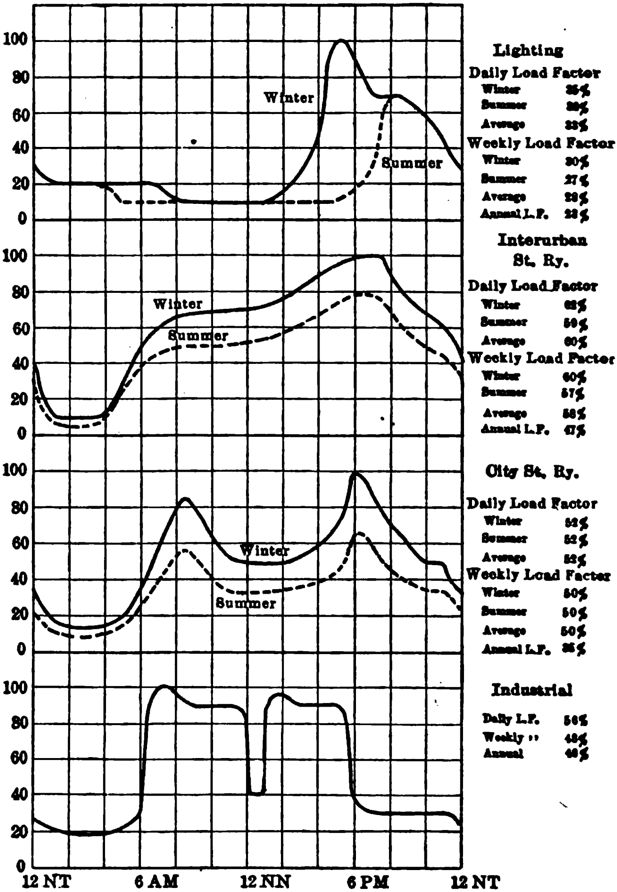

FIG. 139.—Typical load curves.

any specific plant. For typical load curves in very large central stations see *Trans.* A. I. E. E., Vol. XXXI, p. 1473, 1912.

889. Demand factor is the ratio of the maximum power demand of any system or part of a system to the total connected load of the system, or of the part of the system under consideration.

890. Capacity factor is the ratio of the average load to the total rated capacity of the equipment supplying that load. This factor is not very definite on account of variations in methods of rating apparatus.

891. Fixed charges as ordinarily defined with reference to power plants, are the charges necessary to carry the investment and to replace the equip-

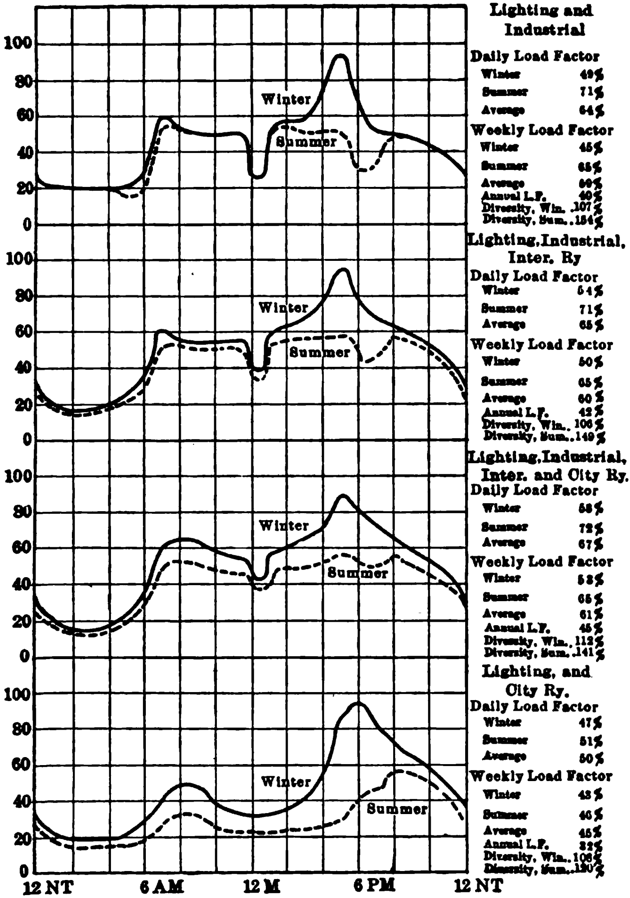

FIG. 140.—Typical load curves.

ment when it is worn out or destroyed. Interest and taxes carry the investment, while insurance and accumulated depreciation funds cover replacement.

892. Interest as used in engineering computations is the annual cost of the money required for the work. It is affected by the credit of the company and the condition of general business at the time money is borrowed. If money is raised by bonds sold below par, as is frequently the case, the cost of money is not only the only interest rate on the bond, but this amount is increased in proportion to the amount the bond is sold below par and, also, by an amount which set aside annually will make up this deficit below par when the bond is retired or paid. Six per cent. should be used as an average cost of money, but it varies between 4 per cent. and 8 per cent., the lower figure for municipalities and the higher for industrial corporations.

893. Profit on the investment, namely, income above the total of all required expenses, interest, etc., should not ordinarily be considered in engineering work.

894. Taxes are proportionately more variable than interest, ranging from less than 0.5 per cent. to as high as 2.0 per cent. It is generally the case, however, that high taxes and low interest coincide, so that the probable variation of the total of interest and taxes is from 6 per cent. to 9 per cent.; 7.5 per cent. is the figure frequently used.

895. Insurance of power plants against fire varies from less than 0.1 per cent. for fire-proof modern plants, to as high as 1 per cent. for the old type of plant with oil-soaked wooden floors, etc. Insurance in a modern plant may seem unnecessary, but the regular visits of insurance inspectors have a beneficial influence on the operation of the plant which is frequently worth more than the cost of the insurance. The figure commonly used for the cost of insurance is 0.5 per cent.

896. The cost of depreciation is one of the most commonly neglected and one of the most important elements of the total cost of power. The existence of depreciation in some form is generally recognised, but it is frequently neglected in actual operation of companies, either because of lack of income or desire for immediate profit.

897. Physical depreciation is the result of deterioration due to wear and tear caused by regular use, decay and the action of the elements.

898. Legally Approved Depreciation Rates

Compiled by Henry Floy. Maintenance not included.

A. Arbitrators, Atlanta, Ga., Street Lighting Controversy.
B. New York Public Service Commission, 1st District.
C. St. Louis Public Service Commission, St. Louis, Mo.
D. Chicago Traction Valuation Commission, Con. Traction Co.
E. Wisconsin Railroad Commission.

Property	Depreciation, per cent. per year (straight line)	Key to authority
Aerial lines	5	C
Air brakes	5	E
Air compressors	4 to 5	D
Arc lamps	6.67	E
Arc lamps	8	C
Belting	5	E
Boilers	3.5 to 4	D
Boilers	6.67	C
Boilers, water-tube	5	B
Boilers, fire-tube	6.67	E
Boilers, water-tube	5	E
Boilers, fire-tube	10	A
Bonds	5	D
Bonds	50 wearing value	B
Bonds	5	E
Breeching and connections	3.5 to 10	D
Buildings	1.5	D
Buildings, brick	2	B

898. Legally Approved Depreciation Rates.—(*Continued*)

Property	Depreciation per cent. per year (straight line)	Key to authority
Buildings	2 to 4	E
Buildings, wood	2	C
Buildings	2	A
Cables, underground, high-tension	5	B
Cables, underground, low-tension	50 maintenance cost	B
Cables, aerial, lead-covered	6.67	E
Cables, underground, lead-covered	4	E
Cables, underground, lead-covered	5	C
Coal and ash handling machinery	7	D
Coal and ash handling machinery	5	B
Coal and ash handling machinery	10	E
Condensers	4	D
Condensers	5	B
Condensers	5	E
Condensers	6.67	C
Conduits	1	B
Conduits	2	E
Conduits	2	C
Cross-arms	8.33 to 12.5	E
Engines, steam	3 to 5	D
Engines, steam	5 to 7.5	B
Engines, gas	6.67	E
Engines, steam, slow-speed	5	E
Engines, steam, high-speed	6.67	E
Engines,	5	A
Engines,	6.67	C
Feeders, weather-proof insulation	Dependent on observed wear	D
Feeders, weather-proof insulation	6.25	E
Foundations, machinery	Same as life of apparatus supported	D
Foundations, machinery	Same as life of apparatus supported	B
Fuel-oil handling machinery	4	D
Generators	3 to 8	D
Generators	5	B
Generators, modern type	5	E
Generators, obsolete	6.67	E
Generators, steam turbo	5	E
Generators, steam turbo	10	A
Generators	6.67	C
Heaters	4 to 6	D
Heaters, feed-water, closed	3.33	E
Heaters, feed-water, open	3.5	E
Meters, electric switchboard	5	E
Meters, electric service	6.67	E
Meters, electric	8	C
Motors, railway	3.33	D
Motors, railway	By inspection	B
Motors, railway	5	B
Motors, railway	5	E
Paving	50 wearing value	B
Piping and covering	4 to 4.5	D
Piping and covering	5 to 6	B
Piping and covering	5	E
Piping and covering	5	A
Piping and covering	6.67	C
Poles, steel	2	B
Poles, wood in concrete	5	E
Poles, wood in earth	5.5 to 8.33	E

898. Legally Approved Depreciation Rates.—(*Continued*)

Property	Depreciation, per cent. per year (straight line)	Key to authority
Poles, iron	2.5	E
Poles, wood	10	A
Pumps	5	D
Pumps	5	B
Pumps, small steam	6.67	E
Pumps	5	A
Pumps	6.67	C
Rolling stock, open car bodies	4	D
Rolling stock, open trailer bodies	4	D
Rolling stock, closed car bodies	5	D
Rolling stock, trucks	3.33	D
Rolling stock, closed & open cars	3.33	B
Rolling stock, trucks	3.33	B
Rolling stock, car bodies and equip	6.67	E
Stack	3	D
Stack, steel	10	B
Stokers, fixed parts	5	D
Stokers, moving parts	20	D
Storage batteries	5	B
Storage batteries	6.67	E
Storage batteries	5	C
Switchboard and wiring	3	D
Switchboard and wiring	6	B
Switchboard and wiring	5	E
Switchboard and wiring	8	C
Telephones	10	E
Track, rail joints	5	D
Track, ties,	5	D
Track, rails	Dependent on observed wear	D
Track, special work	8.33	E
Track, straight and special work	50 % wearing value	B
Track, straight track	5.5	E
Transformers, station service	5	E
Transformers, station service	6.67	C
Turbines, steam	5	E
Turbines, water	3.33	E
Turbines, steam	6.67	C
Wire, trolley	Allowance of 80.5 lb. per 1,000 ft. for wear-wearing value of No. 0 wire	D
Wire, trolley	Allowance of 106.8 lb. for No. 00 wire.	D
Wire, trolley No. 0, under 1 min. headway	50	E
Wire, trolley No. 00, under 1 min. headway	40	E
Wire, trolley, No. 000, under 1 min. headway	33.3	E
Wire, weather proof	6.25	E
Wire, weather proof	7.5	A
Wire, weather proof	50 % maintenance cost	B

899. Functional depreciation is the result of lack of adaptation to function, caused by **obsolescence** and **inadequacy**. Obsolescence is due to changes or advances in the art which renders a piece of apparatus, or a whole class of it, obsolete and uneconomical of use, as compared with new types which have been developed at a later date and which are much more efficient (H. G. Stott, *Trans.* A. I. E. E., p. 1619, 1913).

900. Life expectancy of equipment. The life expectancy of power-plant equipment, taking functional depreciation into account, is as follows;*

Property	Total life (years)	Scrap value, per cent. of original cost
Buildings	75	5
Boilers, stokers and furnaces	20	5
Conveyers, elevators and hoists	20	1
Turbines, complete	12	10
Engines and condensers	12	10
Piping, values and traps	12	3
Pumps	12	5
Synchronous converters, transformers and exciters, etc.	20	10
Switching apparatus and instruments	12	5
Alternators	12	10
Motors	20	10
Tools and sundries	10	3
Storage batteries	10	10

901. Scrap value. It is obvious that in computing the net annual amount of depreciation the scrap value of the apparatus must be deducted from the original or first cost.

902. Methods of caring for depreciation. Charging to repairs all replacement of apparatus, either in part or as a whole, is expected in many companies to care for depreciation. Ordinary repairs will not prevent a machine from finally reaching a point, due to wear and tear, where it will have to be replaced and in small companies this replacement would cost such a large proportion of the total investment that it is desirable to accumulate a fund for the purpose. If replacements are charged to repairs this item will become irregular in amount, which is a very undesirable condition. In very large companies the irregularity becomes less and consequently the method can be used with success.

903. The straight-line method of computing depreciation is based on the assumption of a uniform reduction in value. It is commonly assumed that the accumulated depreciation fund, under this method, bears no interest, but such is not necessarily the case. The method has the great advantage of being very simple in application.

904. The amortization or sinking fund method of computing depreciation assumes that the accumulated depreciation fund is invested and bears interest. The effect is to make the annual rate less, of course, than it would be if the fund bore no interest. This method is not easy of application to actual conditions. Some authorities consider that it represents, more nearly than the straight-line method, the depreciation in actual value of the property as determined by what a purchaser could afford to pay for it.

905. Calculations of depreciation, by whatever method, should be made separately for each type of equipment, taking into account its expected life and its scrap value. There is much chance for error in deciding on a percentage to apply to an entire property, and if used it should be determined from a detailed calculation. It is evidently subject to some variation from time to time as new equipment is added.

906. Obsolescence is commonly regarded as a type of depreciation to be charged to the cost of power. This is not necessarily the case. Obsolescence does not accrue from day to day, like physical depreciation, but accrues coincidently with advances in the art resulting in new and more efficient machinery or methods. The full physical life of equipment is possible in any event, whether or not obsolescence occurs, and the question whether a piece of equipment should be replaced before it wears out is determinable by equating the saving in operating expenses against increased

* Stott, H. G., "Power Costs"; *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 1112.

fixed charges. In comparing different types of plants it is misleading to consider obsolescence as different for the various types.

Physical and functional depreciation costs must not be added. If functional depreciation will shorten the expected life the proper rate to care for this shortened life should be used, which includes physical depreciation. Eminent engineers have incorrectly allowed a percentage for physical depreciation and an additional percentage for functional depreciation.

907. Summary of H. G. Stott's Classification of Operating and Maintenance Costs

(Material and labor separated for each item)

Production costs	Production repairs costs
Management and care	Furnaces and boilers
Boiler room	Boiler accessories
Engine room	Engines
Electrical	Engine accessories
Fuel for steam	Piping
Water for steam	Electric generators
Lubricants	Electrical accessories
Supplies	Tools
Station expense	Building
General	General

908. Power cost data given in this section of the handbook represent as nearly as possible the **present state of the art** rather than old imformation. For instance, a great deal of data are available in reports to the various public service commissions which gives costs far in excess of these indicated here. In almost every instance the reporting companies operated plants which contain a great deal of inefficient apparatus maintained at great expense, but for less cost than the fixed charges of new apparatus. Companies operating modern plants also frequently operate old plants, but do not report them separately. While these reports give valuable data as to what is being done under old designs, they are of little use for the purpose of estimating costs in truly modern plants.

909. Boiler Room Equipment Costs per Rated Boiler Horse-power using Coal for Fuel*

	Dollars per h.p.	
	High	Low
Boilers exclusive of masonry setting	$11.00	$8.00
Superheaters	3.00	0
Stokers	5.50	3.00
Masonry settings for boilers	3.50	2.00
Flues	1.50	0.75
Stacks	4.00	2.00
Economizers	4.00	0
Mechanical draft	3.00	0
Feed pumps	1.50	0.60
Feed heaters	1.00	0.40
All piping and pipe covering	10.00	6.00
Coal chutes and ash hoppers	1.25	0
Various, such as indicating and recording devices, damper regulator, ladders and runways, painting, etc., etc	1.00	0.50
Totals	$50.25	$23.15

* Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.

910. Classification of operating expenses. A very complete form of cost analysis has been given by Mr. H. G. Stott, whose paper* should be consulted for details. His summary is presented in Par. **908**.

911. Analysis of the Average Losses in the Conversion of 1 Lb. of Coal into Electricity†

	B.t.u.	Percent.	B.t.u.	Percent.
1. B.t.u. per pound of coal supplied	14,150	100.		
2. Loss in ashes			340	2.4
3. Loss to stack			3,212	22.7
4. Loss in boiler radiation and leakage			1,131	8.0
5. Returned by feed-water heater	441	3.1		
6. Returned by economizer	960	6.8		
7. Loss in pipe radiation			28	0.2
8. Delivered to circulator			223	1.6
9. Delivered to feed-pump			203	1.4
10. Loss in leakage and high-pressure drips			152	1.1
11. Delivered to small auxiliaries			51	0.4
12. Heating			31	0.2
13. Loss in engine friction			111	0.8
14. Electrical losses			36	0.3
15. Engine radiation losses			28	0.2
16. Rejected to condenser			8,524	60.1
17. To house auxiliaries			29	0.2
	15,551 14,099	109.9 99.6	14,099	99.6
Delivered to bus bar	1,452	10.3		

912. Analysis of Thermal Losses in Power Plants ‡

Range of Common Practice

British thermal units per pound of fuel	14,000		
Average yearly overall boiler and furnace efficiency	50	to	70
Effective British thermal units per pound of fuel	7,000	to	9,800
Boiler pressure, pounds per square inch, gage	125	to	190
Superheat, degrees Fahrenheit	0	to	125
Average feed-water temperature, degrees Fahrenheit	120	to	200
British thermal units per pound of steam (approx.)	1,100	to	1,100
Pounds of water evaporated per pound of fuel, actual	6.36	to	8.91
Pounds of fuel per standard boiler h.p. (33,305 b. t. u. s)	4.76	to	3.40
Average overall station water rate kw	30	to	20
Pounds of coal per k.w. generated	4.72	to	2.35
British thermal units in coal per kw. generated	66,000	to	31,500
Thermal efficiency of station	5.2 %	to	10.8 %

* Stott, H. G. and Gorsuch, W. S., "Standardization of Method for Determining and Comparing Power Costs in Steam Plants;" *Trans.* A. I. E. E., 1913, p. 1099.

† H. G. Stott, "Power-plant Economics," *Trans.* A. I. E. E., 1906, p. 3.

‡ Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.

913. Power Plant Costs per Kilowatt
(H. G. Stott)

	Min.	Max.
1. Real estate	$3.00	$7.00
2. Excavation	0.75	1.25
3. Foundations, reciprocating engines	2.00	3.00
4. Foundations, turbines	0.50	0.75
5. Iron and steel structure	8.00	10.00
6. Building (roof and main floor)	8.00	10.00
7. Galleries, floors, and platforms	1.50	2.50
8. Tunnels, intake and discharge	1.40	2.80
9. Ash storage pocket	0.70	1.50
10. Coal hoisting tower	1.20	2.00
11. Cranes	0.40	0.60
12. Coal and ash conveyors	2.00	2.75
13. Ash cars, locomotives, and tracks	0.15	0.30
14. Coal and ash chutes	0.40	1.00
15. Water meters, storage tanks, and mains	0.50	1.00
16. Stacks	1.25	2.00
17. Boilers	9.50	11.50
18. Boiler setting	1.25	1.75
19. Stokers	1.30	2.20
20. Economizers	1.30	2.25
21. Flues, dampers, and regulators	0.60	0.90
22. Forced draft blowers, air ducts	1.25	1.65
23. Boiler, feed, and other pumps	0.40	0.75
24. Feed-water heaters	0.20	0.35
25. Piping, traps, and separators	3.00	5.00
26. Pipe covering	0.60	1.00
27. Valves	0.60	1.00
28. Main engines, reciprocating	22.00	30.00
29. Exciter engines, reciprocating	0.40	0.70
30. Condensers, barometric or jet	1.00	2.50
31. Condensers, surface	6.00	7.50
32. Electric generators	16.00	22.00
33. Exciters	0.60	0.80
34. Steam-turbine units, complete*	$10.00	$15.00
35. Converters, transformers blowers	0.60	1.00
36. Switchboards, complete	3.00	3.90
37. Wiring for lights, motors, etc	0.20	0.30
38. Oiling system	0.15	0.35
39. Compressed air system and other small auxil.	0.20	0.30
40. Painting, labor, etc	1.25	1.75
41. Extras	2.00	2.00
42. Engineering expenses and inspection	4.00	6.00

914. Analysis of the Average Losses in the Conversion of 1 Lb. of Coal Containing 12,500 B.t.u. into Electricity. Producer Gas Engine Plant†

	B.t.u.	Per cent.
1. Loss in gas producer and auxiliaries	2,500	20.0
2. Loss in cooling water in jackets	2,375	19.0
3. Loss in exhaust gases	3,750	30.0
4. Loss in engine friction	813	6.5
5. Loss in electric generator	62	0.5
6. Total losses	9,500	76.0
7. Converted into electrical energy	3,000	24.0
	12,500	100.0

* Edited by Author.

† H. G. Stott, "Power Plant Economics," *Trans.* A. I. E. E., 1906, p. 3.

915. Cost of 1 H. P. per Year, Compound Condensing Engines, 10-hr. basis, 308 Days per Year*
(Wm. O. Webber, Engineer U. S., Feb. 2, 1903, p. 144)

Size of plant	Horse-power			
	200	600	1,000	2,000
Cost of plant per horse-power	$146.00	$85.00	$60.00	$56.00
Fixed charges at 14 per cent.	24.40	11.90	8.40	7.85
Coal per horse-power hour, pounds	6.5	4.5	2.5	1.5
Cost of fuel at $4.00 per ton	35.70	24.70	13.75	8.25
Attendance, 10-hr. basis	10.00	5.40	3.50	3.00
Oil, waste, supplies	2.00	1.08	0.70	0.60
Total	68.10	43.08	26.35	19.70
With coal at $5.00 per ton.	77.10	49.28	29.80	21.75
With coal at $4.00 per ton.	68.10	43.08	26.35	19.70
With coal at $3.00 per ton.	59.20	36.88	22.90	17.65
With coal at $2.00 per ton.	50.25	30.73	19.47	15.57

916. Example of operating expense. Operating cost in station containing: one, 4,000 kw. turbo-generator, new; two, 1,000 kw. turbo-generators, old; one, 500 kw. turbo-generator, old; six, 350 h.p. hand-fired boilers. Peak load 4,455 kw. Kw-hr. generated, 11,970,000 kw-hr. Year ending June 30, 1913.

	Total	Mills per kw-hr.
1. Fuel delivered in boiler room average cost $4.07 per ton	$56,728	4.742
2. Oil and waste	620	0.052
3. Water	1,601	0.134
4. Wages in station incl. superintendence	16,108	1.345
5. Building repairs	810	0.068
6. Steam plant repairs	2,089	0.175
7. Electric plant repairs	3,088	0.258
8. Tools and appliances, etc.	1,853	0.155
	82,898	6.929

917. National Electric Light Association, Form for Power Cost Record. (*Condensed*)

1. Station Wages:
   (a) Superintendence and office force:
   (b) Boiler labor.
   (c) Engine labor.
   (d) Electrical labor.
   (e) Miscellaneous labor.
2. Fuel.
3. Water:
   (a) Feed water.
   (b) Condensing water.
   (c) House water.
4. Lubricants.
5. Station supplies and expense:
   (a) Supplies.
   (b) Expense.
6. Station Buildings: maintenance, including labor:
   (a) Structure.
   (b) Fittings.
7. Steam Equipment: maintenance, including labor:
   (a) Boilers and furnaces.
   (b) Boiler auxiliaries.
   (c) Piping.
   (d) Prime movers.
   (e) Mechanical apparatus.
   (f) Tools and instruments.
8. Electrical Equipment: maintenance, including labor:
9. Hydraulic Equipment: maintenance, including labor.
   (a) Dam and pipe lines, etc.
   (b) Turbine and gates.
10. Gas Equipment: maintenance, including labor:
   (a) Gas engines and auxiliaries.
   (b) Other apparatus.
11. Purchased Power.

* Gebhardt, "Steam Power Plant Engineering," p. 711.

918. Unit Costs of Hydroelectric Developments
(O. S. Lyford, Trans. A. I. E. E., 1909)

Plant	A	B	C	D	E	F	G
	Cash	cost	per	kilowatt	of	generator	capacity
Land and water rights	$14.10	$12.86	$8.89	$14.20	$22.22	$13.07	$15.00
Hydraulic construction (dam, canals, flumes, head-gates, etc. Power house building and substructure	35.00	43.41	49.50	44.53	51.30	62.42	56.71
Hydraulic equipment	14.00	13.95	13.00	9.05	7.76	7.84	7.56
Power house electrical equipment	21.00	22.73	19.20	13.85	14.50	13.53	12.50
Transmission line, including right of way	17.20	6.26	18.30	9.00	20.70	17.50	28.50
Substation buildings and equipment	5.72	6.51	9.75	7.55	6.82	8.40	8.40
Distribution system	10.00	6.94	4.58	4.45	15.67	14.58	12.00
Interest during construction	6.30		5.54	4.75	8.40	6.18	6.16
Engineering	5.90	7.36	6.14	6.30	7.00	6.87	6.84
General and legal exp.	3.70		6.20	4.45	5.77	7.48	6.84
Total	$132.92	$120.02	$141.10	$118.13	$160.14	$157.87	$160.51

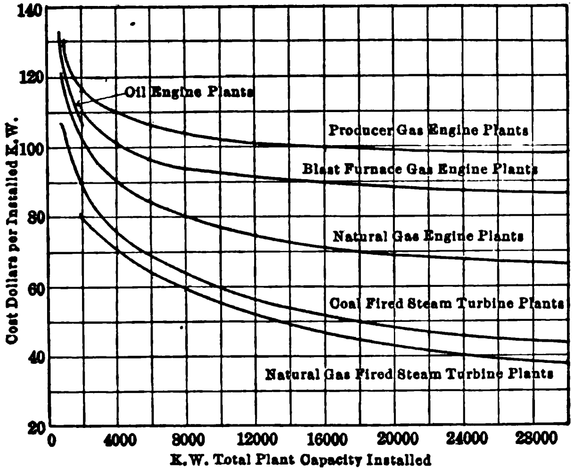

FIG. 141.—Plant installment costs (E. D. Dreyfus, *Elec. Jour.*, 1912).

919. Cost of Producer Gas Installations, 1912
(Bureau of Mines Bulletin No. 55, p. 29)

Horse-power	Cost of gas producer and engine erected, including foundations	Cost of complete plant, exclusive of buildings (a)	Cost of complete plant, including buildings (a)	Cost per horse-power		
				Gas producer and engine erected, including foundations	Complete plant, exclusive of buildings (a)	Complete plant, including buildings (a)
50	$4,300	$5,300	....	$86.00	$106.00	....
100	6,250	7,800	$9,100	62.50	78.00	$91.00
200	12,400	15,800	17,500	62.00	79.00	87.50
200	13,200	16,200	....	66.00	81.00	....
250	14,800	18,200	....	58.20	72.80	....
300	17,000	22,000	23,800	56.65	73.35	79.35
500	25,000	29,500	....	50.00	59.00	....
500	32,500	47,500	....	65.00	95.00	....
1,000	48,500	57,500	....	48.50	57.50	....
1,000	56,000	84,000	....	56.00	84.00	....
3,000	145,500	202,000	....	48.50	67.35	....

(a) Includes producer, engine, electric generator, piping, switchboard and auxiliaries, all erected with suitable foundations.

920. Influence of load factor on cost of power.

(a) **Fixed charges.** It is obvious that this cost varies inversely as the load factor. It is important, however, that the proper factor be used, namely the annual capacity factor of the total equipment installed.

(b) **Operating labor.** It is obvious that in small plants, or plants of very few units, a large amount of labor is unaffected by the load on the plant. As the number of units increases, this portion becomes relatively smaller. It is probable that the ratio of full-load labor costs per hour to no-load costs varies from 2 to 1 in plants of a single unit, to 5 to 1 in plants of a large number of units.

(c) **The coal** required to maintain a plant ready for instant service with one unit running at no-load, consists of that required for its no-load steam, that of the auxiliaries and that for banked fires under sufficient boiler capacity to carry the peak load. This total no-load coal ranges from 25 per cent. of full-load coal in a plant of one unit to 8 per cent. in a plant of many units.

(d) **Operating repairs** and other expenses are very indefinite and uncertain except over a long period of time, but probably vary in direct proportion to the load, thus being independent of the load factor.

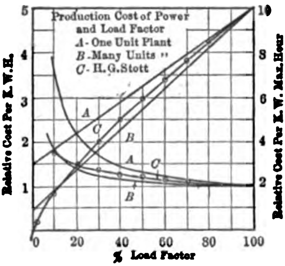

Fig. 142.—Variation in cost of power with load factor.

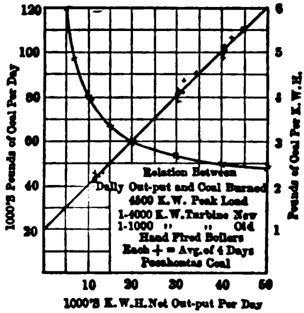

Fig. 143.—Variation in coal consumption with load factor.

(e) **Total production cost** at no-load varies from 30 per cent. of that at full load in plants of a single unit, to 10 per cent. in plants having many units. Mr. H. G. Stott has found that experience shows a variation in cost per kw.-hr. inversely as the fourth root of the load factors. Curves showing these costs are given in Figs. 142 and 143.

(f) **Period of load factor.** Since the no-load costs in a station are determined largely by the peak load expected during the month or week, it is evident that load factors for a shorter period than a year are advisable. Possibly the average daily or weekly load factor will give the best method of comparing these costs.

921. Comparison of power costs in different plants will lead to unreliable results unless certain fundamental conditions are taken into account. The chief of these are:

(a) **Certainty that costs include the same items** for each plant. Management, general expenses and building repairs are frequently omitted and care must be exercised to ascertain just what makes up the total cost. Hence the necessity of standard methods of cost accounting.

(b) **Load factors** if different require reductions of costs to the same basis. Fixed charges are inversely as the first power, and operating costs inversely as the fourth root of the load factors. Variations from 20 per cent. to 60 per cent. can be compared closely by this method.

(c) **Coal costs must** be compared on some common basis such as the cost per 1,000,000 B.t.u. available after deducting the B.t.u. in the ash.

(d) **Labor costs** must be treated similarly on the basis of the average wage per hour per man.

(e) **Fixed charges** must be on the same basis, not necessarily with the same life of equipment, but with the same method of figuring depreciation costs. It is also important to know how much spare apparatus is being maintained and whether or not the plant is complete, or one in which there is room for considerable additional apparatus.

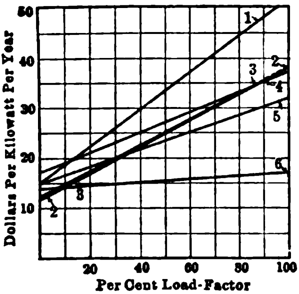

FIG. 144.—Coal cost $1.50 per ton; 11,000 B.t.u. per lb.*

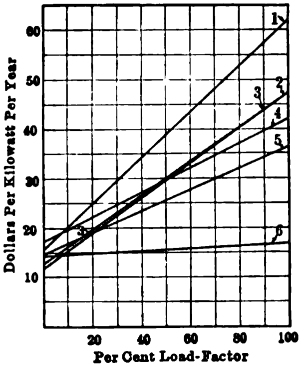

FIG. 145.—Coal cost $3.00 per ton; 14,500 B.t.u. per lb.*

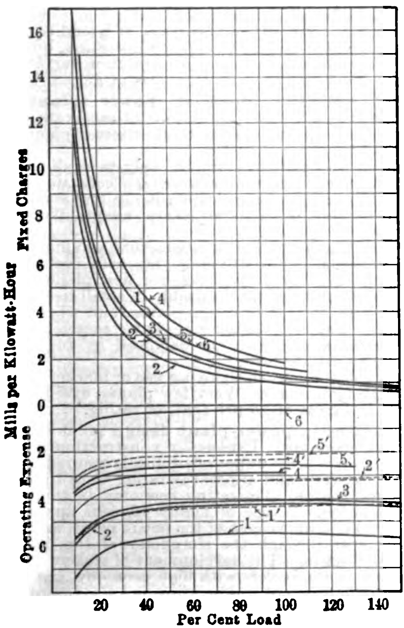

FIG. 146.—Cost of energy. (H. G. Stott, *Trans.* A. I. E. E., Dec., 1908.)

Line 1, Reciprocating steam plant; line 2, steam turbine plant; line 3, engines and low pressure turbines; line 4, gas engine plant; line 5, gas engine and steam turbine plant; line 6, hydraulic plant.

Coal cost $1.50 per ton; 11,000 B.t.u. per lb., Fig. 144 and dotted lines, Fig. 146. Coal cost $3.00 per ton; 14,500 B.t.u. per lb., Fig. 145 and solid lines, Fig. 146.

* For significance of curve numbers, see caption of Fig. 146.

922. Example of comparison of power costs.* Let C_1, C_2 = total cost per kw-hr. in plants 1 and 2,

I_1, I_2 = fixed charges per kw-hr. in plants 1 and 2,

F_1, F_2 = fuel costs per kw-hr. in plants 1 and 2,

L_1, L_2 = labor costs per kw-hr. in plants 1 and 2,

O_1, O_2 = total other costs per kw-hr. in plants 1 and 2,

f_1, f_2 = cost per 1,000,000 B.t.u. in plants 1 and 2,

l_1, l_2 = average hourly wage in plants 1 and 2,

R_1, R_2 = average daily load factors in plants 1 and 2.

C_2^1 = total cost in plant 2 reduced to plant 1 conditions.

Example:

C_1 = 6.5 mills per kw-hr.	C_2 = 7.5 mills per kw-hr.
I_1 = 2.0 mills per kw-hr.	I_2 = 2.5 mills per kw-hr.
F_1 = 3.0 mills per kw-hr.	F_2 = 3.0 mills per kw-hr.
L_1 = 1.0 mills per kw-hr.	L_2 = 1.5 mills per kw-hr.
O_1 = 0.5 mills per kw-hr.	O_2 = 0.5 mills per kw-hr.
f_1 = 10 cents per 1,000,000 B.t.u.	f_2 = 8 cents per 1,000,000 B.t.u.
l_1 = 30 cents per hour	l_2 = 40 cents per hour
R = 50 per cent.	R = 40 per cent.

$$C_2^1 = I_2\frac{R_2}{R_1} + \left[F_2\frac{f_1}{f_2} + L_2\frac{l_1}{l_2} + O_2\right]\left[\frac{R_2}{R_1}\right]^{\frac{1}{4}} = 2.5\times\frac{40}{50} + \left[3.0\times\frac{10}{8} + 1.5\times\frac{30}{40} + 0.5\right]\left[\frac{40}{50}\right]^{\frac{1}{4}}$$

$$= 2.0 + [3.75 + 1.125 + 0.5]\,[0.945] = 7.08 \text{ mills per kw-hr.}$$

That is, if the second plant were operated under the same labor and fuel cost and the same load factor as the first plant, it would cost 7.08 mills per kw-hr., as against 6.5 mills; this is less efficient operation, but not as bad as indicated by the uncorrected figures. The correction for fixed charges should more properly have been made on the basis of annual load factors.

923. Suitability of different types of power plants. Steam-electric plants are most suitable under conditions of moderate or low load factor and fuel costs. Gas-driven and hydraulic-electric plants are suitable only with high load factors and fuel costs.

The steam-engine-driven plant is suitable only in small sizes or where it is necessary to run non-condensing, under which conditions it is more economical than the turbine. It is more expensive in first cost in all sizes.

The **steam-turbine-driven plant** is of general adaptability to all sizes and loads with the above exceptions.

The **low-pressure turbine** offers a very satisfactory and most economical method of extending existing engine-driven plants with economy equal to best modern practice. It has little advantage for new plants, however.

Gas-engine driven-plants are most suitable in small sizes where first cost is not greatly in excess of that of steam plants, and where the difference in economy is much greater. Larger sizes have excessive investment costs and expensive maintenance which are balanced by fuel saving only with high load factors and steady load.

Hydraulic plants are suitable when there is a use or market for a seasonal delivery of power at high load factor. Very few plants, except at Niagara, have a summer output in excess of 25 per cent. of rating.

924. Modern tendencies in power-plant design point to inexpensive plants of high operating economy. Expense of construction is reduced by simplicity in design, using few large units; reliability is secured by the use of the highest quality of materials and apparatus rather than by duplication, with its attendant complication. Operating economy is secured through better control of combustion, the use of highly efficient apparatus whose efficiency adds relatively little to the cost of the entire plant, and the attendant reduction in labor cost through the simplicity of the plant and the small number of operating units. The development of stokers allowing very high rates of evaporation in the boilers with high economy, has reduced the investment costs in boiler equipment and building and also improved operating economy by reducing the amount of coal consumed in banked fires. There is a strong tendency toward compactness of layout, allowing only

* Adapted from Stott, H. G., Gorsuch, W. S., *Trans.* A. I. I. E.

sufficient floor space for the dismantling of apparatus during repair. The perfection of the mechanical design of turbo-generators permits the use of skeleton foundations in which the condenser can be placed with great space economy. The electrical switching equipment still has a tendency toward expensive complication, which the writer believes will gradually give way to simplicity and ruggedness, except in the largest plants.

925. Improvement of economy of existing plants requires, first of all, an accurate knowledge of all the elements entering into the cost in that particular plant, and then a gradual elimination of the elements producing inefficiency.

926. Boiler-room practice affords probably the most fruitful field for improvement, as it has hitherto been the most neglected. Numerous instruments, meters and devices are on the market which make possible a continual check on the efficiency of the boiler room. It is not only possible to know the overall efficiency, but to determine readily just what are the causes of inefficiency; there are automatic devices, also, which remove some of these causes. A careful study should be made as to the variation in efficiency with peak load and load factor, so that the inherent improvement in economy with good load factor shall not be mistaken for the results of better operation. Determinations should be made as to the proper number of boilers to use, the relation between active fire hours and banked fire hours, and just when it is profitable to let the fires go out. It is highly important that the boilers themselves be kept clean both inside and out; means are available to facilitate this work, both chemical and mechanical. The firemen should be carefully instructed in proper methods of firing and closely watched to see that they follow instructions.

927. Engine or turbine room operation offers a less fruitful field for improvement since the inherent economy of the units, more particularly of the turbines, is less under the control of the operators. With engines, however, it is highly important that valve settings be maintained properly. The proper loading of units has some influence on economy. The balance of exhaust steam produced and that needed for feed-water heating is particularly important at light loads, when ordinarily there is an excess of steam which is wholly wasted. Electric drive of some of the auxiliaries frequently serves as a corrective. Air leakage into the condenser is an important source of loss.

928. Electrical operation offers a relatively limited field for improvement in economy. It is frequently possible, however, by rearranging the ventilation of windings and keeping them properly clean, to carry a better average load on the prime movers, which adds to the economy and also to the effective size of the station.

929. Labor shifts. Labor costs can frequently be reduced by arranging overlapping shifts, thus providing the necessary men during peak loads, without unnecessary men before and after. The efficiency of labor should be measured not alone by its cost per kw-hr., but by the cost per unit of work performed.

930. Repairs should be made as soon as their necessity is discovered. A high grade of maintenance is usually cheaper than lax maintenance, and increases the effective life of the apparatus.

931. Economy in supplies does not mean cheap materials, but the choice of those best adapted to the work and which give the lowest total cost for the object accomplished.

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SECTION 11

POWER TRANSMISSION

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SECTION 11

POWER TRANSMISSION

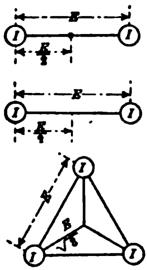
TRANSMISSION SYSTEMS

1. Systems in common use. There are three systems in common use to-day: the direct-current (Thury) system, abroad only; the single-phase system, in railway work; and the three-phase system, for general transmission. These systems may be compared as follows, in terms of effective current and voltage.

Direct-current:
- Current per wire $= I$
- Voltage between wires $= E$
- Voltage to neutral $= E/2$
- Power $= EI$

Single-phase:
- Current per wire $= I$
- Voltage between wires $= E$
- Voltage to neutral $= E/2$
- Power $= EI \cos\theta$

Three-phase:
- Current per wire $= I$
- Voltage between wires $= E$
- Voltage to neutral $= E/\sqrt{3}$
- Power $= \sqrt{3}EI \cos\theta$



2. Copper efficiency of the various systems*
(Comparisons based on effective values)

	Relative current per wire	Relative e.m.f. between wires	Relative loss per wire	Total relative conductor weight
Direct-current:				
Same max. pressure..	70.7	141	50	50
Same effective pressure..............	100	100	100	100
Single-phase........	100	100	100	100
Three-phase........	57.7	100	66.7	75

3. Direct-current (Thury) system.† Direct-current transmission is at present limited by the difficulty of obtaining a voltage sufficiently high for economical transmission, but Thury has developed in Europe a high-voltage, direct-current system, and a number of such plants are at present

* Voltage between wires, transmission distance, power transmitted and power loss are fixed; unity power-factor assumed. With the same effective voltage to *neutral*, all systems have the same copper efficiency.

† See Bibliography, Par. 242, No.'s 11, 12 and 13.

giving satisfactory service (Fig. 1). The required line voltage is obtained by connecting series-wound generators, in series, the voltage per commutator ranging from 1,300 to 4,000 volts. Each generator is mounted on an insulated platform and connected to its prime mover by an insulated coupling. When not in use, the generator is short-circuited. In this system the current is maintained constant by automatic devices which control the prime-mover speed, shift the brushes, and shunt the field, and the voltage is made to vary with the load. The power is delivered to motors similar in construction to the generators. The motor speed is controlled by shifting the brushes, and simultaneously shunting the field. Line voltages approximating 70,000 volts are in use, and a transmission distance of 112 miles (Moutier-Lyons) has been reached.

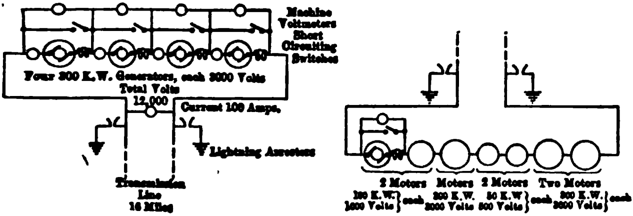


FIG. 1.—Typical Thury system.

4. Advantages claimed for Thury system: (a) power-factor always unity; (b) higher effective pressures for the same line insulation (tests by Thury indicate that with given line insulation, direct current may be twice the alternating current voltage). The maximum pressure occurs only during maximum loads; (c) no dielectric losses; (d) two wires only to be insulated; (e) underground single-conductor cable can be obtained for 60,000 volts, and with grounded neutral, the line pressure would be 120,000 volts; (f) no inductance or capacity troubles such as surges and abnormal voltage rises; (g) a number of stations can be operated in series and a station can be connected to the line at any point; (h) switching arrangements very simple; (i) in hydraulic stations under variable head, greater efficiency can be obtained since constant speed is unnecessary; (j) adapted for industrial work requiring constant torque; (k) line repairs can be easily and safely made while the line is in operation after grounding the conductor at the point in question (not applicable to systems with grounded neutral).

5. Disadvantages of Thury system: (a) insulated floors and couplings; (b) generating units must necessarily be of moderate capacity, though several generators may be connected to one prime mover; (c) the line loss is constant and independent of the load, although the current may be somewhat decreased on light loads; (d) constant-head water-wheel not ideal for constant current (variable speed); (e) special regulating devices required on motors; (f) impossibility of securing overload torque on the motors, even for a short period; (g) greater liability of damage to generators, due to lightning, and hence more expensive protective devices are required.

6. Single-phase systems, except in occasional railway installations, are little used in transmitting large amounts of energy for great distances, since for a given voltage between lines, the copper efficiency is 75 per cent. of that of the three-phase system. For power purposes the single-phase motor is less satisfactory than the polyphase motor. The output of a given single-phase generator is less than when polyphase wound.

7. Three-phase systems. Three-phase transmission and distribution are superseding the other systems, due to greater copper efficiency, the balanced condition of voltage (even under unbalanced loads) and the smaller number of conductors required in comparison with the two-phase system. The great flexibility of the three-phase system, and its advantages with respect to the use of both induction and synchronous machinery, are also important considerations in its favor.

ELECTRICAL CALCULATIONS

8. The required size of conductor for a direct-current line may be readily estimated. With a given power, P, to be delivered at voltage, E, the value of current, I, is determined from the relation:

$$I = \frac{P}{E} \quad \text{(amp.)} \qquad (1)$$

One mil-foot of copper has a resistance of about 10 ohms at 15 deg. cent. (62 deg. fahr.). If the conductor is operated at a normal current density of 0.001 amp. per cir. mil, the drop per ft. will be 0.01 volt, regardless of the size of conductor.

9. The total voltage drop may be expressed:

$$e = 0.01 \times l \quad \text{(volts)} \qquad (2)$$

where l is the total length of conductor in ft. If the current density is different from this normal value, e will be in direct proportion to the current density. Thus, if the density is 1 amp. per 1,200 cir. mils, and $l = 100,000$ ft., then $e = 0.01 \times 100,000\ (1,000/1,200) = 833$ volts.

10. Efficiency of transmission may be expressed:

$$\eta = \frac{E}{E+e}\,100 \quad \text{(per cent.)} \qquad (3)$$

If the receiver voltage in the above case were 10,500, then $\eta = 10,500/(10,500+833)$ or 92.6 per cent.

Power lost per mil-foot of copper at the normal density is represented by the expression:

$$I^2r = (10^{-3})^2\ 10 = 10^{-5} \quad \text{(watts)} \qquad (4)$$

Total power lost at the normal density is

$$I^2R = 10^{-5} \times c.m. \times l \quad \text{(watts)} \qquad (5)$$

where $c.m.$ is the conductor cross-section in cir. mils, and l is the total length of conductor in ft. If the current density differs from the normal, the right-hand side of Eq. 5 must be multiplied by the square of the ratio of the densities. Constant current high-voltage systems are usually so designed that the line losses are kept within prescribed limits.

11. Example of design. Required to transmit 2,000 kw. 15 miles, with 10 per cent. line loss.

It is customary to allow 1,000 volts per transmission mile, but this may be modified somewhat by considerations of line cost. Assuming a pressure at the receiver of 15,000 volts. $I = 2,000,000/15,000 = 133$ amp. The permissible voltage drop $= 1,500$. Let $e' =$ voltage drop at normal current density; then $e' = 0.01 \times 30 \times 5,280 = 1,584$ volts at normal density. Actual density must be $\frac{1,500}{1,584}$ amperes per 1,000 cir. mils. Hence the cir. mils required are $133 \times \frac{1,584}{1,500} \times 1,000 = 140,000$.

12. The regulation and efficiency of a single-phase or a symmetrical polyphase system may be calculated by considering one conductor only, assuming a neutral which has zero resistance and zero reactance, as the return wire. A three-phase system may also be treated as a single-phase system transmitting one-half the power.

13. Alternating-current transmission-line calculations. A single-phase or symmetrical polyphase system having resistance per wire R ohms and reactance per wire X ohms and a load current to neutral of I (amp.) at power-factor, $\cos\theta$, is represented in Fig. 2 and the voltage relations are shown vectorially in Fig. 3. The electrostatic capacity is assumed negligible.

Knowing the receiver voltage, E_r, the generator voltage, E_g, may be readily calculated.

$$E_g = \sqrt{(E_r\cos\theta + IR)^2 + (E_r\sin\theta + IX)^2} \qquad (6)$$

$$\text{Per cent. regulation} = \frac{E_g - E_r}{E_r}100 \qquad (7)$$

$$\text{Efficiency} = \frac{E_rI\cos\theta}{E_rI\cos\theta + I^2R} \qquad (8)$$

If E_g is fixed and it is desired to determine E_r (6) may be used, but a cumbersome quadratic equation as a rule results. For practical work, the regulation may be assumed, the value of E_r determined from (7) and substituted in (6). If the calculated regulation then differs materially from that assumed, another trial may be necessary. If the receiver rather than the generator voltage be fixed, the problem is much simplified.

14. Example of single-phase calculation. Transmission distance, 20 miles; generating voltage, 33,000 volts; frequency, 60 cycles per sec., full-load power-factor, 85 per cent., spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated.

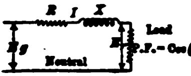


FIG. 2.—Equivalent transmission line to neutral.

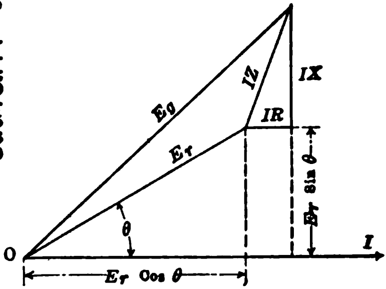


FIG. 3.—Vector diagram of transmission line.

Assumed power at receiver = 5,000 kw. Assuming 15 per cent. regulation, the e.m.f. at the receiver equals 28,700 volts, and the voltage from wire to neutral at the receiver is 14,350 volts. Current per wire = 5,000,000/(28,700 × 0.85) = 205 amp. Loss per wire = (0.10/0.90) × (5,000/2) = 278 kw. Resistance per wire = 278,000/(205)² = 6.61 ohms. Resistance per mile = 6.61/20 = 0.331 ohms.

From the table of Par. 38 the nearest size of wire is No. 000 A.W.G. copper having 0.336 ohms per mile or a total resistance (20 miles) of 6.72 ohms.

Reactance per mile (Par. 40) of single conductor, 0.692 ohms. Total reactance, 13.84 ohms. Substituting in (6)

$$E_g = \sqrt{[(14,350 \times 0.85) + (205 \times 6.72)]^2 + [(14,350 \times 0.527) + (205 \times 13.84)]^2}$$
$$= 17,070 \text{ volts.}$$

$$\text{Regulation} = \frac{17,070 - 14,350}{14,350} 100 = 18.95 \text{ per cent.}$$

This calculation shows material error. Assume 19 per cent. regulation, and

$$E_g = \sqrt{[(13,870 \times 0.85) + (212 \times 6.72)]^2 + [(13,870 \times 0.527) + (212 \times 13.84)]^2}$$
$$= 16,690 \text{ volts.}$$

The calculated regulation is then $\frac{16,690 - 13,870}{13,870} 100 = 20.3$ per cent. As this checks closely with the 19 per cent. regulation assumed, another trial is unnecessary, unless greater refinement is desired.

The efficiency then becomes $\eta = 2,500/[2,500 + (205)^2 6.72]$ or 90 per cent.

With aluminum as the conductor, the reactance drop would be slightly less.

15. Example of three-phase calculation of a line having the same constants as are given in Par. 14. Transmission distance, 20 miles; generating station line voltage, 33,000 volts; frequency, 60 cycles; load power-factor, 85 per cent.; spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated; power at receiver, 5,000 kw.; voltage to neutral, generating station $33,000/\sqrt{3} = 19,050$ volts. Assuming 15 per cent. regulation, voltage at receiving station = 19,050/1.15 = 16,570 volts. Current per wire = 5,000,000/(3 × 16,570 × 0.850) = 118.4 amp. Loss per wire, to neutral = $\frac{5,000}{3} \times \frac{0.10}{0.90} = 185$ kw. Resistance per wire = 185,000/(118.4)² = 13.20 ohms. Resistance per mile = 13.20/20 = 0.660 ohms.

From Par. 38 the nearest wire size is No. 1 A.W.G. which has a resistance of 0.672 ohms per mile.

Total resistance = 20×0.672 = 13.44 ohms.
Reactance per mile (Table 40)........................ 0.734 ohms.
Total reactance ....14.68 ohms.
Substituting in (6)

$$E_g = \sqrt{[(16,570\times 0.85)+(118.4\times 13.44)]^2+[(16,570\times 0.527)+(118.4\times 14.68)]}$$
$$= 18,840 \text{ volts.}$$

$$\text{Regulation} = \frac{18,840-16,570}{16,570}100 \text{ or } 13.70 \text{ per cent.}$$

This checks well enough with the 15 per cent. regulation assumed.
Efficiency

$$\eta = \frac{1,667,000}{1,667,000+(118.4)^2 13.44} = 1,667,000/1,855,000 \text{ or } 90 \text{ per cent.}$$

16. Use of complex quantity. Analytical solutions of problems involving vector quantities may be made by resolving each vector into two components, one along a horizontal or X axis, called the axis of reals, and the other along the vertical, or Y axis, called the axis of imaginaries. The latter component is preceded by $j = (\sqrt{-1})$ with + or − sign according to whether it leads or lags with respect to the positive real component, lag being measured in a clockwise direction.

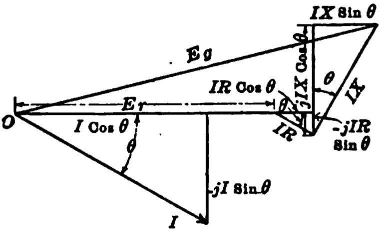


Fig. 4.—Vector diagram of transmission line using complex quantities.

Fig. 3 may be treated by this method. Referring to Fig. 4, each quantity may be resolved along E_r.

$$E_g = e + je' = E_r + I\ (\cos\theta - j\sin\theta)\ (R + jX) \qquad (9)$$

Each quantity represented in Fig. 4 is obtained by performing the multiplication in (9). (The effect of each component of current is treated as if the other did not exist.)

17. Example of analytical solution of three-phase line using complex quantity. Consider the problem of Par. 15.
Here $E_g = 16,570 + 118.4(0.850 - j0.527)(13.44 + j14.68) = 16,570 + 1,354 + j1479 - j840.0 + 917 = 18,840 + j639$. Hence $E_g = \sqrt{18,840^2 + 639^2} = 18,840$

$$\text{Regulation} = \frac{18,840-16,570}{16,570}100 = 13.70 \text{ per cent., as before.}$$

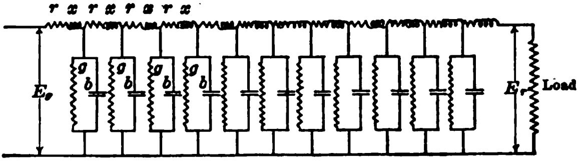


Fig. 5.—Equivalent transmission line showing capacity and leakage.

18. Line capacity has negligible effect on short or low-voltage lines, and, for such lines, may be neglected. On the longer lines of higher voltage the line charging current has a marked influence on the line regulation, and hence must be considered in the design of the line.

19. A transmission line may be represented by a single conductor having a uniform linear resistance ($R = r + r + r$) and reactance ($X = x + x + x$), and an infinite number of leaks ($g, g, g,$) and condensers or capacity susceptances ($b, b, b,$) in parallel between the line and neutral (see Fig. 5). The exact analytical treatment of such a line is rather complicated, and for practical purposes the line capacity may be considered as concentrated

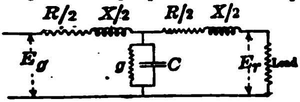


Fig. 6.—Nominal "T" line.

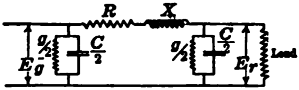


Fig. 7.—Nominal "π" line.

at the centre of the line (Fig. 6), or in two condensers, each of one-half this capacity and placed at opposite ends of the line (Fig. 7). The former is termed a nominal T* and the latter a nominal π,* or a split condenser. In the former case the entire charging current flows over half the line and in the latter case one-half the charging current flows over the entire line. The leakage current can usually be neglected. Where the corona and insulator losses are not negligible their effect may be included. If the transformers are to be included with the line, their equivalent single-phase resistance and leakage reactance must be added to the line resistance and reactance respectively; the energy component of the no-load current must be added to the line-leakage current and the quadrature component or magnetizing current must be subtracted from the line-charging current.

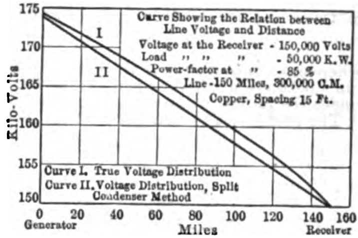


Fig. 8.—Voltage drop in line.

20. Voltage distribution. The true voltage distribution and the approximate voltage distribution for a 150-mile, 150,000-volt line are shown in Fig. 8. It will be noticed that the difference is very slight, especially near the ends.

21. The charging current for a given voltage, E_c, is

$$I_c = 2\pi f E_c C \qquad \text{(amp.)} \qquad (10)$$

where f is the frequency in cycles per sec., E_c the pressure across the condenser terminals in volts, and C the condenser capacity in farads. The values of I_c for different spacing and sizes of conductor are given in Par. 42, 43.

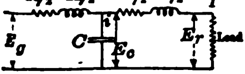


Fig. 9.—Nominal "T" line.

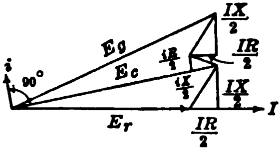


Fig. 10.—Vector diagram of nominal "T" line. Power-factor = 1.0.

22. A nominal "T" line is shown in Fig. 9, and Fig. 10 shows the vector relations in the circuit for unity power-factor load. Fig. 11 gives the vector diagram when the load current lags by an angle θ with respect to the load voltage. It will be observed that the condenser charging current is in quadrature with and leading the voltage E_c, consequently the IR drop leads E_c by 90 deg. and iX leads E_c 180 deg. It will also be noted that E_c is at some potential between E_g and E_r, but for practical considerations, E_c is assumed equal to E_r, and no appreciable error results. In fact, the cal-

* See Bibliography 16.

culated charging current may be in error many times this amount, due to the fact that the e.m.f. wave of the alternator may differ appreciably from a sine-wave. This last factor should be carefully investigated if a high degree of accuracy is desired. It is evident, from inspection, that Figs. 10 and 11 are not capable of simple geometrical solution.

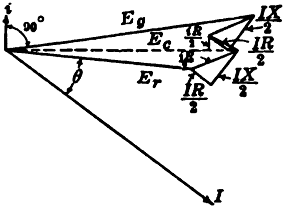


FIG. 11.—Vector diagram of nominal "T" line. Power-factor = cos θ.

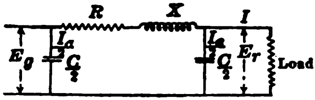


FIG. 12.—Nominal "π" line.

23. A nominal π line is shown in Fig. 12, and the vector diagram is shown in Fig. 13. The condenser current $I_c/2$ leads E_r by an angle of 90 deg., and is readily combined with the current I to form the total current I_o.

$$I_o = \sqrt{(I \cos \theta)^2 + (I \sin \theta - I_c/2)^2} \tag{11}$$

$$\cos \theta_o = I \cos \theta / I_o \tag{12}$$

where $\cos \theta$ and $\cos \theta_o$ are the load and resultant power-factors, respectively. Sin θ becomes negative, when I leads E_r, but the square of the second term under the radical still remains positive.

The problem is then treated by the method employed in Par. 12 to 17.

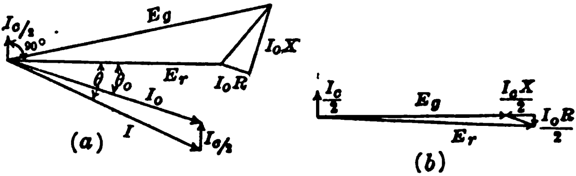


FIG. 13.—Vector diagram showing effect of line charging current.

24. Example of calculation of a three-phase system with capacity considered. Power to be transmitted, 50,000 kw. Substation e.m.f., 140,000 volts. Distance, 120 miles. Frequency, 60 cycles. Full-load power-factor, 90 per cent. Spacing of wires, 168 in. Allowable power loss in line, 10 per cent. of power at receiver. Power lost in each wire = 5,000,000/3 = 1,667,000 watts. Voltage to neutral (receiver) = $140{,}000/\sqrt{3} = 80{,}830$. Load current per wire $= \dfrac{50{,}000{,}000}{3 \times 80{,}830 \times 0.90} = 229.2$ amp. Resistance per wire = $1{,}667{,}000/(229.2)^2 = 31.75$ ohms. Resistance per mile = $31.75/120$ = 0.2646 ohms.

From Table 38, 0000 copper or 336,420 cir. mil. aluminum have the nearest resistance, 0.2667 ohm per mile. The total resistance is $0.2667 \times 120 = 32$ ohms. From Table 41, by interpolation, the reactance per mile of wire = 0.795 ohm. Total reactance = $0.795 \times 120 = 95.40$ ohms. From Table 42 the charging current per mile per 100,000 volts is found to be 0.541 amp. Total charging current $= \dfrac{80{,}830 \times 0.541 \times 120}{100{,}000} = 52.47$ amp. Charging current at the end of the line $I_c/2 = 52.47/2 = 26.24$ amp. From Eq. 11 and 12, Par. 23, $I_o = \sqrt{(229.2 \times 0.90)^2 + (229.2 \times 0.4358 - 26.24)^2} =$ 219.0 amp.

$$\cos \theta_o = (229.2 \times 0.90)/219 = 0.9420$$

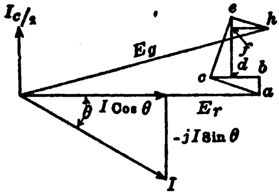
$$E_g = \sqrt{[(80{,}830 \times 0.9420) + (219.0 \times 32.00)]^2 + [(80{,}830 \times 0.3355) + (219.0 \times 95.40)]^2} = 96{,}020 \text{ volts}$$

When the receiver load is removed, the substation voltage will rise, due to the line charging current flowing through the inductance of the line. From (b) Fig. 13. E_r will be, on open circuit:

$$E_r = \sqrt{E_g^2 - \left(\frac{I_c}{2}R\right)^2} + \frac{I_c}{2}X \tag{13}$$

The $\frac{I_c}{2}R$ term is negligible. $E_r = 96{,}020 + (26.24 \times 95.40) = 96{,}020 + 2{,}500 = 98{,}520$ volts.

Regulation $= \frac{98{,}520 - 80{,}830}{80{,}830}$ or 21.90 per cent. Efficiency $= 50{,}000/[50{,}000 + (3 \times 219.0^2 \times 32.00)]$ or 91.55 per cent.



$ab = +jI_cR/2$
$bc = -I_cX/2$
$cd = +IR\cos\theta$
$de = +jIX\cos\theta$
$ef = -jIR\sin\theta$
$fh = +IX\sin\theta$

Fig. 14.—Vector diagram of line using complex quantities.

25. The analytical solution of a nominal π line having appreciable capacity may be obtained by adding the voltage drops due to the load current and that due to one-half the total line charging current (passing through the line impedance) to the receiver voltage.

$$E_g = E_r + I(\cos\theta - j\sin\theta)(R + jX) + \frac{jI_c}{2}(R + jX) \tag{14}$$

where E_g = the generator voltage from phase wire to neutral; E_r = the receiver voltage from wire to neutral; I = the load current; θ = the phase angle of the load; R = the resistance per wire; X = the reactance per wire; and I_c = the total charging current. The geometrical position of each quantity is shown in Fig. 14.

This diagram determines the effect upon the generator voltage of different load conditions at the receiver, the receiver voltage being kept constant.

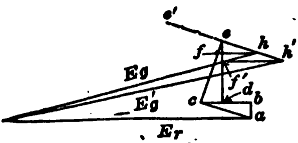


Fig. 15.—Constant load, variable power-factor.

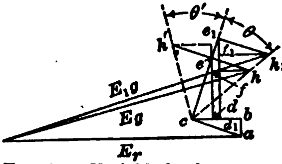


Fig. 16.—Variable load, constant power-factor.

26. Constant load and variable power-factor. Since the receiver voltage is assumed constant, triangle abc (Fig. 15) will not change. Triangles cde and efh, are similar. Triangle cde will not change, since $I\cos\theta$ is fixed. $eh/ce = fh/de = (IX\sin\theta)/(IX\cos\theta) = \tan\theta$. $I = W/(E_r\cos\theta)$ or $I\sin\theta = W\tan\theta/E_r$. ce, W and E_r are fixed, hence $I\sin\theta$ varies as $\tan\theta$. Therefore the point h must move along eh, toward h' if the lag of the current increases and toward e' if the lead of the current increases, and eh must be proportional to $\tan\theta$.

27. Variable load and constant power-factor. (Fig. 16). $ef/cd = (IR\sin\theta)/(IR\cos\theta) = \tan\theta$.

Since cde and efh are similar triangles, $ef/cd = eh/ce = \tan\theta$.

Therefore, angle $ech = \theta$, which is constant, and h must always lie on ch.

Since cd, and de, are both proportional to I, e will move along ce and eh will always be perpendicular to ce. θ' shows the construction for a leading current.

28. Constant voltage maintained at receiver by use of synchronous apparatus. The generator voltage, assumed constant, will move along arc h_3h_1 (Fig. 17). The length ce_1 is equal to $I\cos\theta\,(R+jX)$ at no-load. It is then proportional to the power taken by the synchronous apparatus, and e_1 will move along ce_3 with increase of load. e_1h_1 is equal to $I\sin\theta\,(R+jX)$, hence is proportional to the quadrature component of the current. In order to maintain constant voltage conditions, with increase of load, e_1h_1 must decrease until at e_2 it is equal to zero and this point must correspond to unity power-factor. With further increase of load e_1h_1 reverses and the current leads as at e_3h_3. This condition may be obtained by compounding, or by changing the excitation of the synchronous apparatus, either automatically, or by hand.

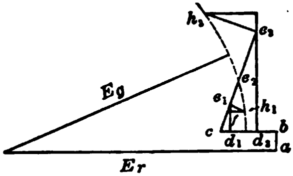


FIG. 17.—Constant voltage at receiver.

29. Example of analytical solution of nominal π line using complex quantity. Consider problem of Par. **24**, see Par. **25**, $E_g = 80{,}830 + 229.2(0.90 - j0.4358)\;(32.00 + j95.40) + (j52.47/2)(32.00 + j95.40) = 80{,}830 + 6{,}600 + j19{,}680 - j3{,}200 - j^2 9{,}530 + j840 + j^2 2{,}500 = 94{,}460 + j17{,}320 = 96{,}020$ volts.

At no-load $96{,}020 = E_r + (j52.47/2)(32.00 + j95.40)$.

The quadrature resistance drop is negligible. Hence $E_r = 96{,}020 + (26.24 \times 95.40) = 98{,}520$ volts, which checks with the result obtained in Par. **24**.

30. Exact methods of calculating regulation may be necessary if the line is long, the line voltage high or if harmonics need be taken into consideration. A simple method of making the necessary corrections in such cases has been developed by A. E. Kennelly.*

Fig. 18 shows a nominal π line of linear impedance $Z = R + jX$, and a capacity admittance, $Y/2$ at each end of the line. If $R+jX$ be multiplied by $(\sinh\theta)/\theta$, and $Y/2$ by $(\tanh\theta/2)/(\theta/2)$, where $\theta = \sqrt{ZY}$, the line as far as the ends (and beyond) are concerned will behave exactly as if the line constants were uniformly distributed. The new line is then considered an *equivalent* π and its characteristics are then calculated by the method of either Par. **24** or **25**.

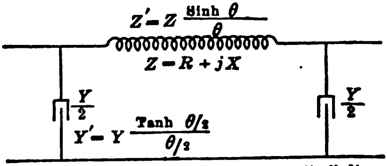


FIG. 18.—Nominal and equivalent "π" line.

31. The general equations of the transmission line in hyperbolic functions are:

$$E_1 = E_2 \cosh\sqrt{ZY} \pm I_2\sqrt{Z/Y}\,\sinh\sqrt{ZY} \qquad (15)$$

$$I_1 = I_2 \cosh\sqrt{ZY} \pm \left(E_2/\sqrt{Z/Y}\right)\sinh\sqrt{ZY} \qquad (16)$$

where E_1 and E_2 are the respective voltages from phase wire to neutral at the sending and receiving ends of the line if the sign is assumed positive. If the sign is taken negative E_1 and E_2 are the respective voltages at the receiving and sending ends of the line. The same relation holds true for the currents, I_1 and I_2. Ordinarily the positive sign is used, as the receiver voltage and load current are generally known.

Z is the impedance per wire $= R + jX$, and Y is the admittance from phase wire to neutral $= G + jB$, though the leakage G is usually negligible in an actual line.

Expanding the cosh and sinh terms in a converging series by Maclaurin's Theorem, and neglecting the terms after the second, the following expressions are obtained.

$$E_1 = E_2\,(1 + ZY/2) \pm ZI_2(1 + ZY/6) \qquad (17)$$

$$I_1 = I_2\,(1 + ZY/2) \pm YE_2(1 + ZY/6) \qquad (18)$$

* Bibliography 16.

32. Example of calculation using general equation Par. 31. Consider again the problem of Par. 24.

$E_1 = E_g$ = generator voltage, $E_2 = E_r$ = receiver voltage = 80,830 volts. $Z = R + jX = 32.00 + j95.40$, $Y = G + jB = 0 + j6.49 \times 10^{-4}$, I_1 = generator current, to be determined. $I_2 = I(\cos\theta - j\sin\theta) = 229.2(0.900 - j0.4358) = 206.3 - j99.88$.

$$E_g = 80{,}830\left[1 + \frac{(32.00 + j95.40)(j6.49 \times 10^{-4})}{2}\right] + (32.00 + j95.40)(206.3 - j99.88)\left[1 + \frac{(32.00 + j95.40)(j6.49 \times 10^{-4})}{6}\right]$$
$$= 94{,}260 + j17{,}230 = 95{,}820 \text{ volts}$$

The no-load receiver voltage and the regulation may be found as in Par. 24, Eq. 13.

Likewise I_g is readily determined.

$$I_g = (206.3 - j99.88)\left[1 + \frac{(32.00 + j95.40)(j6.49 \times 10^{-4})}{2}\right] + (j6.49 \times 10^{-4})(80{,}830)\left[1 + \frac{(32.00 + j95.40)(6.49 \times 10^{-4})}{6}\right]$$
$$= 200.8 - j42.74 = 205.2 \text{ amp.}$$

33. Charts and diagrams, when drawn to a sufficiently large scale, are convenient for determining the electrical characteristics of transmission lines. It is essential, however, that the precision and limitations of the curves be known. Even if great refinement of calculation be desired, such diagrams are useful for checking computed results. In a handbook it is not possible to present the diagrams on a sufficiently large scale. It has seemed wise to explain their construction with data, their methods of use, and also to refer to the original articles in which they are described.

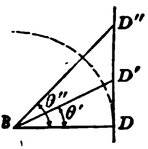


FIG. 19.

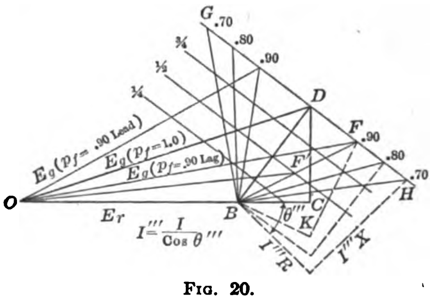


FIG. 20.

FIGS. 19 AND 20.—Perrine-Baum diagram.

34. The Perrine-Baum* regulation diagram, originally proposed by F. A. C. Perrine and F. G. Baum and based on the diagram shown in Fig. 13, forms a convenient method of studying transmission line regulation. To facilitate use of the diagram, the effect of phase displacement is taken into account by rotating the impedance triangle *BDC*.

The load current is proportional to $1/\cos\theta = \sec\theta$, and the impedance drop, being directly proportional to the load current, is obtained by laying off the phase angle as shown in Fig. 19. If *BD* is the impedance drop for unity power-factor, then $BD' = BD \sec\theta'$ is the impedance drop for the power-factor $\cos\theta'$, and $BD'' = BD \sec\theta''$ is the drop for the power-factor $\cos\theta''$, etc.; that is, the impedance-drop vector always terminates on a straight line, drawn at right angles to the drop *BD* for unity power-factor.

The diagram is shown in Fig. 20, in which the line capacity is neglected. Its use will be clear from the following example:

* Bibliography 1.

35. Example of calculation using Perrine-Baum regulation diagram. Assume 1,000 kw. to be transmitted to a substation at 90 per cent. power-factor, lagging, the voltage at the substation to be maintained constant at 10,000 volts. The line has a resistance of 8 ohms and an inductive reactance of 15 ohms. The line capacity is neglected. With unity power-factor the line current is 1,000,000/10,000 = 100 amp. Referring to Fig. 20, lay off $OB = 10{,}000$ volts, $BC = 100 \times 8 = 800$ volts, and $CD = 100 \times 15 = 1{,}500$ volts. If the power-factor were unity, OD would be the voltage at the generating station. To determine the generator voltage for 90 per cent. power-factor, lagging, draw GH perpendicular to BD and lay off to the right of BD an angle, DBF, whose cosine is equal to 0.90. The line impedance drop will be represented by BF, hence OF shows the voltage at the generating station for this power-factor. For any other power-factor, cos θ, lay off the angle θ to the right of BD for lagging currents, and to the left of BD for leading currents. The voltage at the generating station will be determined by the line joining O with the terminal of the line impedance drop for the given cos θ. For other loads, hence other values of line current, BD is divided into proportional parts, and lines parallel to GH are drawn as shown. For example, the voltage at the generating station at one half-load and with a power-factor of 0.9 (lagging), is represented in the diagram by the line OF'.

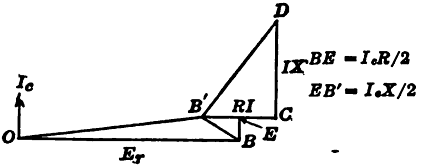


Fig. 21.—Effect of charging current.

Line capacity is taken into account by assuming a constant load voltage; from this assumption the charging current is calculated, taking this current as in quadrature, leading, with respect to the receiving voltage, if the power-factor is unity. The drop due to the charging current in one-half the line impedance is laid off from the receiving voltage vector as shown in triangle BEB′, Fig. 21, and the usual impedance triangle B′CD constructed at the end of the capacity vector. The usual diagram, such as is shown in Fig. 20, is then constructed upon the impedance triangle. It will be noted that this method assumes constant position of the capacity vector, which, though not strictly accurate, is sufficiently so for most purposes in overhead line calculation, except for lines of great length. Compared to the errors due to non-sinusoidal voltage wave the error due to this capacity effect is negligible.

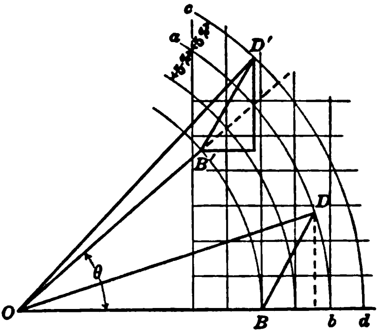


Fig. 22.—Mershon diagram.

36. The Mershon* diagram. If the e.m.f. diagram shown in Fig. 3 is rotated about O as a centre through an angle θ, where cos θ is the power-factor, and all e.m.fs. are expressed in per cent. of the voltage generated at unity power-factor, the line drop, neglecting capacity effect, being measured along a radius with centre O, then a simple diagram for determining regulation may be developed. Such a diagram is constructed by drawing a series of concentric circles ab, cd, etc. (Fig. 22) upon a coordinate system of equal squares; a side of one of these squares is equal to the difference in radii between any two consecutive circles. The radius Ob is taken as 100 per cent., and the coordinate spaces may conveniently represent intervals of 5 per cent.

* Bibliography 22.

The power-factor is cos θ and is numerically equal to the projection of OB' upon the horizontal axis. Having definite line constants, and with a load of given power-factor, the resistance and the reactance voltage drops are calculated in per cent. of the receiver voltage. Starting at the foot of the ordinate representing the load power-factor, follow this ordinate up to its intersection with the first circle, which is the locus of the point B of the impedance triangle. From this last point lay off on the coordinates the impedance triangle. The circle upon which the apex D lies will give the per cent. drop directly. The diagram constructed to scale is given in Sec. 12, Fig. 11, and the table of Sec. 12, Par. 31 is calculated for use with it.

37. Example showing use of the Mershon diagram. A transmission of 250 kw. at 80 per cent. power-factor, lagging, is to be made at 2,000 volts to a receiver 10,000 ft. distant from the generator. The frequency of the system is 60 cycles per sec.; the size of wire No. 0; the spacing of the line wires 18 in. Find the line loss and the line drop. 250,000/0.8 = 312,500 apparent watts. 312,500/2,000 = 156.25 amp.

From Par. 31, Sec. 12 for 18 in. spacing and No. 0 wire the reactance constant is 0.228.

0.228 × 10 × 156.25 = 356.3 volts. 356.3/2,000 = 0.178 or 17.8 per cent.

From Sec. 12, Par. 31, the resistance constant for No. 0 wire is 0.196. 0.196 × 10 × 156.25 = 306.3 volts. 306.3/2,000 = 0.153 or 15.3 per cent.

Now referring to the diagram, Fig. 11, Sec. 12, starting at 0.8 power-factor, follow the vertical ordinate to its intersection with the curve, 0. From this point lay off the resistance drop, 15.3 per cent., parallel to the base of the diagram, remembering that a side of each square represents 5 per cent. Then from the extremity of the resistance drop lay off the reactance drop, 17.8 per cent., parallel to the altitude, again using the squares. The end of this line will be found on circular arc 23. This then is the total drop given in per cent. of the receiver voltage. The generator voltage is:

$$23/(100+23) = 0.187 \text{ or } 18.7 \text{ per cent.}$$

greater than the receiver voltage. The total line-drop then is 18.7 per cent. The I^2R loss is

$$306.3 \times 156.25 = 47.9 \text{ kw.},$$

and, in per cent., is

$$47.9/(250+47.9) = 0.161 \text{ or } 16.1 \text{ per cent.}$$

In order to find the size of wire necessary for a given drop one must solve by trial and error. Assume a size of wire and solve for the drop. This first error will indicate the proper choice for a second trial, etc., as in Par. 14.

38. Resistance of copper and aluminum. Ohms per mile
(*Solid aluminum*, 61 *per cent. conductivity*)

Aluminum, size in Cir. Mils	Ohms at 68 deg. fahr. 20 deg. cent.	Size equivalent copper 97 per cent. conductivity
795,500	0.1127	500,000 Cir. Mils
715,500	0.1254	450,000 Cir. Mils
636,000	0.1409	400,000 Cir. Mils
556,500	0.1611	350,000 Cir. Mils
477,000	0.1879	300,000 Cir. Mils
397,500	0.2253	250,000 Cir. Mils
336,420	0.2667	No. 0000 A.W.G.
266,800	0.3360	No. 000 A.W.G.
211,950	0.4229	No. 00 A.W.G.
167,800	0.5342	No. 0 A.W.G.
133,220	0.6720	No. 1 A.W.G.
105,530	0.8486	No. 2 A.W.G.
83,640	1.071	No. 3 A.W.G.
66,370	1.350	No. 4 A.W.G.
52,630	1.703	No. 5 A.W.G.
41,740	2.147	No. 6 A.W.G.

TABLES OF INDUCTIVE REACTANCE AND CHARGING CURRENT

39. The inductance and capacity of transmission lines may be calculated from the formulas given in Sec. 2. The values of inductive reactance and charging current for wires of standard size, with usual spacings, at both 25 cycles and 60 cycles, are given in the tables in Par. 40-43.

40. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f(80 + 741.1 \log \frac{D}{r})\, 10^{-6}$

Solid wire
25 cycles per sec.

Size A.W.G.	Spacing, in. 12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
0000	0.212	0.233	0.247	0.268	0.282	0.293	0.303	0.311	0.318	0.323	0.328	0.333	0.338	0.342	0.345	0.349
000	0.218	0.239	0.253	0.273	0.288	0.299	0.309	0.316	0.323	0.329	0.334	0.339	0.343	0.348	0.351	0.355
00	0.224	0.244	0.259	0.279	0.294	0.305	0.314	0.322	0.329	0.335	0.340	0.345	0.349	0.354	0.357	0.361
0	0.230	0.250	0.265	0.285	0.300	0.311	0.320	0.328	0.335	0.341	0.346	0.351	0.355	0.360	0.363	0.366
1	0.236	0.256	0.271	0.291	0.306	0.317	0.326	0.334	0.341	0.346	0.352	0.357	0.361	0.365	0.369	0.372
2	0.242	0.262	0.277	0.297	0.312	0.323	0.332	0.340	0.347	0.352	0.358	0.363	0.367	0.371	0.375	0.378
3	0.248	0.268	0.283	0.302	0.318	0.329	0.338	0.346	0.352	0.358	0.364	0.369	0.373	0.377	0.381	0.384
4	0.253	0.274	0.288	0.308	0.324	0.335	0.344	0.351	0.358	0.364	0.370	0.374	0.378	0.383	0.386	0.390
5	0.259	0.280	0.294	0.314	0.330	0.340	0.350	0.357	0.364	0.370	0.376	0.380	0.384	0.389	0.392	0.396
6	0.265	0.285	0.300	0.320	0.335	0.346	0.356	0.363	0.370	0.376	0.381	0.386	0.390	0.394	0.398	0.401
7	0.271	0.291	0.306	0.326	0.341	0.352	0.361	0.369	0.376	0.382	0.387	0.392	0.396	0.400	0.404	0.407
8	0.277	0.297	0.312	0.332	0.347	0.358	0.367	0.375	0.382	0.387	0.393	0.398	0.402	0.406	0.410	0.413

To be used on all circuits with quantities measured *to neutral.*

40. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f\left(80 + 741.1 \log \frac{D}{r}\right) 10^{-6}$

Size A.W.G.	60 cycles per sec. Spacing, in.															
	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
0000	0.510	0.558	0.594	0.642	0.677	0.704	0.726	0.746	0.762	0.776	0.788	0.800	0.810	0.820	0.829	0.838
000	0.524	0.572	0.608	0.656	0.692	0.718	0.740	0.760	0.776	0.790	0.802	0.814	0.824	0.834	0.843	0.852
00	0.538	0.586	0.622	0.670	0.706	0.732	0.754	0.774	0.790	0.804	0.816	0.828	0.838	0.848	0.857	0.866
0	0.552	0.600	0.636	0.684	0.720	0.746	0.768	0.788	0.804	0.818	0.830	0.842	0.852	0.862	0.871	0.880
1	0.566	0.614	0.649	0.698	0.734	0.760	0.782	0.802	0.818	0.832	0.844	0.856	0.866	0.876	0.885	0.894
2	0.580	0.628	0.664	0.712	0.748	0.774	0.796	0.816	0.832	0.846	0.858	0.870	0.880	0.890	0.899	0.908
3	0.594	0.642	0.678	0.726	0.762	0.788	0.810	0.829	0.846	0.860	0.872	0.884	0.894	0.904	0.913	0.922
4	0.608	0.657	0.692	0.740	0.776	0.803	0.824	0.843	0.860	0.874	0.886	0.898	0.908	0.918	0.927	0.936
5	0.622	0.671	0.706	0.754	0.790	0.817	0.838	0.858	0.874	0.888	0.900	0.912	0.922	0.932	0.941	0.950
6	0.636	0.684	0.720	0.768	0.804	0.831	0.853	0.872	0.888	0.902	0.915	0.926	0.936	0.946	0.955	0.964
7	0.650	0.698	0.734	0.782	0.818	0.845	0.867	0.886	0.902	0.916	0.929	0.940	0.950	0.960	0.97[illegible]	0.978
8	0.663	0.712	0.748	0.796	0.832	0.859	0.880	0.900	0.916	0.929	0.943	0.954	0.964	0.974	0.984	0.992

To be used on all circuits with quantities measured *to neutral*.

41. Inductive reactance per single conductor, ohms per mile

Size cir. mils A.W.G.	Stranded conductor 25 cycles per sec. Spacing, in. 12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
500,000	0.1885	0.208	0.223	0.243	0.258	0.269	0.279	0.287	0.293	0.299	0.304	0.309	0.313	0.317	0.321	0.325
450,000	0.1911	0.211	0.226	0.246	0.261	0.272	0.281	0.289	0.296	0.301	0.307	0.311	0.316	0.320	0.324	0.327
400,000	0.1941	0.214	0.229	0.249	0.264	0.275	0.284	0.292	0.299	0.305	0.310	0.315	0.319	0.323	0.327	0.330
350,000	0.1974	0.217	0.232	0.252	0.267	0.278	0.288	0.296	0.302	0.308	0.313	0.318	0.322	0.326	0.330	0.334
300,000	0.201	0.221	0.236	0.256	0.271	0.284	0.291	0.299	0.306	0.311	0.317	0.321	0.326	0.330	0.334	0.337
250,000	0.206	0.226	0.241	0.261	0.275	0.287	0.296	0.304	0.310	0.316	0.321	0.326	0.331	0.335	0.338	0.342
0000	0.210	0.230	0.245	0.265	0.280	0.291	0.300	0.308	0.315	0.320	0.326	0.330	0.335	0.339	0.343	0.346
000	0.216	0.236	0.251	0.271	0.286	0.297	0.306	0.314	0.320	0.326	0.331	0.336	0.341	0.345	0.348	0.352
00	0.222	0.242	0.257	0.277	0.291	0.302	0.312	0.320	0.326	0.332	0.337	0.342	0.347	0.350	0.354	0.358
0	0.227	0.248	0.262	0.282	0.297	0.308	0.318	0.326	0.332	0.338	0.343	0.348	0.353	0.356	0.360	0.364
1	0.233	0.254	0.268	0.288	0.303	0.314	0.324	0.331	0.338	0.344	0.349	0.354	0.358	0.362	0.366	0.370
2	0.240	0.260	0.275	0.295	0.309	0.320	0.330	0.338	0.344	0.350	0.355	0.360	0.365	0.368	0.372	0.376
3	0.245	0.265	0.280	0.300	0.315	0.326	0.336	0.344	0.350	0.356	0.361	0.366	0.370	0.374	0.378	0.382
4	0.251	0.271	0.286	0.306	0.321	0.332	0.342	0.349	0.356	0.361	0.367	0.372	0.376	0.380	0.384	0.387

To be used on all circuits with quantities measured *to neutral.*

41. Inductive reactance per single conductor, ohms per mile

60 cycles per sec.																
Size cir. mils A.W.G.	Spacing, in.															
	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
500,000	0.451	0.500	0.535	0.584	0.619	0.647	0.669	0.688	0.703	0.718	0.730	0.742	0.752	0.762	0.771	0.780
450,000	0.458	0.506	0.541	0.591	0.625	0.653	0.675	0.693	0.709	0.724	0.736	0.748	0.758	0.767	0.777	0.785
400,000	0.464	0.514	0.548	0.598	0.632	0.660	0.682	0.700	0.716	0.731	0.743	0.755	0.765	0.775	0.784	0.793
350,000	0.472	0.522	0.556	0.606	0.640	0.668	0.690	0.708	0.724	0.739	0.751	0.763	0.774	0.783	0.792	0.800
300,000	0.482	0.532	0.566	0.615	0.650	0.677	0.699	0.718	0.734	0.748	0.760	0.772	0.783	0.792	0.801	0.810
250,000	0.493	0.542	0.577	0.626	0.661	0.688	0.711	0.729	0.745	0.759	0.772	0.783	0.794	0.804	0.812	0.821
0000	0.503	0.552	0.587	0.636	0.672	0.698	0.722	0.739	0.755	0.770	0.782	0.793	0.804	0.814	0.822	0.831
000	0.517	0.566	0.601	0.650	0.685	0.713	0.735	0.754	0.769	0.784	0.796	0.808	0.818	0.828	0.836	0.845
00	0.531	0.580	0.615	0.664	0.699	0.726	0.748	0.767	0.782	0.798	0.810	0.822	0.832	0.842	0.850	0.859
0	0.546	0.595	0.629	0.678	0.714	0.740	0.762	0.781	0.797	0.812	0.824	0.836	0.846	0.856	0.865	0.873
1	0.560	0.608	0.643	0.693	0.728	0.755	0.777	0.796	0.812	0.826	0.838	0.850	0.860	0.870	0.879	0.888
2	0.574	0.624	0.658	0.707	0.742	0.770	0.792	0.810	0.826	0.841	0.853	0.865	0.875	0.885	0.894	0.902
3	0.588	0.638	0.672	0.722	0.756	0.783	0.806	0.824	0.840	0.854	0.867	0.878	0.889	0.898	0.907	0.916
4	0.603	0.652	0.686	0.736	0.770	0.798	0.820	0.838	0.854	0.869	0.881	0.893	0.903	0.912	0.922	0.930

To be used on all circuits with quantities measured *to neutral.*

42. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

From formula $I = \frac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)} E = \frac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

Solid wire 25 cycles per sec.																
Size A.W.G.	Spacing, in.															
	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
0000	0.355	0.322	0.302	0.278	0.263	0.252	0.244	0.238	0.233	0.228	0.224	0.221	0.218	0.215	0.213	0.211
000	0.345	0.314	0.295	0.272	0.257	0.247	0.240	0.234	0.228	0.224	0.220	0.217	0.214	0.212	0.209	0.207
00	0.335	0.306	0.288	0.266	0.252	0.242	0.235	0.229	0.224	0.220	0.216	0.213	0.211	0.208	0.206	0.204
0	0.326	0.298	0.281	0.260	0.247	0.238	0.230	0.225	0.220	0.216	0.213	0.210	0.207	0.204	0.202	0.200
1	0.318	0.291	0.275	0.255	0.242	0.233	0.226	0.221	0.216	0.212	0.209	0.206	0.203	0.201	0.199	0.197
2	0.310	0.284	0.269	0.249	0.237	0.229	0.222	0.217	0.212	0.209	0.205	0.203	0.200	0.198	0.196	0.194
3	0.302	0.278	0.263	0.244	0.233	0.224	0.218	0.213	0.209	0.205	0.202	0.199	0.197	0.195	0.193	0.191
4	0.295	0.272	0.257	0.240	0.228	0.220	0.215	0.209	0.205	0.202	0.199	0.196	0.194	0.192	0.190	0.188
5	0.288	0.266	0.252	0.235	0.224	0.216	0.210	0.206	0.202	0.198	0.196	0.193	0.191	0.189	0.187	0.185
6	0.281	0.260	0.247	0.230	0.220	0.213	0.207	0.202	0.198	0.195	0.192	0.190	0.188	0.186	0.184	0.182
7	0.275	0.254	0.242	0.226	0.216	0.209	0.203	0.199	0.195	0.192	0.189	0.187	0.185	0.183	0.181	0.180
8	0.269	0.249	0.237	0.222	0.212	0.205	0.200	0.196	0.192	0.189	0.186	0.184	0.182	0.180	0.179	0.177

E = volts to neutral; D = distance between wires; d = diameter of wires.

42. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

Size A.W.G.	60 cycles per sec. Spacing, in.															
	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
0000	0.852	0.773	0.725	0.667	0.631	0.606	0.587	0.571	0.559	0.548	0.539	0.531	0.523	0.517	0.511	0.506
000	0.828	0.753	0.708	0.652	0.618	0.593	0.575	0.560	0.548	0.538	0.529	0.521	0.514	0.508	0.502	0.497
00	0.805	0.734	0.691	0.638	0.605	0.582	0.564	0.550	0.538	0.528	0.519	0.512	0.505	0.499	0.494	0.489
0	0.783	0.716	0.675	0.624	0.593	0.570	0.553	0.540	0.528	0.519	0.510	0.503	0.497	0.491	0.486	0.481
1	0.763	0.690	0.660	0.611	0.581	0.559	0.543	0.530	0.519	0.510	0.502	0.495	0.488	0.483	0.478	0.473
2	0.763	0.682	0.645	0.598	0.569	0.549	0.533	0.520	0.510	0.501	0.493	0.486	0.480	0.475	0.470	0.465
3	0.725	0.667	0.631	0.586	0.558	0.539	0.523	0.511	0.501	0.492	0.485	0.478	0.472	0.467	0.462	0.458
4	0.707	0.652	0.618	0.575	0.548	0.529	0.514	0.502	0.492	0.484	0.477	0.470	0.465	0.460	0.455	0.451
5	0.690	0.638	0.605	0.564	0.538	0.519	0.505	0.494	0.484	0.476	0.469	0.463	0.458	0.453	0.448	0.444
6	0.674	0.624	0.592	0.553	0.528	0.510	0.497	0.485	0.476	0.468	0.462	0.456	0.450	0.446	0.441	0.437
7	0.659	0.611	0.580	0.544	0.519	0.501	0.488	0.477	0.469	0.461	0.455	0.449	0.444	0.439	0.435	0.431
8	0.645	0.598	0.569	0.533	0.510	0.493	0.480	0.470	0.461	0.454	0.448	0.442	0.437	0.432	0.429	0.425

43. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

From formula $I = \frac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)} E = \frac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

Stranded conductor, 25 cycles per sec.

Size cir. mils A.W.G.	Spacing, in.															
	12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
500,000	0.420	0.374	0.346	0.315	0.295	0.282	0.274	0.264	0.256	0.252	0.247	0.243	0.240	0.236	0.233	0.230
450,000	0.412	0.367	0.341	0.310	0.292	0.279	0.269	0.261	0.254	0.250	0.245	0.241	0.237	0.234	0.231	0.228
400,000	0.404	0.361	0.337	0.306	0.288	0.275	0.265	0.258	0.251	0.247	0.242	0.239	0.234	0.231	0.229	0.226
350,000	0.396	0.355	0.342	0.302	0.284	0.271	0.262	0.254	0.248	0.244	0.240	0.235	0.232	0.229	0.227	0.224
300,000	0.388	0.348	0.325	0.297	0.280	0.268	0.258	0.251	0.245	0.241	0.236	0.232	0.229	0.226	0.224	0.221
250,000	0.377	0.342	.0319	0.291	0.275	0.263	0.254	0.247	0.242	0.236	0.233	0.229	0.226	0.223	0.221	0.219
0000	0.370	0.334	0.312	0.286	0.269	0.259	0.250	0.243	0.239	0.233	0.229	0.226	0.223	0.220	0.217	0.215
000	0.357	0.325	0.304	0.280	0.264	0.253	0.246	0.238	0.234	0.229	0.225	0.222	0.219	0.216	0.214	0.212
00	0.349	0.317	0.296	0.273	0.259	0.248	0.241	0.234	0.229	0.225	0.221	0.218	0.214	0.213	0.211	0.208
0	0.339	0.308	0.290	0.267	0.253	0.243	0.236	0.230	0.225	0.221	0.217	0.214	0.210	0.209	0.207	0.204
1	0.329	0.300	0.282	0.261	0.248	0.238	0.232	0.225	0.221	0.216	0.213	0.211	0.207	0.205	0.203	0.201
2	0.319	0.291	0.275	0.255	0.243	0.233	0.227	0.221	0.216	0.212	0.209	0.207	0.204	0.202	0.1995	0.1974
3	0.311	0.285	0.269	0.250	0.237	0.229	0.223	0.217	0.213	0.209	0.206	0.203	0.201	0.1985	0.1965	0.1942
4	0.303	0.279	0.263	0.245	0.233	0.225	0.219	0.213	0.209	0.206	0.203	0.1995	0.1973	0.1953	0.1931	0.1910

E = volts to neutral; D = distance between wires; d = diameter of wires.

43. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

Size cir. mils A.W.G.	60 cycles per sec. Spacing, in. 12	18	24	36	48	60	72	84	96	108	120	132	144	156	168	180
500,000	1.01	0.896	0.830	0.755	0.709	0.676	0.653	0.634	0.615	0.605	0.593	0.582	0.574	0.567	0.560	0.553
450,000	0.989	0.880	0.819	0.746	0.700	0.668	0.644	0.626	0.609	0.599	0.588	0.577	0.569	0.561	0.554	0.547
400,000	0.970	0.866	0.808	0.734	0.691	0.661	0.636	0.618	0.602	0.593	0.582	0.572	0.562	0.555	0.550	0.542
350,000	0.951	0.851	0.796	0.725	0.681	0.651	0.628	0.610	0.595	0.585	0.575	0.565	0.556	0.548	0.543	0.537
300,000	0.932	0.836	0.780	0.711	0.671	0.641	0.619	0.601	0.588	0.577	0.568	0.557	0.549	0.541	0.536	0.531
250,000	0.904	0.818	0.765	0.698	0.659	0.631	0.610	0.592	0.581	0.568	0.559	0.550	0.542	0.534	0.530	0.524
0000	0.887	0.800	0.749	0.686	0.646	0.620	0.600	0.583	0.572	0.560	0.549	0.542	0.534	0.527	0.522	0.516
000	0.857	0.780	0.730	0.671	0.633	0.608	0.590	0.572	0.562	0.550	0.539	0.532	0.524	0.520	0.514	0.508
00	0.836	0.760	0.712	0.656	0.620	0.595	0.579	0.562	0.550	0.539	0.529	0.523	0.514	0.510	0.506	0.499
0	0.813	0.740	0.695	0.640	0.608	0.583	0.568	0.551	0.539	0.529	0.521	0.514	0.505	0.502	0.496	0.490
1	0.789	0.719	0.676	0.626	0.595	0.570	0.556	0.540	0.529	0.519	0.512	0.505	0.496	0.493	0.487	0.482
2	0.765	0.699	0.661	0.613	0.582	0.560	0.545	0.529	0.519	0.509	0.502	0.496	0.489	0.484	0.480	0.474
3	0.747	0.683	0.646	0.601	0.570	0.550	0.534	0.520	0.510	0.501	0.494	0.488	0.483	0.476	0.471	0.466
4	0.726	0.668	0.631	0.588	0.560	0.540	0.524	0.512	0.502	0.494	0.487	0.479	0.474	0.469	0.463	0.458

To be used on all circuits with quantities measured *to neutral.*

GENERAL FEATURES OF DESIGN

44. The conductor for a given transmission system is influenced by such factors as climate, topography, length of span, reliability, amount of power, transmission distance and the economics of the problem. Copper and aluminum (see Sec. 4), except in special cases, are used exclusively for the conductors. Copper has high conductivity, is very ductile, is not easily abraded, has high tensile strength, a high melting point, and can be readily soldered. Aluminum has a conductivity about 60 per cent. that of copper. For the same conductance, it has only one-half the weight of copper. It is ductile and easily abraded; has 1.4 times the linear coefficient of expansion of copper, giving greater sag, and would therefore require higher towers for the same length of span. The tensile strength is much less than that of copper, though the ratio of tensile strength to weight is greater for aluminum. The melting point of aluminum is lower than that of copper, so that aluminum will be more easily burned by arcs and short-circuits. For the same conductance, aluminum offers a greater surface to wind-pressure, so towers must be designed with greater transverse strength. Neither copper nor aluminum is attacked by the atmosphere to any extent. In the United States, the price of aluminum is always held slightly below that of copper of the same conductance. In view of increased cost of pole line necessary to its employment, there is comparatively little incentive to use aluminum in small sizes of wire. In Canada and on the Continent of Europe, aluminum has found favor.

45. For extra long spans, it may be found economical to use either iron or steel as conductors, because of their much greater tensile strength. As these metals are subject to corrosion, they must either be galvanized or "copper-clad." Phosphor-bronze has been proposed, but its much higher cost for the same conductance practically prohibits its use. The table in Par. 46 shows a comparison of various conductor materials, and more complete tables may be found in Sec. 4.

46. Comparison of conductor materials on basis of equal conductance

Metal	Diameter	Weight	Strength	*Cost relation
Copper	1.00	1.00	1.00	1.00
Aluminum	1.27	0.485	0.65	2.06
Iron	2.72	6.36	5.30	0.157
Steel	3.41	10.00	41.5	0.100
Copper-clad steel	1.52	2.12	4.46	0.47

NOTE.—Skin effect has been neglected. Skin effect tables are given in Sec. 4. The relative resistances have been taken as follows: copper = 1; aluminum = 1.61; iron = 7.4; steel = 11.6; copper-clad steel = 2.3. The specific gravities are: copper = 8.89; aluminum = 2.68; iron and steel = 7.64; and copper-clad steel = 8.20. The elastic limits are: copper = 35,000 lb. per sq. in.; aluminum (stranded) = 14,000 lb. per sq. in.; iron = 25,000 lb. per sq. in.; steel = 125,000 lb. per sq. in.; and copper-clad steel = 68,000 lb. per sq. in.

47. Required size of conductor is determined by (a) mechanical strength; (b) permissible energy loss; (c) required voltage regulation; (d) corona; (e) cost; (f) current-carrying capacity.

(a) **Mechanical strength** is a primary consideration in any transmission line. It becomes especially important where long spans are necessary.

(b) **Permissible energy loss** is determined by such factors as the cost of generating power, selling price, load-factor, and other economic considerations. Where power is produced cheaply, it may be more economical to lose power in the line than to pay the fixed charges incident to heavier conductors and poles. (See Economics.)

(c) **Required voltage regulation** is, in general, not difficult to secure, as automatic regulators and synchronous apparatus may take care of any

* The last column in the table shows what *should* be the relation in cost per lb. of the various materials to result in the same total cost of conductor where the conductance of the line is fixed.

voltage fluctuations at the substations. If, however, the inductive line drop for a given cross-section of conductor is too great, two separate lines of half the cross-section may be used. The additional cost of insulators, poles and construction seldom justifies duplicate lines, where better regulation alone is the requirement.

(d) **Corona** may make the energy loss in excess of the permissible value, in which case, it will be necessary to increase the conductor diameter or the effective size of conductor. See Par. 48 to 53.

(e) **Cost,** such as the relative cost of line, of plant, and of line maintenance may determine the size of line conductors. Since the salvage value of the line is in general low, whereas the engines and dynamos of the central station may be transferred without excessive loss to another plant and again used, it is advantageous to put more money into the generating station and to build the line as cheaply as possible if the system is a temporary affair. The amount of money available may make it necessary to build the system at a minimum cost, in which case the line conductors must be so chosen that the cost of the line plus the cost of the station, to supply both the net load and the line loss, shall be a minimum. The larger the line conductors, the smaller will be the energy loss, but the fixed charges for the line will be increased. The conductors may be so chosen that the sum of these last two quantities is a minimum. See Par. 225.

(f) **Current-carrying capacity** of the conductors under continuous operating conditions, is usually ample when the size of wire is determined by the permissible energy loss. An emergency demand, however, may overload the line for a short time, and where this is likely to occur, the conductor should be of such size as to operate within safe temperature limits. Tables of safe carrying capacity are given in Sec. 12.

CORONA

48. Corona, or the luminous discharge into the atmosphere from conductors at high voltage, may result in a considerable loss of power. H. J. Ryan, R. D. Mershon, J. B. Whitehead, and F. W. Peek have made studies of this phenomenon. *Peek's results are the latest obtained under actual operating conditions, and their accuracy is unquestioned. The relations may be expressed by the following formulæ:

The visual critical voltage is:

$$E_v = M_v\, g_o \delta r \left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \log_e \frac{S}{r} \text{ kv. to neutral} \qquad (19)$$

$$P = \frac{k}{\delta} f \sqrt{\frac{r}{S}} (e - e_o)^2 10^{-5} \text{ (per kilometer of single conductor)} \qquad (20)$$

where $e_o = g_o M_o r \delta \log_e \frac{S}{r}$

e_o is the *disruptive critical voltage* to *neutral* and is always lower than E_v. The tables in Par. 49 and 50 give values of e_o.

(To obtain kw. per mile, multiply by 1.61)

Where E_v = effective kilovolts from phase wire to neutral at which corona becomes visible. $M_v = M_o = 1$ to 0.93 for wires, the higher value applying to a polished wire. $M_v = 0.72$, local corona all along conductor and 0.82, decided corona all along conductor for seven-strand cables; $g_o = 21.1$ kv. per cm., being the dielectric strength of air at 25 deg. cent. and 76 cm. pressure; δ = air density factor $= 3.92b/(273+t)$; $\delta = 1$ at 76 cm. pressure and 25 deg. cent. b = barometric pressure, in cm.; t = temperature deg. cent.; r = radius of conductor, cm.; S = distance between centres of conductors, cm.; $\log_e = 2.303 \log_{10}$; P = power per kilometer wire, kilowatts; $k = 344$; f = frequency cycles per sec.; e = effective kilovolts to neutral of conductor; M_o = irregularity factor of conductor; $M_o = 1$ for polished wires; 0.98 to 0.93 for roughened or weathered wires; 0.87 to 0.83 for seven-strand cable.

For three wires equally spaced in a plane, an exact calculation is too complicated for practical work. If the average spacings are assumed in calculating the critical voltage, corona will start on the centre conductor at a voltage about 5 per cent. lower than the calculated value, and on the two outside conductors at a voltage about 5 per cent. higher than the calculated value. For practical work it is sufficiently accurate to neglect this correction unless the spacing is quite uneven.

* Bibliography 25–30 in.

Smoke, fog, sleet, rain and snow all lower the critical and visual voltages, and increase the losses. Fig. 23 shows the increased loss due to snow.

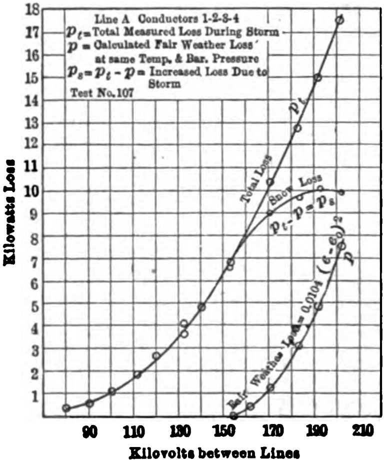


FIG. 23.—Corona loss during snowstorm.

In calculating corona loss, it must be remembered that the entire line is not at the same potential, and that a small change in e.m.f. above the critical value, e_o, makes a large percentage change in the loss. It has been suggested to make use of this last fact in dissipating energy associated with an abnormal rise of voltage due either to a line surge or to lightning.

The part of the loss curve between E_v and e_o is affected to a considerable degree by the conditions of the wire surface as to dirt, weather, etc., and hence varies from day to day. In practice it is generally not advisable to operate at a higher voltage than that corresponding to e_o, otherwise the loss would become very high during wet weather or when the conductor surface became roughened. Local brushes also occur which may cause deterioration of the conductor by nitric acid formation, especially at the points of support. The voltages in the tables (Par. 49) correspond to e_o voltages reduced to kilovolts between conductors at 25 deg. cent. and 76 cm. barometer.

49. Corona limits of voltage. Kilovolts between lines (three-phase) at sea level

(Cables)

From formula $e_o = \sqrt{3}\, g_o M_o r \delta \log_e \frac{S}{r}$ where $M_o = 0.87$

A.W.G.	Diam., in.	Spacing—feet									
		3	4	5	6	8	10	12	14	16	20
4	0.230	...	56	58	60	62	64	66	68	69	71
3	0.261	...	62	65	67	70	72	74	76	77	80
2	0.290	...	...	71	73	76	79	81	83	85	87
1	0.330	...	...	79	81	85	88	91	93	95	97
0	0.374	...	...	...	90	95	98	102	104	106	109
00	0.420	...	...	...	98	104	108	111	114	117	121
000	0.470	...	...	...	...	114	118	121	124	127	132
0,000	0.530	...	...	...	...	125	130	135	138	141	146
250,000	0.590	...	...	...	...	138	144	149	152	156	161
300,000	0.620	...	...	...	...	....	151	156	161	165	171
350,000	0.679	...	...	...	...	....	161	166	170	175	180
400,000	0.728	...	...	...	...	....	171	176	180	185	192
450,000	0.770	...	...	...	...	....	178	184	190	194	200
500,000	0.818	...	...	...	...	....	188	194	199	205	210
800,000	1.034	...	...	...	...	....	....	234	241	244	256
1,000,000	1.152	...	...	...	...	....	....	256	264	270	281

(Solid wires) $M_o = 0.93$

A.W.G.	Diam, in.	Spacing—feet									
		3	4	5	6	8	10	12	14	16	20
4	0.204	51	54	56	58	60	62	64	65	66	68
3	0.229	...	59	62	64	66	68	70	72	74	76
2	0.258	...	...	69	70	74	76	78	80	82	84
1	0.289	...	...	75	77	81	83	86	88	90	92
0	0.325	...	...	...	85	89	92	95	97	99	102
00	0.365	...	...	...	94	98	102	105	107	110	113
000	0.410	...	...	...	...	109	113	116	119	121	124
0000	0.460	...	...	...	...	120	125	128	131	134	138

To find the voltage at any altitude, multiply the voltage found above by the δ corresponding to the altitude as given in Par. **50**.

For single-phase or two-phase circuits find the value of volts for the corresponding three-phase circuit above, and multiply by 1.16.

50. Altitude correction factor δ

Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ
0	1.00	2,000	0.92	5,000	0.82	9,000	0.71
500	0.98	2,500	0.91	6,000	0.79	10,000	0.68
1,000	0.96	3,000	0.89	7,000	0.77	12,000	0.63
1,500	0.94	4,000	0.86	8,000	0.74	14,000	0.58

51. To decrease corona loss, either the frequency or the voltage must be reduced. These, however, are usually fixed. The spacing may be increased, but this decreases the loss but slightly, and the increased conductor spacing would increase the line cost considerably. As the meteorological conditions cannot be controlled, the diameter of conductor must be increased. This may be done without increasing the conductor weight by using aluminum, hemp- or steel-cored cable, or hollow conductors. The first is the most practicable method and in future, it may become necessary to use aluminum for very high voltage lines. Hemp-cored cable has been tried, but the core soon rots and the conductor strands become disarranged. Hollow conductors reduce the skin-effect, but the cost of manufacture makes their use prohibitive.

52. Example of calculation of corona loss. Line, 3-phase; length of line, 120 miles; size conductor, 00 copper; e.m.f., 110 kv.; frequency, 60 cycles; spacing, 10 ft. Assume 20 deg. cent., 76 cm. barometric pressure, and a coefficient of roughness, $M_o = 0.95$. $d = (3.92 \times 76)/(2.73 + 20) = 1.01$; diameter of 00 wire $= 365$ mils; $r = 0.463$ cm.; $S = 10 \times 12 \times 2.54 = 305$ cm.; $e = 110/\sqrt{3} = 63.5$ kv.. to neutral; $e_o = 21.1$ kv.; $\log_{10} \dfrac{305}{0.463} = 2.82$; $P = \dfrac{344}{1.01} \times 60 \times 0.039\ [63.5 - (21.1 \times 0.95 \times 0.463 \times 1.01 \times 2.303 \times 2.82)]^2 \times 1.61 \times 10^{-5} = 797(63.5 - 60.9)^2 \times 1.61 \times 10^{-5} = 0.0864$ kw. per wire per mile; total corona loss $= 0.0864 \times 3 \times 120 = 31.1$ kw.

LINE INSULATORS

53. Requirements. The successful operation of a transmission system depends to a large extent upon the degree of insulation attained, and the most important factor is the insulator. Up to a few thousand volts, there is no difficulty whatever in maintaining good insulation, but as the voltage reaches higher values, the difficulties increase and factors such as leakage and capacity effects, which are entirely negligible in low-tension systems, become of major importance.

54. Insulators have appreciable capacity, and act like condensers of complicated construction. The dielectric is made up of alternate layers of air and porcelain or glass of varying thicknesses. Some of the charging current to the pin must pass over the surface of the insulator, which has a very high resistance, so the insulator may be represented by a resistance, shunted by a number of small condensers as shown in Fig. 24, where E is the voltage from the line to the pin, I the total current taken by the insulator, i_c the charging current, and i_r the leakage current. The vector diagram simply illustrates the theory, and no attempt has been made to give the proper relative values to the various quantities. *Measurements by C. E. Skinner

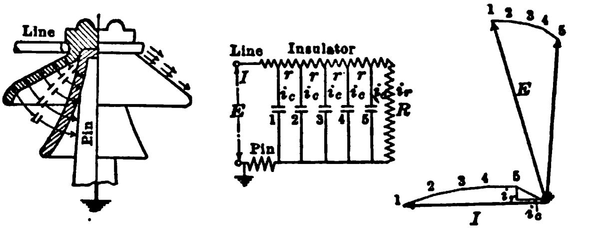


FIG. 24.—Insulator, equivalent circuits.

indicate that the ohmic resistance of porcelain insulators is practically infinite, and that whatever leakage takes place passes over the surface. The effect of capacity tends to increase this surface leakage, which ionizes the air, and thereby decreases the leakage resistance. Insulators should, therefore, be designed with small petticoat areas; the material should have a low dielectric flux constant, and the capacity should be so distributed that there will be no local stresses tending to cause a breakdown. Flaring the petticoats increases the thickness of the dielectric and decreases its dielectric flux constant, since that of air is only about one-fifth that of porcelain; therefore, by flaring the petticoats the electrostatic capacity of the insulator is greatly decreased.

55. Insulator adapted to wet-weather conditions. A German firm has substituted a metal top for the topmost petticoat and found that the ability to stand up under high tension is increased, other things being equal. The substitution of metal for porcelain does away with the surface resistance to the charging current on the top petticoat, and equalizes the static strains when the insulator is wet. The tendency is to drive the water to the edge and repel it. This fact is borne out by test. When perfectly dry this type will break down at a slightly lower voltage than a similar one with a porcelain top; due to the extreme lightness of the top, it may be made very broad and its action in rain is to shield the porcelain part of the insulator. In this way the breakdown voltage is considerably increased over that of the ordinary all-porcelain insulator of the same weight.

56. The minimum arcing distance and leakage path are shown in Fig. 25, as $A+B+C$, and ab respectively. The resistance is directly proportional to the length and inversely proportional to the area of the path, so increasing the diameter of the petticoats does not increase the leakage resistance appreciably. Increasing the number of petticoats increases the length of path without necessarily increasing the area, so that a high leakage resistance is best secured by increasing the number of petticoats. Insulators are usually made of glass, porcelain, or patented compounds.

57. Glass is cheaper than porcelain and when properly annealed, has high dielectric strength and specific resistance. As it is transparent, flaws can readily be detected. On the other hand, moisture condenses on its surface; the action of rain destroys the smoothness of the surface and allows particles of dirt to accumulate diminishing the resistance of the leakage path.

* Measurements made for Ralph D. Mershon, *Trans.* A. I. E. E., Vol. XXVII (1908), p. 928.

58. Porcelain gives less leakage trouble, is stronger mechanically than glass, and is less affected by changes of temperature. On the other hand, it is more expensive, and slight imperfections in the glaze are common. As flaws, such as blow-holes, strata, or cracks cannot be readily detected by simple inspection, each section should be subjected to a voltage test before and after assembling.

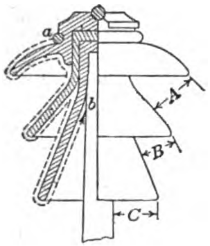


FIG. 25.—Arcing and leakage paths.

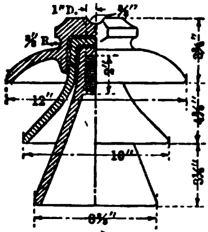


FIG. 26.—Pin-type insulator.

59. Patented compounds are on the market, possessing better mechanical characteristics than either porcelain or glass. It is somewhat doubtful, however, if these compounds can successfully withstand the effects of weather and the high electrostatic stresses incident to high-tension power transmission.

60. Pin-type insulators are made of either glass or porcelain. Glass insulators of this type are now being manufactured to operate at 50,000 volts pressure. Porcelain pin-type insulators can be used for pressures as high as 90,000 volts. (See Fig. 26.)

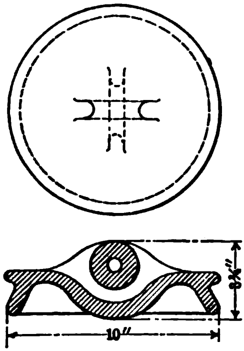


FIG. 27.—Hewlett suspension insulator.

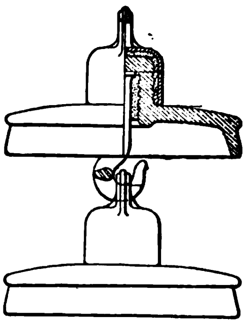


FIG. 28.—One-piece cemented insulator, suspension type.

61. Suspension insulators can be operated at about 20,000 volts per unit, and are used for voltages in excess of 70,000, as the pin-type insulator then becomes too large, heavy, expensive, and mechanically weak. When suspension insulators are used, the cost and weight are practically proportional to the line voltage, but beyond a certain point it is difficult, even with additional units, to secure increased insulation. There are two common types, the Hewlett, or interlinking type of insulator, shown in Fig. 27, where the two suspension cables loop through each other and are separated by a layer of porcelain; and the cemented type, in which the porcelain or glass is cemented into a metal cap, and the pin is cemented into the insulator. Fig. 28 shows a one-piece cemented unit and Fig. 29 shows a two-piece cemented unit. The Hewlett type has not as yet met the mechanical requirements of very heavy power work. It is probably more difficult to replace than the cemented type, and the electric stresses are not so well distributed. The cemented type has given trouble due to failures at the base of the cap, and in design this factor should be carefully considered. The present tendency in insulator design is toward smaller discs and closer spacing. This results in higher puncture strength for a given flash-over voltage.

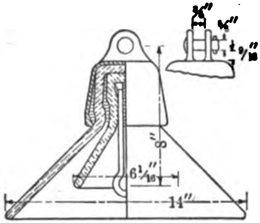


FIG. 29.—Two-piece cemented insulator, suspension type.

62. The string efficiency* of n suspension insulator units is the ratio of their total flash-over voltage, to n times the flash-over voltage of one insulator. Although certain unpublished 500,000-volt tests have shown this ratio to be practically unity, the majority of experiments show that the string efficiency decreases when the number of insulators is increased. Fig. 30 shows the results of the tests made by F. W. Peek, Jr. This lowering of flash-over voltage is due to the fact that each insulator has a certain capacity to ground, the insulator nearest the line carrying the charging current of the whole string of n insulators. The second insulator carries the charging current of $n-1$ insulators, etc., so the unit next the line is subjected to the greatest stress, the second unit to a lesser stress, etc. The string efficiency is nearer unity under the wet test, as the leakage current is then so increased that the effect of the capacity current is negligible. The string efficiency is increased by making the ratio of mutual capacity to ground capacity large; that is by hanging the insulator units near together but having each string at some distance from the pole or tower.. (Par. 67.)

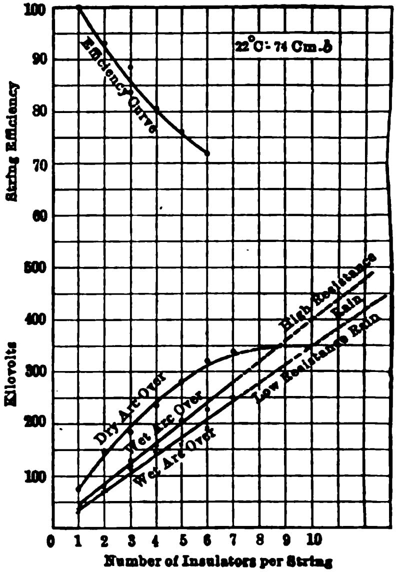


FIG. 30.—Insulator string efficiency.

63. The Watts insulator, shown in Fig. 31, proposed by *A. S. Watts, of Germany, is 1 ft. long and has withstood 100,000 volts. It is claimed that in so far as cost and weight go, this insulator is similar to the suspension type, in that the cost and weight are about proportional to the voltage. The small grooves are not so deep that they will collect dirt and foreign material which can-

* Bibliography 39.

not be removed by the action of the elements. If struck by lightning the charge can pass to ground by jumping from one ridge to another, and the insulator will remain unharmed.

64. Strain insulators are used when the line is dead-ended; at intermediate anchor towers; on sharp curves where the line would tend to overturn the insulator, break the pin, or pull a string of suspension insulators out of alignment; and on extra long spans, as at river crossings. For voltages up to

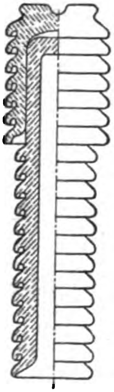


FIG. 31.—The Watts insulator.

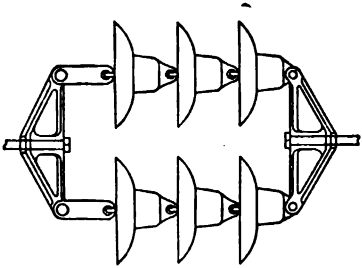


FIG. 32.—Strain insulator with yoke.

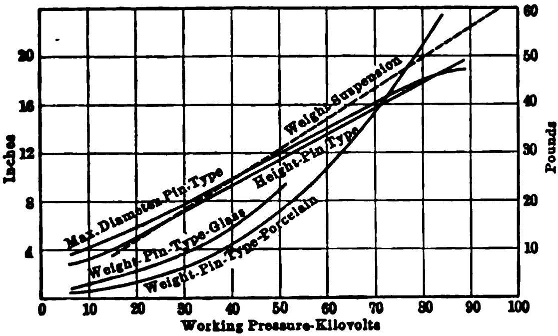


FIG. 33.—Weights and sizes of insulators.

30,000, a pin-type may be used. For voltages in excess of 30,000, either the link-type or the cemented type (Fig. 32) is used. Fig. 33 gives the approximate sizes and weights of the various types of insulators.

65. Insulators are usually designed to flash over, rather than to puncture. To assist in securing this result, particularly on high frequency impulses, arcing rods are used (Fig. 35). These have the further effect of

* Bibliography 35.

holding the power arc away from the insulator. Another type is the *Nicholson arcing ring. (Fig. 34.)

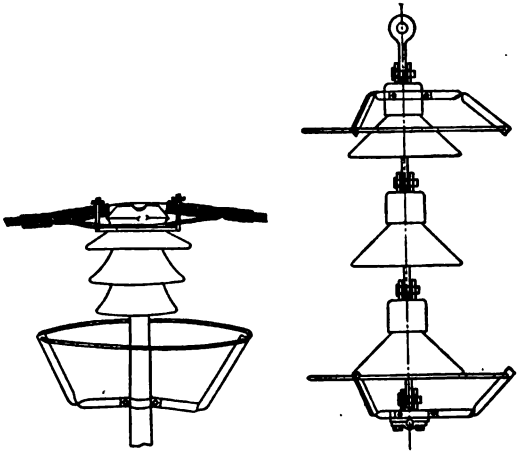


Fig. 34.—Nicholson arcing rings.

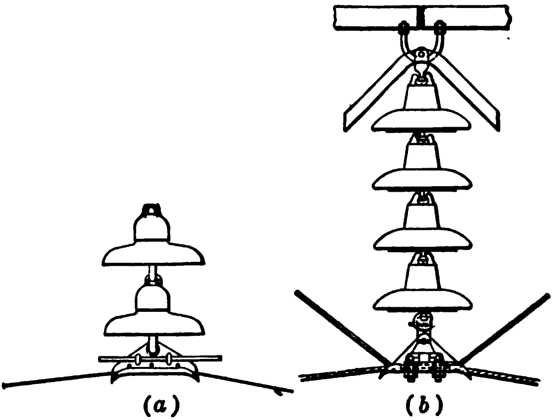


Fig. 35.—Arcing rods.

66. The line conductor should also be protected from burning off, due to the heat of the arc. The arcing rods shown in Fig. 35, and the Thomas Line Protector shown in Fig. 36 may be used.

*** Bibliography 36.**

67. *Effect of high frequency on insulators. Insulators that only flash over at commercial frequencies may puncture at the same voltage if the frequency be high. This is probably due in part to the altering of stress distribution caused by the change in the ratio of susceptance to leakage conductance brought about by high frequency. It is also due in part to the corona not having time to form and relieve the stress by rupture of the air. To prevent puncture due to high frequency disturbances, the ratio of flash-over voltage to puncture voltage should be low.

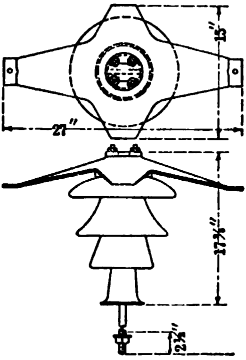


FIG. 36.—Thomas line protector.

68. Insulator testing† is of two kinds, design tests and routine tests. Design tests cover those features that are important to the purchaser, such as dry and wet flash-over, puncture voltage, tensile strength, and are usually made on the assembled unit or string. The insulator should be tested under conditions approximating those attained in service, such as mounting or suspending from a grounded pin and cross arm, well away from other objects. The potential should be applied between the pin, and a short length of cable, representing the line conductor, tied or clamped to the insulator. The standard wet test is to spray water over the insulator at an angle of 45 deg. and at a precipitation rate of 0.2 in (0.508 cm.) of water per min. As results are largely dependent on the electrolytic nature of the water, distilled water is to be preferred, as more uniform results are obtained by its use. Insulators, under ordinary conditions, flash over before puncturing, so in order to obtain the puncture voltage, the insulators must be immersed in oil.

Routine tests should be made on each part of every insulator before assembling, and also on the complete unit. The object is not to flash over the insulator but rather to detect existing faults before the insulator is put in service. The parts of pin and suspension type insulators are inverted in water thus forming one terminal. Water is also placed inside the insulator

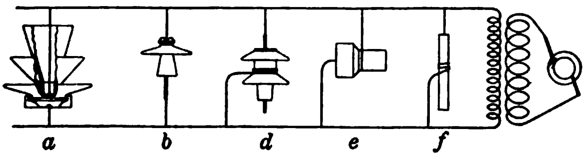


FIG. 37.—Insulator testing.

covering the threads in the threaded parts, and from 0.5 to 0.75 in. (1.27 to 1.9 cm.) deep in the other parts, thus forming the other terminal as shown in a, Fig. 37. Dry tests are often made on the assembled unit, b, c, d, e (Fig. 37) and are necessary on strain insulators and bushings. The *breakdown voltage of insulators* is a function of the time during which the voltage is applied, as has been shown by A. O. Austin.‡ A higher potential for a short time will eliminate poor insulators in the same manner as a lower potential for a longer time. Such curves for 100 kv. and 85 kv. are shown in Fig.

* See Bibliography 40.
† See Bibliography 34, 37–41 incl.
‡ See Bibliography 37.

38. Thus 100 kv. for one-half minute will eliminate 2.2 per cent., whereas 85 kv. must be applied 4.7 minutes to produce the same result.

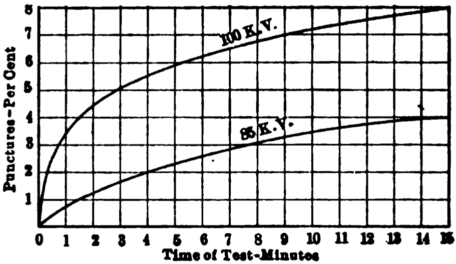


Fig. 38.—Insulator time-puncture curves.

SYSTEM DISTURBANCES

69. Surges* and disturbances occur in a transmission circuit, when circuit conditions are in any way altered. An **oscillation** is a recurring disturbance due usually to the oscillation of energy between the electrostatic and electromagnetic fields. An oscillation of low frequency, or one that is rapidly damped, is called a **surge.** Disturbances may be produced by causes within the system itself, such as switching, grounds, changes of load, or they may be produced by external causes, such as lightning.

In an oscillation, the energy passes from one form to the other, so that assuming no loss,

$$\tfrac{1}{2}Li^2 = \tfrac{1}{2}Ce^2$$

or

$$e/i = \sqrt{L/C} \qquad (21)$$

The term $\sqrt{L/C}$ is the *natural impedance* of the line.

From Eq. 21, the maximum voltage possible to occur on interruption of the current I is:

$$e = I\sqrt{L/C} \qquad (22)$$

This rise of voltage limits the current that may safely be interrupted and renders a short circuit dangerous.

Any change in load will alter either e or i and as the energy of the electrostatic and electromagnetic fields cannot change in zero time, e and i must pass through some transient values before the steady state is again reached.

If r, the resistance, is equal to or greater than $\sqrt{L/C}$, the transient is non-oscillatory, and quickly dies out. If r is less than $\sqrt{L/C}$, the transient is oscillatory. The energy is dissipated as heat in the resistance, in hysteresis losses in the fields themselves, or the insulation of the system may break down allowing the energy to manifest itself in an arc.

70. The frequency at which the transient oscillates is

$$f = 1/(4\sqrt{LC}) \qquad (23)$$

when the circuit constants are distributed, as in the case of a transmission line. f is the *natural frequency* of the circuit. The transmission frequency should be so chosen that the natural frequency is not exactly an odd multiple thereof.

71. Forced oscillations are produced by a source of energy external to the circuit, such as lightning, whose frequency has no relation to the circuit constants.

* Par. 247.

72. Effect of transients. When a traveling wave passes from one part of a circuit into another of different constants, the voltage wave, e_1, will change its magnitude to e_2, as follows,

$$e_2 = e_1 \frac{Z_2}{\left(\frac{Z_1 + Z_2}{2}\right)} \tag{24}$$

and the current

$$i_2 = i_1 \frac{Z_1}{\left(\frac{Z_1 + Z_2}{2}\right)} \tag{25}$$

where Z_1 and Z_2 are the natural impedances $\sqrt{L_1/C_1}$ and $\sqrt{L_2/C_2}$ of the two parts of the circuit, respectively. (See Par. 69.) Thus a wave passing from one part of a circuit to another having a greater ratio of inductance to capacity will develop an increased voltage and a decreased current. This explains the breaking down of transformer windings, due to surges entering them. On the other hand, if a wave passes from an overhead system into a cable, the voltage will be reduced, and the current increased. This explains the self-protecting quality of cables to surges.

73. A line whose length is a quarter wave is determined by

$$L = \frac{183{,}000}{4f} \tag{26}$$

where L is the length in miles, f the frequency in cycles per sec., and 183,000 the velocity of an electric wave in miles per sec. It can be shown that such a line, with constant generator voltage, tends to regulate for constant current at the receiving end, and the maintenance of constant voltage at the load therefore becomes difficult. The voltage may rise to dangerous values when the circuit is opened, though a transformer at the receiving end will practically neutralize this abnormal potential. The frequency corresponding to a quarter wave length of line is the lowest frequency at which the line can freely oscillate. It cannot oscillate at a frequency corresponding to either a half or a whole wave length when the circuit is open at one end.

74. Oscillations originating in the transformer. High voltage transformers have an appreciable electrostatic capacity between turns, and also to ground, together with a large equivalent reactance. This not only tends to create very high frequency oscillations in the transformer itself but also to produce voltage rises that may puncture the insulation. Protective apparatus must therefore be so designed that these oscillations may readily pass from the transformer to the line, and, at the same time, outside disturbances will be prevented from passing in the reverse direction.

75. Lightning disturbances* may be due to a charge induced on the line by a nearby cloud which discharges, thus allowing the line charge to flow suddenly to ground; to inductive action of a nearby discharge; to direct stroke. Such disturbances may be of high frequency and may either start a destructive arc to ground or shatter the insulators near the spot of original disturbance. Waves may be propagated in both directions, causing damage at some remote point.

76. Lightning disturbances may be minimized by the use of one or more overhead ground wires, grounded at very frequent intervals. Damage to apparatus may be practically prevented by installing arresters, preferably of the aluminum cell type, near the apparatus, for example, across the high-tension bus bars at the generating station, at substation entries, and near outdoor transformers and substations. Lines have been protected by operating them just below the critical corona voltage (see Par. 48 to 52). Any disturbance that tends to raise the voltage, immediately increases the corona loss to such an extent that the energy of the disturbance is thereby dissipated.

77. The selection of protective equipment is governed somewhat by local conditions. The degree of protection necessary depends largely upon the value of the power that is being transmitted, and the financial loss involved by a shut-down or by an interruption of the service.

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* Bibliography 56.

78. Local short-circuits may be isolated from the rest of the system by properly selected automatic oil switches equipped with relays which are of either the instantaneous, reverse-energy, or inverse-time-limit types. Lightning arresters should be able to care for any abnormal voltage rise due to switching. (See Par. 69 and 92.) That the current flowing into a short circuit in one portion of the system may not rise to dangerous values, power-limiting reactances are interposed between the different sections of the system.

79. Detection and clearing of grounds. Grounds may be detected by some form of electrostatic detector, placed on the switchboard. An arcing-ground on an ungrounded system may be cleared by the **arcing ground suppressor,*** shown in Fig. 39. The selective relay may operate electrostatically, or electromagnetically by the use of potential transformers. When a ground occurs on any phase, that phase is temporarily grounded by the proper oil switch, selectively operated by the relay. This lowers the voltage across the arc, which therefore ceases, and the switch then opens (through a resistance to prevent oscillations) and the ground is thus cleared. In a cable system the grounded phase is permanently connected to ground, as otherwise the arc would immediately re-form when the switch opened, due to the short distance between core and sheath. Interlocking devices prevent the simultaneous operation of more than one switch at a time, thus avoiding a short circuit on the system.

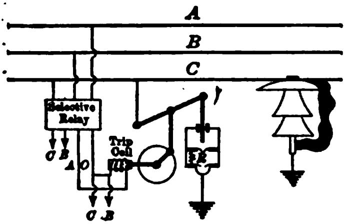

Fig. 39.—Arcing-ground suppressor.

A **short-circuit suppressor** throws a fuse directly between phases, shunting out a short-circuit arc. Subsequently the fuse automatically interrupts its own current. When these are used, power-limiting reactances are desirable in order to protect apparatus from mechanical injury.

80. Overhead ground wires unquestionably reduce the interruptions to service due to lightning, although there are no available data stating just how great the advantage is. It is estimated that one wire will reduce these interruptions about 50 per cent., and that two wires will make a still greater reduction. Galvanized iron and steel, because of their low cost and high tensile strength, have been commonly used for this purpose. Copper-clad conductors may have a lower impedance to the high-frequency discharges of lightning than have galvanized iron or steel.

SYSTEM CONNECTIONS AND SWITCHING

81. System connections should be made in such a manner that continuity of service, flexibility, and safety are secured without undue complications of wiring and switching.

82. Duplicate lines are usually necessary, where continuity of service is important. It is customary to run the two lines on the same poles or towers, especially if these are of steel or concrete, as the total cost of line supports is then much less than it would be for two individual pole lines. Where the power is especially valuable, the two lines may be run over two different routes, removed from each other. This lessens the chance of both lines being disabled at the same time by lightning or by other natural causes. The cost of two such lines is frequently prohibitive. When it is necessary to shut down a line for repairs, the service is interrupted if two lines are not available. Where the regulation would be impaired, or the overload capacity of one line is not sufficient to carry the entire load during such a shut-down, sectionalizing switches may be provided. The section requiring repairs may be isolated and grounded, the two lines being in parallel for the remaining distance. This insures better and more continuous service, though frequently the advantage gained is more than offset by the added expense and

* See Bibliography 56.

switching complication. Fig. 40 shows the connections for a typical power system.

83. Substation connections are made as shown in Fig. 40 and Figs. 73 and 74. See also Sec. 10 and Sec. 12.

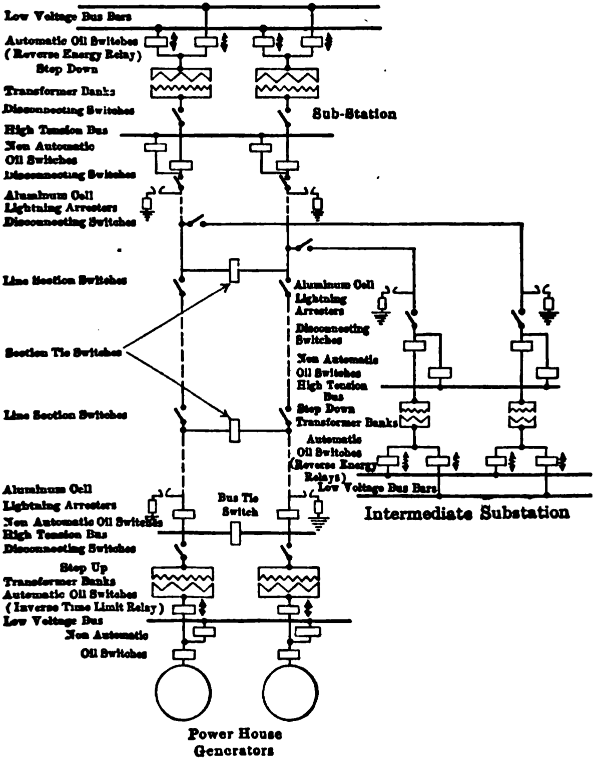

FIG. 40.—Typical system connections.

84. *Advantages of grounded systems are as follows: (a) Except under unusual transient conditions, the voltage from line wire to ground never exceeds the *Y* voltage, so the line insulation need not have so large a factor of safety, as with isolated systems; (b) a ground on one wire opens the breakers and warns the operator of trouble; (c) the dynamic arc to ground has but little tendency to create high frequency oscillations; (d) disturbances to the telephone system due to electrostatic unbalancing are a minimum.

85. Disadvantages of grounded systems are: (a) The line is inoperative if a ground occurs; (b) the short-circuit current may produce strong mechanical forces in generator and transformer windings, causing

* See Bibliography 67, 68.

serious damage; (c) the dynamic arc may shatter the insulators or burn off the conductors, because of the large amount of energy available; (d) inductive effects of the earth circuit may affect the telephone and telegraph circuits, though the earth current is practically negligible except in case of an accidental ground.

86. Conditions of advantageous grounding. A system in excess of 60,000 volts may well be grounded, unless absolute continuity of service is essential. A line connected as a part of a large system should be grounded. It will then be automatically disconnected and cannot subject the entire system to the delta voltage between line wire and ground. A cable system* should be grounded, as oscillations and transients are of common occurrence, and a ground in one part of the system may otherwise cause a breakdown in the insulation at some other point. To locate and repair a ground in a cable system is expensive, requiring considerable time.

87. The ground† connection may be made by connecting the neutral to a copper plate buried in charcoal; by connecting to a metal plate immersed in a nearby body of water; by connecting to metal work in contact with the earth or water; by driving iron pipes of about 1 in. (2.54 cm.) or so in diameter and 6 ft. (2 m.) length into the earth 6 ft. (2 m.) apart, and pouring salt water around them. To limit the short-circuit current, a resistance may be inserted in the neutral connection, though to secure one having the necessary resistance and carrying capacity is expensive. A reactance should not be used in the neutral as it may increase the probability of oscillations. The ground should be made at only one point of the system, at the power-house, as otherwise earth currents tend to flow and to disturb telephone and telegraph circuits in the vicinity of the line.

88. Ungrounded systems‡ have the following advantages: (a) an accidental ground does not shut down the system; (b) the earth may serve as a third conductor until the damage can be repaired; (c) an arcing ground may be cleared by the arcing ground suppressor; (d) under normal conditions, there is little effect on telephone and telegraph lines.

89. Disadvantages of ungrounded systems are as follows: (a) Though the neutral of the system should be at ground potential, experiment has shown that excessive voltage may exist between neutral and ground; (b) the insulation of the system must be designed to withstand the delta voltage, and therefore must have 1.7 times the insulation for the same factor of safety; (c) an arc to ground is in series with the line capacity, and therefore tends to set up destructive high-frequency oscillations; (d) any electrostatic unbalancing affects neighboring telephone and telegraph systems.

90. Ungrounded systems should be used where the voltage is moderate; where a shut-down would be a serious matter; where the apparatus may well withstand the full-line potential.

91. Transformer connections§ may be either delta or star. Transformers connected in delta must be able to withstand the total voltage between lines, hence their cost is greater than for star-connected transformers. They are more reliable than the star-connected, for if one transformer is disabled the system will continue to operate connected open delta. Transformers connected in delta may be heated by the third harmonic circulatory current. The star connection affords an accessible neutral, and the transformers need be designed to withstand only 58 per cent. of the line voltage. There is no third-harmonic circulatory current possible, and any third-harmonic voltage does not appear on the line. If one transformer goes out, the system must either be operated single-phase, or be shut down, unless a spare unit is available. Voltage taps are easily brought out from the transformer winding in the star connection. See Sec. 6.

92. Switching‖ a transmission line may give rise to transients causing

* See Bibliography 46.
† See Bibliography 63.
‡ Bibliography 67, 68.
§ Bibliography 23.
‖ See Bibliography 48, 49.

serious damage to line and apparatus. The matter is further complicated by the characteristics of the oil switches themselves. When the switch contacts approach each other on closing the circuit, small arcs of decreasing magnitude are set up between them. These may result in high frequency oscillations corresponding in period to the natural frequency of the transformer windings. In a three-phase switch the three contacts may not close at the same instant which further complicates the problem. Similar phenomena occur when the switch opens the circuit, the arcs between contacts increasing in magnitude. The maximum possible voltage rise as the switch opens is given by

$$e = i\sqrt{L/C} \qquad (27)$$

where i is the current at the moment of break and L and C are the circuit inductance and capacity respectively. The voltage does not usually approach this limiting value as the arcs formed between the contacts introduce resistance which diminishes the voltage rise. The switch also absorbs some of the energy stored in the line. The voltage rise, under ordinary switching conditions, may not exceed the normal operating value more than from 50 to 75 per cent. The excessive rises in potential occur under short-circuit conditions, when the current may reach many times full-load value. Aluminum arresters and power-limiting reactances offer the best solution of the problem.

93. High-tension and low-tension switching are both extensively employed, there being no consensus of opinion as to which is more desirable. The following methods are used in switching on a substation.

(a) Connect the line to the high-tension bus at the generating station, and then switch the substation transformers.

(b) Connect substation transformers to the dead line, and then switch the line to the high-tension bus at the generating station.

(c) Connect the open line to the transformers at the generating station, switch these on the low side, and then connect the substation transformers at the end of the live line.

(d) Connect the substation transformers to the dead line and step up transformers and switch these latter on the low tension side.

(a) and (b) come under the classification of high tension switching and (c) and (d) low-tension switching. The reverse order may be followed, when switching off.

Transformer switching may result in abnormal current rushes, if the circuit is closed on a point of the e.m.f. wave, which does not correspond to the residual magnetic state of the transformer.

POWER-FACTOR CORRECTION

94. Power-factor correction* may often be made on transmission lines, whereby the voltage regulation may be materially improved, the generating capacity increased and the copper losses reduced. This correction may be made by the over and the under excitation of synchronous apparatus at the receiving end of the line. When used for this purpose exclusively, such apparatus is called a synchronous condenser. This synchronous apparatus may be a part of the receiver and used for further distribution of power, or it may merely float on the end of the line, its sole function being to regulate the power-factor, or the voltage. As synchronous motors are not wound for voltages much in excess of 13,000 volts, they must be connected to the low sides of transformers if the line voltage exceeds this value. When the motor is installed solely to improve transmission efficiency, the cost of the power required by the motor plus its maintenance and fixed charges, must not exceed the cost of the power saved, and must be less than the interest on the cost of installing more copper. As the synchronous apparatus may fall out of step, or be damaged by surges or short-circuits, it is generally desirable to install copper, which will give greater reliability, and has a better scrap value.

When improved regulation is the result desired, the installation of synchronous apparatus may be justified regardless of the energy saving. Where large amounts of power are concerned, it is impracticable to install synchronous condensers to take care of the entire quadrature current, although they may be used for purposes of improved regulation.

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* Bibliography 71–77 incl.

95. Calculations for power-factor correction. The per cent. quadrature current required for unity power-factor at the receiver may be determined from Fig. 41, or may be calculated for a three-phase system as follows:

$$I_1 = \frac{W}{3E} \tag{28}$$

$$I_2 = \frac{W}{3E} \tan \theta \tag{29}$$

where I_1 and I_2 are the energy and quadrature components of current respectively, W is the power, in watts, at the receiver, E is the voltage, from line wire to *neutral*, at the receiver, and θ is the angle between the current and voltage vectors. It will be noted, from Fig. 41 that it requires a much larger synchronous motor to bring the power-factor from 95 per cent. to 100 per cent., than it would require to bring it from 90 per cent. to 95 per cent. As a rule, it is not economy to install apparatus large enough to obtain the last 5 per cent.

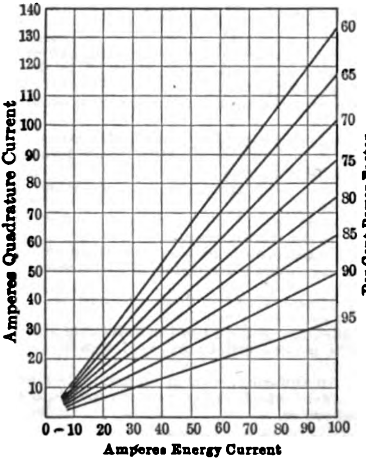

Fig. 41.—Energy and quadrature currents.

96. Constant receiver voltage* **may be obtained** by varying the excitation of the synchronous apparatus, either by use of an automatic regulator which acts on the exciter or by compounding, if the synchronous apparatus is a motor-generator or a rotary converter. When the variations in voltage are not severe, hand regulation may be employed. Machines cannot always be compounded to give constant voltage at all loads, though the condition of constant voltage may be approximated. As the voltage of a line may rise on open circuit to a value in excess of the generator voltage, due to the line charging current, the synchronous apparatus must be able to shift its phase from leading to lagging current. The power-factor being known, the quadrature current and the required capacity of synchronous apparatus may be determined by plotting Fig. 17 (Par. 28) to a large scale. For more complete discussion consult the bibliography references.

STRESSES IN SPANS

97. Mechanical stresses in a span are produced by: (a) the dead weight of the conductor, which acts vertically; (b) the weight of any ice, sleet, or snow that may cling to the wire; and (c) the wind pressure, which is assumed to act horizontally, at right angles to the line, and on the projected area of the conductor, and its sleet loads.

The weights of copper and aluminum conductors are given in Par. 99. The weight of ice is 57 lb. per cu. ft., or 0.033 lb. per cu. in. and the weight of sleet and snow is somewhat less than this. For the average climate of the United States, a layer of ice 0.5 in. (1.27 cm.) thick is assumed to be the worst condition of loading, though in the mountainous regions, sleet may form to a greater thickness than this. The table in Par. 99 gives the ice and conductor loads with 0.5-in. and 0.75-in. layers of ice, for both copper and aluminum conductors.

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* Bibliography 73, 75, 77.

The wind pressure is a function of the wind velocity and may be expressed by Buck's* formula

$$p = 0.0025V^2 \quad \text{(lb. per sq. ft.)} \qquad (30)$$

Where p is the pressure in lb. per sq. ft. and V is the actual velocity of the wind in miles per hr. Fig. 42 shows the relation between velocity and wind pressure. Buck gives the following as the relation between actual velocity and that indicated at the Government observation stations.

Indicated velocity...	10	20	30	40	50	60	70	80	90	100
Actual velocity......	9.6	17.8	25.7	33.3	40.8	48.0	55.2	62.2	69.2	76.2

Fig. 43 shows the wind pressure at different heights above ground, and Par. 99 gives the pressure for the various conductors and ice loads.

The resultant force acting on the conductor, is the vector sum of the horizontal and vertical forces shown in Fig. 44. The resultant loading for various conditions of component loading on line conductors is given in Sec. 4.

98. The general span formulæ, assuming that the span has the form of a parabola, and that the weight is uniformly distributed, are as follows:

$$t = \frac{S^2 w}{8d} \quad \text{(lb.)} \qquad (31)$$

$$d = \frac{S^2 w}{8t} \quad \text{(ft.)} \qquad (32)$$

$$l = S + \frac{8d^2}{3S} \quad \text{(ft.)} \qquad (33)$$

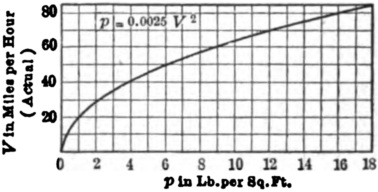


Fig. 42.—Wind velocity and pressure.

where t is the horizontal tension in lb., S is the span length in ft., d is the sag in ft., w is the weight in lb. per ft. of the conductor plus the sleet or snow, and l is the length of the conductor in ft. The total tension T in the conductor at the support, is the sum of the horizontal component t, and the vertical component due to the dead load.

$$T = t + wd \quad \text{(lb).} \qquad (34)$$

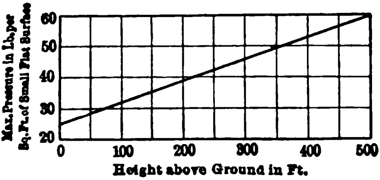


Fig. 43.—Wind velocity and height.

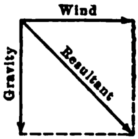


Fig. 44.—Resultant force on the wire.

The second term is usually very small, and for ordinary sags is negligible.

If in Eq. 32 the conductor is considered by itself, ignoring sleet and wind loads, then

$$d = \frac{S^2\left(\frac{w}{A}\right)}{8\left(\frac{t}{A}\right)} = \frac{S^2 W}{8F} \quad \text{(ft.)} \qquad (35)$$

where W is the weight of the conductor per ft. of length and for 1 sq. in. cross-section, and F is the tension in lb. per sq. in. The required deflection may then be determined for the allowable unit stress.

* See Bibliography 82.

99. Loading tables*

Copper wire—stranded

Cir. mils and A.W.G.	Diam., inches	Area, sq. in.	Hard drawn: Ultimate tension, lb.	Hard drawn: Allow. tension	Soft drawn: Ultimate tension, lbs.	Soft drawn: Allow. tension	Load per lin. foot, vertical: Dead	Load per lin. foot, vertical: Dead + ½ in. ice	Load per lin. foot, vertical: Dead + ¾ in. ice	Load per lin. foot, horizontal: 15.0 lb. p. sq. ft.	Load per lin. foot, horizontal: 8.0 lb. p. sq. ft., ½ in. ice	Load per lin. foot, horizontal: 11.0 lb. p. sq. ft., ¾ in. ice	Max. load per lin. foot, plane of resultant: Class A load'g	Max. load per lin. foot, plane of resultant: Class B load'g	Max. load per lin. foot, plane of resultant: Class C load'g	EA: E(hard drawn) 16,000,000	EA: E(annealed) 12,000,000
500,000	0.819	0.3924	23,540	11,750	13,340	6,650	1.525	2.345	2.989	1.024	1.213	2.126	1.837	2.640	3.668	6,278,400	4,708,800
350,000	0.679	0.2750	16,500	8,250	9,350	4,650	1.068	1.801	2.401	0.849	1.119	1.997	1.364	2.120	3.123	4,400,000	3,300,000
0,000	0.530	0.1662	9,970	5,000	5,650	2,800	0.645	1.286	1.831	0.663	1.020	1.861	0.925	1.641	2.611	2,659,200	1,994,400
000	0.470	0.1318	7,910	3,950	4,480	2,250	0.513	1.116	1.651	0.588	0.980	1.806	0.780	1.485	2.446	2,108,800	1,581,600
00	0.420	0.1045	6,270	3,150	3,555	1,750	0.406	0.978	1.498	0.525	0.947	1.760	0.664	1.361	2.311	1,672,000	1,254,000
0	0.375	0.0829	4,970	2,500	2,820	1,400	0.322	0.866	1.372	0.469	0.917	1.719	0.569	1.261	2.199	1,326,400	994,800
1	0.330	0.0657	3,940	1,950	2,235	1,100	0.255	0.771	1.263	0.413	0.887	1.678	0.485	1.175	2.100	1,051,200	788,400
2	0.291	0.0521	3,130	1,550	1,770	900	0.203	0.695	1.174	0.364	0.861	1.642	0.417	1.107	2.019	833,600	625,200
3	0.261	0.0413	2,480	1,250	1,405	700	0.160	0.633	1.103	0.326	0.841	1.614	0.363	1.053	1.955	660,800	495,600
Copper wire—solid																	
0000	0.460	0.1662	8,310	4,150	5,650	2,800	0.641	1.238	1.770	0.575	0.973	1.797	0.861	1.575	2.522	....	....
000	0.410	0.1318	6,590	3,300	4,480	2,250	0.509	1.074	1.591	0.512	0.940	1.750	0.722	1.427	2.365	....	....
00	0.365	.1045	5,220	2,600	3,555	1,750	0.403	0.940	1.443	0.456	0.910	1.709	0.608	1.309	2.237	....	....
0	0.325	0.0829	4,560	2,300	2,820	1,400	0.320	0.833	1.323	0.406	0.883	1.673	0.517	1.214	2.133	....	....
1	0.289	0.0657	3,740	1,850	2,235	1,100	0.253	0.744	1.223	0.362	0.860	1.640	0.442	1.137	2.046	....	....
2	0.258	0.0521	3,120	1,550	1,770	900	0.202	0.673	1.142	0.322	0.838	1.611	0.380	1.075	1.975	....	....
3	0.229	0.0413	2,480	1,250	1,405	700	0.159	0.613	1.073	0.287	0.820	1.585	0.328	1.024	1.914	....	....
4	0.204	0.0328	1,960	1,000	1,115	550	0.126	0.564	1.016	0.255	0.803	1.567	0.284	0.981	1.863	....	....
5	0.182	0.0260	1,560	800	885	450	0.100	0.524	0.969	0.227	0.788	1.542	0.248	0.946	1.821	....	....
6	0.162	0.0206	1,240	600	700	350	0.079	0.491	0.930	0.203	0.775	1.524	0.218	0.917	1.785	....	....

99. Loading tables.—(*Continued*)

Aluminum wire—stranded

Cir. mils and A.W.G.	Diam., inches	Area, sq. in.	Hard drawn: Ultimate tension, lb.	Hard drawn: Allow. tension	Soft drawn: Ultimate tension, lb.	Soft drawn: Allow. tension	Load per lin. foot, vertical: Dead	Load per lin. foot, vertical: Dead + ½ in. ice	Load per lin. foot, vertical: Dead + ¾ in. ice	Load per lin. foot, horizontal: 15.0 lb. p. sq. ft.	Load per lin. foot, horizontal: 8.0 lb. p. sq. ft., ½ in. ice	Load per lin. foot, horizontal: 11.0 lb. p. sq. ft., ¾ in. ice	Max. load per lin. foot, plane of resultant: Class A load'g	Max. load per lin. foot, plane of resultant: Class B load'g	Max. load per lin. foot, plane of resultant: Class C load'g	*EA*: E (hard drawn) 16,000,000	*EA*: E (annealed) 12,000,000
																9,000,000	
500,000	0.814	0.3924	9,025	4,500	......	......	0.460	1.280	1.919	1.018	1.209	2.121	1.117	1.762	2.860	3,531,600	
350,000	0.679	0.2750	6,325	3,150	......	......	0.322	1.055	1.655	0.849	1.119	1.997	0.908	1.538	2.594	2,475,000	
0000	0.522	0.1662	3,820	1,900	......	......	0.195	0.831	1.382	0.652	1.015	1.853	0.681	1.312	2.312	1,495,800	
000	0.464	0.1318	3,160	1,600	......	......	0.155	0.755	1.288	0.580	0.976	1.800	0.600	1.234	2.213	1,186,200	
00	0.414	0.1045	2,510	1,250	......	......	0.122	0.691	1.208	0.518	0.943	1.754	0.532	1.168	2.130	940,500	
0	0.368	0.0879	1,990	1,000	......	......	0.097	0.637	1.140	0.460	0.912	1.712	0.470	1.112	2.057	746,100	
1	0.328	0.0657	1,575	800	......	......	0.077	0.592	1.082	0.410	0.885	1.676	0.417	1.065	1.995	591,300	
2	0.291	0.0521	1,250	600	......	......	0.061	0.533	1.032	0.364	0.861	1.642	0.368	1.023	1.939	468,900	
3	0.261	0.0413	990	500	......	......	0.049	0.522	0.992	0.326	0.841	1.614	0.329	0.990	1.894	371,700	
4	0.231	0.0328	790	400	......	......	0.039	0.494	0.954	0.289	0.821	1.587	0.292	0.958	1.846	295,200	

NOTE: Class A loading = dead load + 15.0 lb. per sq. ft. wind pressure. Class B loading = dead load + 0.5 in. ice + 8.0 lb. wind pressure. Class C loading = dead load + 0.75 in. ice + 11.0 lb. wind pressure. *E* = modulus of elasticity, in.-lb. *A* = conductor area. *EA* = product of modulus of elasticity and conductor area.

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A.

100. Stresses at centres of spans resulting from a given deflection

Deflection in decimal parts of spans

Spans in ft.	0.001	0.002	0.005	0.010	0.015	0.020	0.030	0.040	0.050	0.060	0.070
	Multipliers										
10	1,250.001	625.003	250.008	125.016	83.358	62.533	41.716	31.316	25.083	20.933	17.973
20	2,500.003	1,250.006	500.016	250.033	166.716	125.066	83.433	62.633	50.166	41.866	35.947
40	5,000.006	2,500.013	1,000.033	500.066	333.433	250.133	166.866	125.266	100.333	83.733	71.895
50	6,250.008	3,125.016	1,250.041	625.083	416.791	312.666	208.583	156.583	125.416	104.666	89.869
70	8,750.011	4,375.023	1,750.058	875.116	583.508	437.733	292.016	219.216	175.583	146.533	125.816
100	12,500.016	6,250.033	2,500.083	1,250.166	833.583	625.333	417.166	313.166	250.833	209.333	179.738
120	15,000.020	7,500.040	3,000.100	1,500.200	1,000.300	750.400	500.600	375.800	301.000	251.200	215.685
140	17,500.023	8,750.046	3,500.116	1,750.233	1,167.016	875.466	584.033	438.433	351.166	293.066	251.633
150	18,750.025	9,375.050	3,750.125	1,875.250	1,250.375	938.000	625.750	469.750	376.250	314.000	269.607
170	21,250.028	10,625.056	4,250.141	2,125.283	1,417.091	1,063.066	709.183	532.383	426.416	355.866	305.554
200	25,000.033	12,500.066	5,000.166	2,500.333	1,667.166	1,250.666	834.333	626.333	501.666	418.666	359.476

Deflections in decimal parts of spans

Spans in ft.	0.080	0.085	0.090	0.095	0.100	0.110	0.120	0.130	0.140	0.150	0.160	0.170	0.180	0.190	0.200
	Multipliers														
10	15.758	14.847	14.038	13.316	12.666	11.546	10.616	9.832	9.161	8.583	8.079	7.636	7.244	6.895	6.583
20	31.516	29.695	28.077	26.632	25.333	23.093	21.233	19.664	18.323	17.166	16.158	15.272	14.488	13.791	13.166
40	63.033	59.390	56.155	53.264	50.666	46.187	42.466	39.328	36.647	34.333	32.316	30.545	28.977	27.582	26.333
50	78.791	74.237	70.194	66.581	63.333	57.734	53.083	49.160	45.809	42.916	40.395	38.181	36.222	34.478	32.916
70	110.308	103.932	98.272	93.213	88.666	80.828	74.316	68.824	64.133	60.083	56.554	53.453	50.711	48.269	46.083
100	157.583	148.475	140.388	133.162	126.666	115.469	106.166	98.320	91.619	85.833	80.791	76.362	72.444	68.956	65.833
120	189.100	178.170	168.466	159.794	152.000	138.563	127.400	117.984	109.942	103.000	96.950	91.635	86.933	82.747	79.000
140	220.616	207.865	196.544	186.427	177.333	161.657	148.633	137.648	128.266	120.166	113.108	106.907	101.422	96.538	92.166
150	236.375	222.713	210.583	199.743	190.000	173.204	159.250	147.480	137.428	128.750	121.187	114.544	108.666	103.434	98.750
170	267.891	252.408	238.661	226.375	215.333	196.298	180.483	167.144	155.752	145.916	137.345	129.816	123.155	117.225	111.916
200	315.166	296.950	280.777	266.324	253.333	230.939	212.333	196.641	183.238	171.666	161.583	152.725	144.888	137.912	131.666

161. Total lengths of wires in spans

Deflections in decimal parts of spans

Spans in ft.	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050	0.055	0.060	0.070	0.080
	Lengths of wires												
10	10.002	10.006	10.010	10.016	10.024	10.032	10.042	10.054	10.066	10.080	10.096	10.130	10.170
20	20.005	20.012	20.021	20.033	20.048	20.065	20.085	20.108	20.133	20.161	20.192	20.261	20.341
40	40.010	40.024	40.042	40.066	40.096	40.130	40.170	40.216	40.266	40.322	40.384	40.522	40.682
50	50.013	50.030	50.053	50.083	50.120	50.163	50.213	50.270	50.333	50.403	50.480	50.653	50.853
70	70.018	70.042	70.074	70.116	70.168	70.228	70.298	70.378	70.466	70.564	70.672	70.914	71.194
100	100.026	100.060	100.106	100.166	100.240	100.326	100.426	100.540	100.666	100.806	100.960	101.306	101.706
120	120.032	120.072	120.128	120.200	120.288	120.392	120.512	120.648	120.800	120.968	121.152	121.568	122.048
140	140.037	140.084	140.149	140.233	140.336	140.457	140.597	140.756	140.933	141.129	141.344	141.829	142.389
150	150.040	150.090	150.160	150.250	150.360	150.490	150.640	150.810	151.000	151.210	151.440	151.960	152.560
170	170.045	170.102	170.181	170.283	170.408	170.555	170.725	170.918	171.133	171.371	171.632	172.221	172.901
200	200.053	200.120	200.213	200.333	200.480	200.653	200.853	201.080	201.333	201.613	201.920	202.613	203.413

Deflections in decimal parts of spans

Spans in ft.	0.090	0.100	0.110	0.120	0.130	0.140	0.150	0.160	0.170	0.180	0.190	0.200
	Lengths of wires											
10	10.216	10.266	10.322	10.384	10.450	10.522	10.6	10.682	10.770	10.864	10.962	11.066
20	20.432	20.533	20.645	20.768	20.901	21.045	21.2	21.365	21.541	21.728	21.925	22.133
40	40.864	41.066	41.290	41.536	41.802	42.090	42.4	42.730	43.082	43.456	43.850	44.266
50	51.080	51.333	51.613	51.920	52.253	52.613	53.0	53.413	53.853	54.320	54.813	55.333
70	71.512	71.866	72.258	72.688	73.154	73.658	74.2	74.778	75.394	76.048	76.738	77.466
100	102.160	102.666	103.226	103.840	104.506	105.226	106.0	106.826	107.706	108.640	109.626	110.666
120	122.592	123.200	123.872	124.608	125.408	126.272	127.2	128.192	129.248	130.368	131.552	132.800
140	143.024	143.733	144.517	145.376	146.309	147.317	148.4	149.557	150.789	152.096	153.477	154.933
150	153.240	154.000	154.840	155.760	156.760	157.840	159.0	160.240	161.560	162.960	164.440	166.000
170	173.672	174.533	175.485	176.528	177.661	178.885	180.2	181.605	183.101	184.688	186.365	188.133
200	204.320	205.333	206.453	207.680	209.013	210.453	212.0	213.653	215.413	217.280	219.253	221.333

RULE.—To find stress in lb. on wire of given span and deflection, multiply numbers in column answering to span and deflection by the weight per ft. of wire.

102. Calculation of horizontal stress.* The foregoing tables give the factors by which the weight per ft. of conductor may be multiplied, in order to determine the horizontal stress in the span. Values are given up to 200 ft. (61 m.) spans, and to 20 per cent. deflections. For any span greater than 200 ft. (61 m.) the table may still be used, if it be remembered that for a given percentage deflection, the stress is proportional to the span. Thus for a 1,500-ft. (4.57 m.) span having 2.0 per cent. deflection, and a total weight of 0.5 lb. per ft. (1.64 lb. per m.) the horizontal stress will be (from 150-ft. span)

$$t = 938 \times 10 \times 0.5 = 4690 \text{ lb.}$$

In the same way, the length of this span wire (Par. **101**) will be (with 150-ft. span)

$$l = 150.16 \times 10 = 1501.6 \text{ ft.}$$

The tables were computed from formulæ given in Weisbach's "Mechanics of Engineering," page 297 (seventh American edition, translated by Eckley B. Cox, A.M.)

$S \times W$ = horizontal stress in wire at centre of span (lb.) (36)

$$S = y^2/2x + x/6 \text{ (ft.)} \quad (37)$$

$$l = y[1 + (2/3)\ (x/y)^2] \text{ (ft.)} \quad (38)$$

$$x = 3S - \sqrt{9S^2 - 3y^2} \text{ (ft.)} \quad (39)$$

$$y = \sqrt{(3yl - 3y^2)/2} \text{ (ft.)} \quad (40)$$

where y = one-half the span.
l = one-half the length of the span wire.
x = deflection at centre in same units as y.
w = dead weight per ft. of wire.

103. Temperature variations will change the length of the span, and as the sag and tension are very sensitive to changes in the length of span, the effect of change of temperature must be considered. With a change of tension, the length of the wire will be changed, due to stretching or contracting. As stretch and temperature change are inter-related and occur simultaneously, their combined effect must be determined. As an analytical calculation is difficult to make, the solution is better determined by graphical methods. For every degree fahr. change in temperature, the length of unstressed copper will change 0.00096 per cent., and of aluminum 0.00128 per cent. The following table gives stress and temperature data for both copper and aluminum conductors.

104. †Properties of conductor materials

Copper	Ultimate strength per sq. in.	Elastic limit	Mod. elasticity, E	Coef. expansion, θ
Solid, soft-drawn.	32–34,000	28,000	12,000,000	0.0000096
Solid, hard-drawn.	50–55–57–60,000	30–32–34–35,000	16,000,000	0.0000096
Stranded, soft-drawn.	34,000	28,000	12,000,000	0.0000096
Stranded, hard-drawn.	60,000	35,000	16,000,000	0.0000096
Aluminum Stranded........	23–24,000	14,000	9,000,000	0.0000128

105. The maximum stress in a span occurs when it has its greatest loading of ice or sleet, minimum temperature, and maximum wind velocity blowing at right angles to the line. The loading usually assumed is 0.5-in. layer of ice at −20 deg. fahr. (−29 deg. cent.) and a wind pressure of 8 lb. per sq. ft. (at a velocity of about 57 miles per hr.) The load under these conditions may then be determined from Par. **99**, and the stress from Par. **100**, or calculated from Eq. 31, Par. **98**.

106. Example of stress-sag calculation. Problem: Required to find the proper sag for a 600-ft. span of No. 0000 hard-drawn solid copper, at

* From "Wire in Electrical Construction" by John A. Roebling's Sons Co.
† Report of the Joint Committee on Overhead Construction, N. E. L. A.

maximum (summer), minimum (winter-loaded), and stringing (unloaded) temperatures.

From Par. 99 for 0.5-in. ice, and 8 lb. per sq. ft. wind pressure, the total load per lin. ft., w, is 1.575 lb. The allowable tension, t, is 4,150 lb. (corresponding to 25,000 lb. per sq.in.). The sag may be calculated from Eq. 32, Par. 98. $d = [(600)^2 \times 1.575]/(8 \times 4{,}150) = 17.08$ ft. at the assumed minimum temperature.

This is the sag under ice load at −20 deg. fahr.

The maximum sag will occur at +120 deg. fahr., the assumed maximum temperature, with no load other than the conductor itself and no wind.

To determine this sag first consider that all the stress is removed from the conductor, and determine its length under this condition.

The change of length due to removing the load, $\Delta l = \dfrac{tl}{EA}$ (41)

In this expression, t is the tension in lb., l, the length in ft., E, the modulus of elasticity, in-lb., A, the cross-section of the conductor, in sq. in. Values of EA are given in Par. 99.

The original length, from Eq. 33, Par. 98, is $l_1 = 600 + [8 \times (17.08)^2/(3 \times 600)] = 601.297$ ft. $\Delta l = 4{,}150 \times 601.297/2{,}659{,}000 = 0.939$ ft. The span, then, if all stress were removed, would have the hypothetical length at −20 deg. fahr., $601.297 - 0.939 = 600.358$ ft. This often results in a value less than the span length. At zero deg. fahr., the length would be given by

$$l = l_0(1 + \alpha t') \qquad (42)$$

Where l_0 is the length at zero deg. fahr. α is the coefficient of expansion, t' is the temperature deg. fahr. $l_0 = 600.358/[1 + 0.0000096 \times (-20)] = 600.473$ ft. $d_0 = \sqrt{[3 \times 600(600.473 - 600)]/8} = 10.31$ ft. (Eq. 33, Par. 98.)

107. To obtain the sag at zero deg. fahr., no ice and no wind load, the sag-stress curve ab should first be plotted (Fig. 45), having $w = 0.641$ lb. per ft., weight of conductor with load removed (Par. 99). The table of Par. 100 is very convenient for this purpose. The sags for different tensions are then calculated, by finding, first, the length from Eq. 41, and then the sag from Eq. 32, Par. 98. These values are now plotted (curve cd); where this curve intersects the sag-stress curve ab will be the sag at zero deg. fahr., when the conductor has no load other than its own weight.

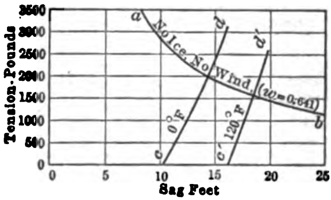


FIG. 45.—Stress-sag curves.

Thus, at a tension of 3,000 lb., $l_1 = 600.473 + [(600.473 \times 3{,}000)/2{,}659{,}000] = 600.473 + 0.678 = 601.151$ ft. (from Eq. 41). $d = \sqrt{[1{,}800(601.151 - 600)]/8} = 16.09$ ft. (from Eq. 33, Par. 98). From the intersections, sag at zero deg. fahr. = 14.4 ft. and tension at zero deg. fahr. = 2,000 lb.

108. The sag at another temperature may be found by increasing the abscisse by a distance, determined from Eq. 42 and Eq. 33, Par. 98. Thus, to find the sag and tension for 120 deg. fahr., $l = 600.472\ (1 + 0.0000096 \times 120) = 601.163$ ft. at 120 deg. fahr. and zero stress, $d = 16.18$ ft.

The sag and stress should then be computed as in Par. 107, and a new stretch line $c'd'$ plotted. The maximum sag (assumed at 120 deg. fahr.) occurs where $c'd'$ cuts ab. It is equal to 18.5 ft., and the corresponding tension 1,560 lb.

109. Data used when stringing. A set of stretch curves for several temperatures should be furnished the foreman in charge of stringing the wire, in order that he may adjust the sag, or tension (by means of a dynamometer) to their proper values for the temperature at the time of stringing. It must be remembered that the temperature of the wire, when the sun is shining, may be several degrees higher than that of the surrounding air.

110. With the supports at different levels, the line forms a catenary, the lowest point of which is no longer midway between supports. The curve can, however, be prolonged until it reaches a point which is at the same level as the higher support (Fig. 46) and the distance x_1 to the lowest point of the catenary will be equal to half the assumed span, S', and may be computed.

$$x_1 = \frac{S}{2} + \frac{ht}{wS}\ {}^{*} \qquad \text{(ft.)} \qquad (43)$$

$$x_1 = S\,\frac{\sqrt{d}}{\sqrt{d-h}+\sqrt{d}} \qquad \text{(ft.)} \qquad (44)$$

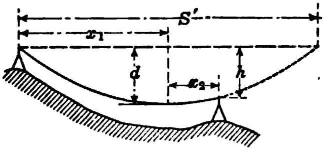


Fig. 46.—Supports at different levels.

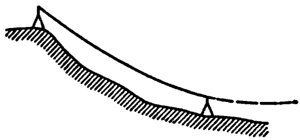


Fig. 47.—Condition for upward pull at lower support.

where S is the horizontal distance between supports, d the sag measured from the higher support, t the tension in the wire in lb. at the higher support, w the weight in lb. per unit length, h the difference in height of supports, all distances expressed in ft.

Eq. 43 is useful when the span and the allowable stress are given; and Eq. 44 when the span and sag are given. Eq. 43 is correct to within 2 to 4 per cent. when neither the sag nor difference in height of supports exceeds 15 per cent. of the span. Eq. 44 has an error of less than 1 per cent. under these conditions.

The sag d may be computed,

$$d = d'\left(1 + \frac{h}{4d'}\right)^2 \qquad \text{(ft.)} \qquad (45)$$

where d' is the sag as determined by Eq. 32 for the same span, S, and the same loading.

also

$$x_2 = \frac{S}{2}\left(1 - \frac{h}{4d'}\right) \qquad \text{(ft.)} \qquad (46)$$

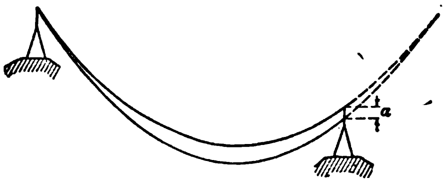


Fig. 48.—Error introduced by assuming constant equivalent span.

Having determined the distance x_1, the span may then be treated like a span S', where $S' = 2x_1$. From Eq. 46 if $h/4d'$ is greater than unity, the vertex of the line will lie outside the span, and there will be an upward pull on the insulator. This is shown in Fig. 47 and the span should be so designed that this condition does not occur.

Load and temperature changes may be computed as in Par. 107 and 108, but a certain error is introduced in assuming that the length of equivalent span remains unchanged. Except for accurate work, this error is negligible. The error increases or decreases with the difference in height of supports by an amount, a, Fig. 48. For accurate work, however, the length of line in the span may be computed from Eq. 33 knowing x_1, x_2 and d (Fig. 46) and the effects of changes of load and of temperature may also be computed. The new distance x_2 is determined and the new equivalent length of span found.

* See Bibliography 88.

111. The Thomas chart* for sag and stress determinations is based on the following: Imagine a given span to be reduced to a length of 1 ft. without changing the shape of the curve. The percentage sag will remain the same, but the sag, stress and length of wire will be reduced in direct proportion. The stress for a definite sag is proportional to the weight per unit length of the wire including ice and wind loads. The curves, Fig. 49, show the relation

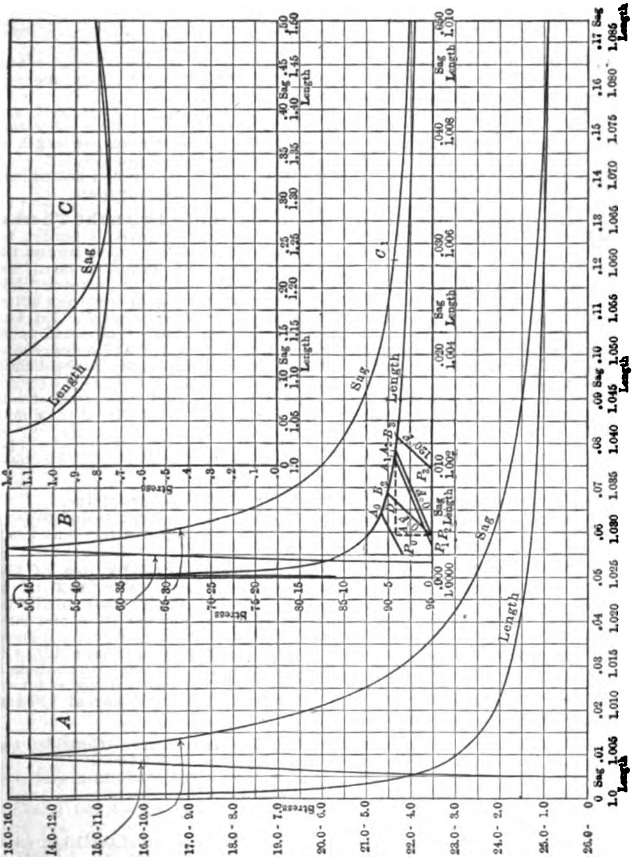


Fig. 49.—Thomas chart.

between sag, length of wire and stress, for a 1-ft. span loaded uniformly with 1 lb., and are based on the equation of the catenary. Three sets of curves, *A*, *B*, and *C*, are given, all plotted to different scales. Curve, *A*, is good for sags from 2 to 15 per cent.; curve *B*, for sags less than 2 per cent.; curve *C*, for very large sags, being especially useful for spans on steeply inclined slopes

* See Bibliography 88.

The chart in Fig. 49 is too small for accurate work but the data from which the curves were plotted may be obtained from the original paper (Bibliography 88).

112. Use of the Thomas chart. By means of these curves, the sag, stress, and length of any span may be easily determined. Divide the allowable stress in the wire, by the span and weight per unit length.

$$t = \frac{T}{w \times S} \quad \text{(lb.)} \qquad (47)$$

where t is the tension in lb. in a 1-ft. span; T the allowable tension in lb. in the actual span; w the weight in lb. per ft. (wire, ice and wind); S the distance in ft. between supports.

From the chart, determine the length and sag corresponding to t, as A_1 and C_1 (Fig. 49). Then the sag and length in the actual span will be the values just obtained multiplied by the actual span in ft. If the sag, or length be given, the other quantities may be found by reversing the process.

With supports at different levels the span may be computed as outlined in Par. 110, and the chart then used for the total equivalent span.

113. The effect of temperature may be determined with the Thomas chart by finding the length of wire, with all stress removed, from Eq. 41, Par. 106, using the stress in the *actual* span, and marking this point on the chart (as P_1, Fig. 49). The elongation of the wire is proportional to the stress, so the straight line P_1A_1 will be the stress-length or "stretch" line for this load and temperature. If the sag is small, P_1 may be less than unity, but the line may be drawn by determining some other point P_e (Eq. 41), and drawing P_eA_e. To determine the sag and stress at any temperature, determine the length of the unstressed wire at zero deg. fahr. (−17.8 deg. cent.) by Eq. 42, Par. 106, as at P_2. For the same loading, the stress-length line at zero deg. fahr., P_2A_2, will be parallel to P_1A_1, and A_2 is the length at zero deg. fahr. of the 1-ft. span. Let this be l_1, and the corresponding stress and sag be t_1 and d_1 respectively. The values in the actual span may then be found.

$$\text{Actual length} = Sl_1 \qquad (48)$$

$$\text{Actual stress} = St_1w' \qquad (49)$$

$$\text{Actual sag} = Sd_1 \qquad (50)$$

Where S is the actual span in ft., and w' the load in lb. per ft. of line.

The length axis may then be marked off in divisions proportional to temperatures, and parallel lines drawn, from which the lengths, stresses and sags may be determined.

114. The effect of ice and wind is determined by use of the Thomas chart as follows: Suppose the values in Par. 113 to be computed for maximum loading (ice and wind). When these loads are removed, the weight per ft. is reduced to w (the weight per ft. of the wire) and the stretch in the wire will be w/w' of what it was before, for a given stress in the 1-ft. span. Therefore, along the abscissa, A_2, make $AD/AA_2 = w/w'$ and draw P_2B_2 through D. The intersection of this line with the length curve will give the results as obtained in Par. 113, substituting w for w'. The temperature lines may be found as before. P_3B_3 being drawn at 120 deg. fahr. (49 deg. cent.) and parallel to P_2B_2.

115. Example of calculation, using Thomas chart. Consider the problem of Par. 106 where $S = 600$ ft., $w' = 1.575$ lb., $T = 4{,}150$ lb.

S is the distance between supports; w' is the weight (including wire, ice, and wind) per unit length; T is the allowable tension.

The tension in a 1-ft. span, having a 1-lb. load, will be $t = 4{,}150/(1.575 \times 600) = 4.395$.

From curve B the sag will be 0.0286 ft. (C_1) and the length 1.00215 ft. (A_1). The true sag and length will be $S = 600 \times 0.0286 = 17.16$ ft. $l = 1.00215 \times 600 = 601.290$ ft. The length unstressed, may be found (Eq. 41, Par. 106).

$$\Delta l = (1.00215 \times 4{,}150)/2{,}659{,}000 = 0.00156 \text{ ft.}$$

$$l_1 = 1.00215 - 0.00156 = 1.00059 \text{ ft.}$$

A line P_1A_1 is drawn from P_1 (length = 1.00059) to A_1, the original point on the length curve. The length at zero deg. fahr. is found from Eq. 42, Par. 106. $l_0 = 1.00059/[1 + 0.0000096 \times (-20)] = 1.00078$ ft. A line P_2A_2 is drawn

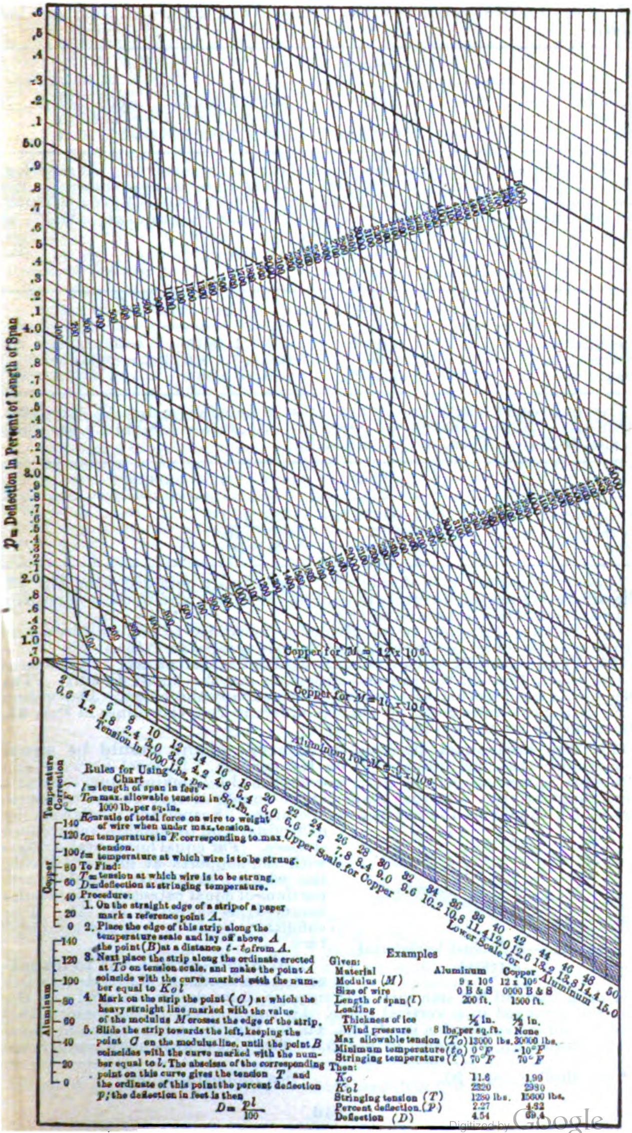


FIG. 50.—Pender and Thomson chart.

(where $P_2 = 1.00078$) parallel to P_1A_1. At zero deg. fahr., with wind and ice loads,

	Chart	Actual
Length................	1.00224 ft.	600 × 1.00224 = 601.344 ft.
Stress................	4.2 lb.	600 × 4.2 × 1.575 = 3,965 lb.
Sag....................	0.0295 ft.	600 × 0.0295 = 17.70 ft.

To find the length, stress and sag when the loads are removed. At zero deg. fahr., no ice, and no wind, $w = 0.641$ lb. At the stress as now shown on the chart of 4.2 lb., the stretch will be $(1.00224 - 1.00078)0.641/1.575 = 0.00059$, and the length $1.00078 + 0.00059 = 1.00137$. Draw P_2B_2 through 1.00137 at the 4.2 lb. ordinate (at D). Graphically

$$AD/AA_2 = 0.641/1.575$$

Then, at zero deg. fahr., no ice or wind,

	Chart	Actual
Length................	1.0015 ft.	600 × 1.0015 = 600.90 ft.
Stress................	5.1 lb.	600 × 5.1 × 0.641 = 1,960 lb.
Sag....................	0.0244 ft.	600 × 0.0244 = 14.6 ft.

The unstressed length at 120 deg. fahr. is found from Eq. 42, Par. **106**. $1.00078(1 + 120 \times 0.0000096) = 1.00193$ ft. At $P_3(l = 1.00193)$ draw P_3B_3 parallel to P_2B_2. Then, at 120 deg. fahr.,

	Chart	Actual
Length................	1.00234 ft.	601.40 ft.
Stress................	4.1 lb.	1,577 lb.
Sag....................	0.031	18.6 ft.

These results check very closely with those already obtained using Fig. 45. The differences are due to errors in reading the charts, and to the assumption of a parabola rather than a catenary.

The distance P_1P_3 may be subdivided proportional to temperatures, and results may be found by drawing stretch lines parallel to P_2B_2.

116. Pender and Thomson tension and deflection chart.* By means of this chart, Fig. 50, the sag and deflection may be found directly. The rules for its use, together with examples, accompany the chart. The values of K_s in the examples given are slightly different from the values in Par. **99**. The problems are worked in lb. per sq. in.

117. The horizontal stresses in adjacent spans should be equal to minimize the longitudinal pull on the support. In level country and with equal spans this may be easily accomplished by making equal sags at a given temperature. Unequal spans can be equalized only at one temperature which should be the average temperature. Suspension insulators, by deflecting, tend to equalize unbalanced stresses. For equal horizontal stresses with the supports at different levels, the wire in each span should form portions of equal catenaries (parabolas assumed) as shown in Fig. 51. This condition holds for but one temperature.

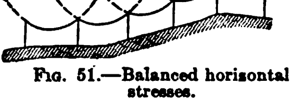


Fig. 51.—Balanced horizontal stresses.

118. Short-circuit due to unbalanced ice loads.† Ice loads on wires may drop from all but one span. If suspension insulators are used and the lines are arranged in a vertical plane, this span, aided by the longitudinal deflection of the suspension insulators, will sag heavily and the adjacent spans will be drawn up, as shown in Fig. 52. The phase wires may readily ap-

* See Bibliography 20.

† See Bibliography 90.

proach within easy arcing distance of one another or even touch in all three spans, thus causing a short-circuit. Also, if one wire alone loses its ice load its whipping up may cause short circuit. This may be partially overcome by the use of shorter spans, more anchor towers, or better, by offsetting the middle conductor, thus making an isosceles triangle arrangement (see Fig. 64, isosceles triangle).

STRENGTH OF SUPPORTING MEMBERS

119. Insulators and pins must be designed to withstand the weight of conductor and any ice, sleet or snow load; the wind pressure acting on the conductor, and any other transverse force produced by a change in direction of the line; the longitudinal force due to unbalanced horizontal stresses in adjacent spans; the longitudinal stress occasioned by the breaking of a line conductor. It is desirable that they withstand a stress equal to the elastic limit of the conductor, when exerted in any direction in a plane perpendicular to the axis of the pin.

120. The cross arms must be designed to withstand the resultant of the forces of Par. **119**, and the dead weight of insulators and attachment. In addition, the cross arms must be secured to the pole so that they will not be wrenched loose by the turning moment which follows the breaking of one or more conductors on the same side of the pole. The results of "Strength Tests of Cross Arms," made by T. R. C. Wilson, are published in U. S. Government Forest Service Circular 204.

121. The supporting structure must be designed to bear the compressive stress, due to its own weight and that of conductors, loads, insulators, cross arms and attachments; the transverse forces due to wind on conductors and supporting structure and also those occasioned by change in direction of the line; the longitudinal stresses due to unbalanced horizontal stresses in adjacent spans; stresses caused by the breaking of one or more conductors.

Wooden, steel, or concrete poles, designed to withstand the horizontal forces, will have the necessary compressive strength to bear vertical loads. With towers of the light wind-mill type, this matter should be carefully considered. Where extreme rigidity at small expense is desired, the structure must be made of many light members, resulting in a more complicated tower, and a shorter life, due to the greater proportionate corrosion. A less rigid tower made of fewer but heavier members will frequently answer the purpose, will be less expensive and of longer life.

122. The transverse force due to the wind on the conductors should be assumed as 8 lb. per sq. ft.* of the projected conductor and ice area. A 0.5-in. (1.27 cm.) layer of ice is usually assumed. Values of the resulting pressure may be found in Par. **99**. The pressure on the pole or tower may be

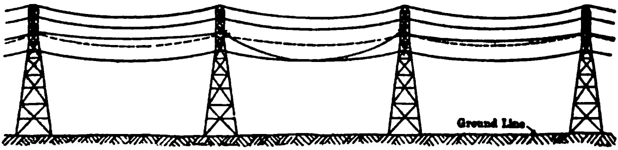


FIG. 52.—Ice loading on single span.

assumed to be 13 lb. per sq. ft. on one and one-half times the projected area of latticed structures. (Also see Sec. 12, Par. **166**.) The overturning moment may be greater without the ice load. Both conditions should be calculated. The stress due to an angle in the line may be readily computed by a simple resolution of the maximum stresses already calculated for the spans. The longitudinal forces due to unbalanced horizontal stresses in adjacent spans, should be small in a well-designed line, and may be determined if the stresses in each span at different temperatures are known. There is some question as to how many conductors may be assumed to be broken at one time. If

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A.

a line is carefully strung with no kinks or abrasions in the wires, and if the ends of the insulator clamps are well rounded, there is small chance of a line conductor breaking under ordinary load conditions. As an extra precaution, however, anchor towers are used at frequent intervals, and are so designed as to safely withstand the simultaneous breaking of several conductors. Where suspension insulators are used, the insulator string is thrown in the unbroken side of the span, hence the increased sag decreases the ultimate pull. The force due to the jerk at the time of breaking is quite severe, and no reduction in the allowable stress should be made even if suspension insulators be used. The line structures should have a factor of safety of from 2 to 4, according to the importance of the line, the assumptions made in the design, and to the local conditions.

123. A wooden pole should be a cubic parabola, to use the material to the best advantage. As this would be impractical, a truncated cone, having the diameter of the top two-thirds of that of the bottom, is the best approximation. With this shape the pole will break theoretically at the ground line.

The allowable horizontal pull, P, on the pole may be calculated

$$P = \frac{T}{n}\,\frac{\pi d_2^3}{32l} \quad \text{(lb.) for a round pole.} \qquad (51)$$

$$P = \frac{T}{n}\,\frac{d_2^3}{6l} \quad \text{(lb.) for a square pole.} \qquad (52)$$

assuming that d_2, the ground diameter in inches, is one and one-half times the top diameter. In these formulæ n is the factor of safety, l the length of the pole in inches, and T the tensile strength or modulus of rupture of the pole material, values of which are given in Sec. 12, Par. 164. The factor of safety should be at least 5 or 6 for wood.

124. The stresses in steel poles cannot readily be calculated due to the complications introduced by lattice work, cross bracing, etc., and the engineer is more or less dependent upon actual tests and manufacturers' guarantees for data relative to the load that a given structure may be expected to carry safely. Steel poles, for the same weight and material, have much less torsional strength than steel towers. Although they may be satisfactory under normal conditions of balanced load, their factor of safety may be much reduced if one or more wires on the same side of the pole should break.

125. The stresses in concrete poles may be computed approximately, knowing the moment of inertia of the top and bottom sections, the cross-section and tensile strength of the reinforcing steel, and the compressive strength of the concrete. Up to the present time, however, very little has been done along this line, and purchasers and manufacturers have been dependent upon actual tests of full-sized poles. The usual mixture of Portland cement (1 : 2 : 4, cement, sand and gravel) has a compressive strength after 7 days of 900 lb.; after 1 month, 2,400 lb.; after 3 months, 3,100 lb.; after 6 months, 4,400 lb. all in lb. per sq. in.

126. Stresses in guys and anchors may be readily computed if the magnitude, direction, and point of application of the resultant force acting on the pole are known. The position of the anchor is determined, and the stress in the guy and anchor can be calculated by the well-known laws governing the composition and resolution of forces. The table in Sec. 4 gives the diameters, strengths and weights of 7-strand galvanized steel wire, such as would be used for guys.

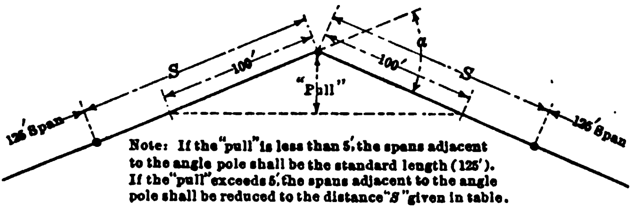
127. The stresses in towers may be computed by the well-known laws of statics. As steel fails in compression rather than in tension the compressive strength of the long unsupported members should be carefully checked by the well-known column formulæ. The ratio of l/r, where l is the length of the unsupported compression member, and r is the radius of gyration of its section, should seldom exceed 150. R. D. Coombs* shows, in the following table, that by using a different angle iron of less cross-sectional area the strength of the main compression members is nearly doubled. This should not be carried too far, however, if a reasonable life is expected. It is

* Letter to *Elect. World*, Vol. LVII (1913), p. 544.

generally conceded that ¼ in. for the legs and $\frac{3}{16}$ in. for the secondary members should be the minimum permissible thicknesses of metal.

Section	Area, sq. in.	Length, ft.	l/r	Breaking strength, lb./sq. in.	Total breaking strength, lb.
4 in. by 4 in. by ¾ in. angle.	5.44	13	202	12,000	65,200
5 in. by 5 in. by $\frac{9}{16}$ in. angle.	5.31	13	159	16,000	85,000
6 in. by 6 in. by $\frac{7}{16}$ in. angle.	5.06	13	131	20,000	101,200

128. Location of poles and side guys may be determined by use of the table given with Fig. 53. The term "pull" refers to the deviation of the line and is equal to the distance from the pole to the straight line joining points on the line 100 ft. each side of the pole.



Angle a	"Pull" in Feet	Span S	No. of 6000 Lb. Side Guys		
			1 Arm 6 Wires	2 Arms 12 Wires	3 Arms 18 Wires
Less than 6°	Less than 5'	125'	None	None	None
6°-11°	5'-10'	115'	None	1	1
11°-15°	10'-13'	105'	1	1	1
15°-22°	13'-19'	95'	1	1	2
22°-30°	19'-26'	85'	1	1	2
Over-30°	Over-26'	75'	1	2	2

Fig. 53.—Location of side guys.

129. Flexible towers* are used with a view to decreasing the line cost; their design is based on the fact that with equal spans and sags on both sides of the tower, the stresses in the direction of the line are balanced. The towers are not intended to carry longitudinal stresses but are designed to withstand any transverse stresses that may occur. They are held in position by the conductors, if pin insulators are used. When suspension insulators are used, a heavy steel galvanized ground wire is necessary to keep the towers in position. If a conductor breaks, the tower will deflect until the increased sag in the conductors and ground wire on the other side of the pole compensates for the unbalanced forces due to breaking. The towers should be designed to deflect from 12 in. to 24 in. without being permanently deformed. The unbalanced pull will not only be taken up by the tower at which the break occurs, but will be gradually absorbed by the other structures in the line. If a tower is actually pulled over, it is not a very serious matter because of its low initial cost, and ease with which another may be erected. About every mile there should be an anchor tower. Methods of computing the deflections and stresses in flexible towers have been published (see Bibliography 91 and 99). Such towers should be designed to carry from $\frac{1}{10}$ to $\frac{1}{20}$

* See Bibliography 91, 99.

the load for rigid towers and with this load should not be stressed beyond the elastic limit.

130. Anchor towers, when used in connection with flexible towers, should be designed to withstand the stress produced by the breaking of all the conductors on one side, even when the line is loaded under the most unfavorable conditions. Under these circumstances, there should be no yielding of the foundations, and the tower should not be stressed beyond the elastic limit. With a line constructed entirely of rigid towers, these conditions may be somewhat modified, as the intermediate towers themselves are designed to take care of one or two broken conductors.

FUNDAMENTAL CONSIDERATIONS OF LINE CONSTRUCTION

131. The line location should in general be direct. Detours are often necessary, to avoid sections subject to severe lightning, to avoid country that may be inaccessible, to avoid swamps or hills that will make the construction difficult and costly. It may be necessary to pass near towns or villages where connected load may be profitable.

The most direct right of way cannot always be obtained at a reasonable figure. County plat maps or U. S. Topographical Survey maps should be carefully studied with special reference to the villages along the route, the proximity of roads, hence accessibility, and the topography that will permit standard structures and spans. When the location is roughly determined, a small surveying party should go over the route, make a profile, locate swamps, streams, railroads, other power, telephone or telegraph lines, and should note the character of ground and probable location of supports. Profiles should be made 100 ft. on each side of the centre line, as well as at the centre line, since a supporting structure might be advantageously located a short distance from the centre, if an abrupt change in profile made an increased height of structure necessary to secure the proper clearance.

132. A private right of way is necessary for most high-voltage transmission lines, as the risk to life and property from high voltages is too great to permit circuits to be carried along highways. The width should be so chosen that no tree or other object located outside the right of way can fall across lines. Where very tall trees do occur, they should be bought and removed. It is advantageous to secure the right of way near a highway, as the construction materials can be easily hauled to the tower locations. The line will also be more accessible for repairs, and patrolling is facilitated. Where the line must pass over private property, if possible it should follow the division lines.

133. The proper form of contract should be executed, when the consent of the proper parties is obtained. In many cases, as in sparsely settled districts, the land may be bought outright. The best practice, however, is to acquire perpetual right under easement, or for a term of years, with the right to renew the contract at the expiration of this time. Legal questions of importance should be settled by counsel. (Also see Bibliography 113–115 incl.)

134. The conductor material will be either copper or aluminum and the relative advantages and disadvantages of these are described in Par. 44 to 47 incl.

135. The spans for any line will usually vary in length. For level or undulating country a standard span, ranging from 100 to 800 ft. may be used. In hilly or broken country the support must be erected at advantageous points regardless of the varied lengths of spans that may result. With increased length of span, the number of structures and insulators (hence maintenance charges) is decreased, but the height of tower is increased. The cost of the tower may vary as the cube of the height. Other things being equal, the span should be so selected that the total line cost is a minimum. (See Par. 224.)

136. Extra long spans must be anchored at each end. To secure sufficient tensile strength in the insulator, it is often necessary to connect a number of strings of suspension insulators in parallel. In order that each string may take its own share of the load, a *strain yoke* (Fig. 32) is used.

137. The conductor spacing should be such that the wires cannot swing within arcing distance of one another in the span. When suspension insulators are used, the wires at the insulators should not be able to swing within arcing distance of the pole or tower. Allow a 45-deg. deflection from the vertical for copper and 60-deg. deflection for aluminum under the worst conditions of loading. Assuming that one of the phase conductors hangs vertical and that the other swings to the above angle, no two conductors must come within arcing distance of each other. Fig. 54* shows the usual spacings employed.

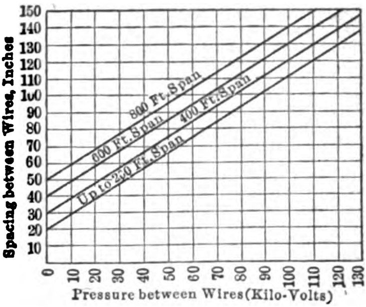


Fig. 54.—Approximate conductor spacing.

138. Weighted conductors. Where small conductors are used with suspension insulators it may be impracticable to increase the spacing by an amount sufficient to prevent the wires swinging more than 60 deg. By hanging a weight on the end of the insulator string, the maximum swing may be kept within this limit. The table in Par. 139, presented by H. W. Buck,† gives the necessary weight per ft. of conductor to bring the deflection to 60 deg. Such weights also tend to prevent the propagation of mechanical waves longitudinally.

139. Deflections and counterweights at various wind pressures

Size conductor A.W.G.	Wind pressure lb. per sq. ft.	Angular deflection without weight	Auxiliary weight per ft. conductor necessary for 60 deg. deflection
Stranded copper			
4	15 lb.	66 deg.	0.041 lb.
3	15 lb.	63 deg.	0.028 lb.
2	15 lb.	60 deg.	0.000 lb.
Stranded aluminum			
2	15 lb.	81 deg.	0.156 lb.
1	15 lb.	79 deg.	0.161 lb.
0	15 lb.	78 deg.	0.171 lb.
00	15 lb.	77 deg.	0.182 lb.
000	15 lb.	75 deg.	0.186 lb.
0000	15 lb.	74 deg.	0.196 lb.
250000	15 lb.	72 deg.	0.190 lb.
300000	15 lb.	71 deg.	0.177 lb.
400000	15 lb.	68 deg.	0.158 lb.
500000	15 lb.	66 deg.	0.125 lb.

140. The type of line construction should be decided upon after the location of the line has been determined. The choice lies between wooden poles, steel poles, concrete poles, rigid steel towers, and the flexible tower system.

When selecting the type of line, the locality through which the line passes, the initial cost, the reliability, the ultimate life, and the maintenance should all be carefully considered.

141. The poles or towers should be staked out by the surveying party; following should come a digging party provided with a steel or wooden template by which the corner holes may be located. This party should be followed by another to install the concrete foundations, if such are to be used, and then by the erecting gang.

* Bibliography 3. † Bibliography 43.

POLES

142. Wooden poles, though apparently the cheapest form of construction, should seldom be used, except on short or relatively unimportant lines. The life of untreated poles (Par. **143**) ranges from 6 to 15 years, depending on the type of wood and the climatic conditions. When treated, their life may reach 20 years or more. Though wooden poles and cross arms give better insulation (per pole) to the system, they may be charred or badly burned by leakage currents or by conductors that fall from insulators. Although less likely to be struck by lightning, they are usually shattered or badly damaged when struck. The large number of poles required per unit length of line, decreases the (total) insulation of the system and increases the number of insulator troubles in direct proportion.

Wooden poles are still used to a considerable extent in transmission. Sixty per cent. of the wooden poles used in the United States are cedar and 20 per cent. are chestnut. On the western coast, redwood is used to a great extent; other woods, such as pine, cypress, juniper, Douglass fir, tamarack, and oak are occasionally used. Cedar, owing to its lightness and to its long life, which varies from 10 to 30 years depending on the climate and soil, is the most common pole timber, although the supply in the eastern states is practically exhausted. Chestnut, though heavy and not as long-lived as cedar, is used in the eastern and middle states. Redwood poles have a long life, and are usually sawed from large trees. Pine, though heavy in resinous products, rots very rapidly and does not last more than 4 or 5 years unless treated. Cypress stands very well in its native climate, but is short lived in the north. The other woods are used only occasionally though the present methods of pole treatment will widely increase the timber available for poles.

143. Average life of untreated poles.

Cedar	15 years	Juniper	8.5 years
Chestnut	12 years	Pine	6.5 years
Cypress	9 years		

144. Preservative treatment of poles is attracting much attention among large users, as the available supply of timber is constantly decreasing and the price rising. Two preservatives are in general use: creosote and zinc chloride, though copper sulphate has also been used to some extent. Creosote, though expensive, is the most satisfactory preservative, as it does not contain water nor is it affected by water, and has valuable antiseptic properties. Zinc chloride is far cheaper, but as it is carried into the wood poles in a water solution, the water must be dried out again, and the pole will readily absorb moisture later.

145. Brush treatment of seasoned poles consists of two applications of hot creosote (220 deg. fahr.) about 24 hr. apart. The treatment should extend at least 2 ft. above the ground line, and the pole should be very dry at the time of application. This is the simplest form of treatment; it costs from 15 to 40 cents per pole, and increases the life 2 to 3 years.

146. In the open tank method of pole treatment the dry pole butts are placed in tanks containing hot creosote at 220 deg. fahr. (105 deg. cent.), for from 4 to 8 hr., and are then allowed to stand in a "cold" bath between 100 and 150 deg. fahr. (38 and 66 deg. cent.) from 2 to 4 hr. Where the top of the pole is subject to rot, as in the south, the whole pole may be treated by this process. The penetration is about three times as great as with the brush treatment, and the cost per pole ranges from \$0.75 to \$1.25, depending on the absorbent properties of the wood. The estimated increase of life is 20 to 25 years. (See Par. **230.**)

147. In the full-cell (Bethel) process of pole treatment, the poles are placed in an iron cylinder, about 125 ft. long and 8 or 9 ft. in diameter. Live steam at 20 lb. pressure is admitted and maintained for several hours. The steam is then blown out of the cylinder, and pumps exhaust as much of the air as possible. At the end of the vacuum period, the preservative at about 150 deg. fahr. (66 deg. cent.) is admitted and is forced into the wood under pressure. This insures a deep penetration of the preservative and a long life to the pole. No data as to the life of such poles are available, but poles in England under similar treatment are still in service at the end of 60 years. The cost is estimated at \$1.10 for a 25-ft. pine pole and \$2.45 for a 35-ft. pole, depending upon the amount of liquid absorbed.

148. The burnettised creosoted butt process of pole preservation is similar to the full-cell method, except that zinc chloride is always used in the tank. The butt, to a foot or two above the ground line, is then impregnated to a slight depth with creosote under pressure. This prevents the zinc chloride from leeching out, and is much cheaper than a complete treatment of creosote.

149. Tabulation of pole cost, per-annum pole cost, and cost of butt treatment—western red cedar*

Price of pole	8 in.–35 ft.	8 in.–40 ft.	8 in.–45 ft.	8 in.–50 ft.	8 in.–55 ft.	8 in.–50 ft.
F.O.B. Central Iowa.........	8.75	10.15	13.20	15.45	17.70	19.90
Cost of setting.............	3.89	4.77	6.05	6.85	7.61	9.08
Total................	$12.64	$14.92	$19.25	$22.30	$25.31	$28.98
Using U. S. Aver. 12 yrs. life..	......	......	......	......	......	......
Cost per annum............	1.05	1.24	1.60	1.86	2.11	2.42
Cost of Butt treatment.....	......	......	......	......	......	......
†Specification "A".........	1.50	1.75	2.00	2.50	3.00	3.50
‡Specification "AA"........	1.20	1.35	1.60	1.85	2.00	2.50
No. years added life to pay entire cost of treatment....	......	......	......	......	......	......
†Specification "A".........	1.4	1.4	1.2	1.3	1.4	1.4
‡Specification "AA"........	1.1	1.08	1.0	1.0	0.9	1.0
Probable increase of life................10 to 15 years.						

150. Char and tar the butts of poles before setting if they are not creosoted. This is done by placing the pole upon a skid over a slow fire, gradually revolving it until the butt to about 1 ft. above ground level is thoroughly charred. While hot it is given two or three coats of tar with a stiff brush and is then set. This will increase its life perhaps a year.

151. Wooden pole specifications. Each pole should be of good quality of live growing timber free from knots and shakes, and sound in all respects; the grain should be close and hard with the annular rings closely pitched and with a sound heart. Each pole should be straight and well proportioned, free from all objectionable bends; should have the natural butt of the tree and should be squarely sawn, without trimming. Poles should vary in size by lengths of about 5 ft.; they should be cut between the first of November and the first of March, and after being felled they should be carefully trimmed, the bark removed and the butt squared. The poles should be piled with open spaces between, raised from the ground and allowed to season for at least a year or more. After seasoning, the top of each pole should be roofed and the suitable number of gains cut for the cross arms. The specifications vary with the kind of wood.

152. §Depth of wooden poles in the ground

Length over all (ft.)	Depth for straight line (ft.)	Depth curves, corners and points of extra strain (ft.)	Length over all (ft.)	Depth for straight line (ft.)	Depth, curves, corners and points of extra strain (ft.)
30	5.0	6.0	60	7.0	7.5
35	5.5	6.0	65	7.5	8.0
40	6.0	6.5	70	7.5	8.0
45	6.5	7.0	75	8.0	8.5
50	6.5	7.0	80	8.0	8.5
55	7.0	7.5			

* Page & Hill, Minneapolis, Minn.
† Specification A. High grade of carbolinium.
‡ Specification AA. Highest grade of creosote oil.
§ Report of Committee on Overhead Line Construction, N. E. L. A.

153. Wooden-pole settings. All holes should be dug large enough to admit the pole without forcing, and should have the same diameter at the top as at the bottom. The pole may be "piked" into position, but it is usually much cheaper to employ a gin wagon, and to use the team for raising the pole. Forty to fifty poles per day can be thus raised, with only two linemen and a teamster. Poles should be set to stand perpendicular when the line is completed, but at terminals and curves the pole can be slightly inclined against the pull. When the pole is in position, only one shovel should be used in filling the hole, while three tampers pack the earth. The earth should be piled about a foot higher than the ground level.

154. Crib-bracing can be used, where the poles are set in loose, or marshy soils. For further discussion see Sec. 12, Par. 173.

155. The sand barrel is a useful expedient in digging holes or setting poles in sandy or loose soils. See Sec. 12, Par. 173.

156. A concrete foundation may be used for wooden poles where exceptional stability is desired. This concrete filling should extend at least a foot from the pole on all sides, should be carried above the ground line and bevelled to shed water, and should consist of one part Portland cement, three parts sand, and six parts broken stone or clean gravel, mixed wet. (See Fig. 47, Sec. 12.)

157. Special pole settings. In marshy ground, more elaborate devices, as shown in Fig. 47, Sec. 12, are often required for a satisfactory foundation.

158. Pole repairs. Wooden poles usually fail by decay at the ground line. If they are long enough, they may be sawed off and set again. A very satisfactory way of repairing such poles without disturbing them is to drive U-shaped rods in the poles at the ground line, as shown in Fig. 55, and fill the space with concrete. Poles reinforced in this way are said to be stronger than when new, and their life is greatly prolonged.

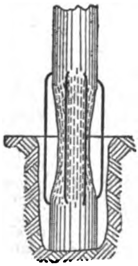


Fig. 55.—Pole repairing at ground line.

159. Steel poles cost but little more than wooden poles, when the erection and labor costs are considered, require no assembling at the point of erection, are not injured by fire, birds and insects, and are not damaged by lightning. Their field is the moderate line, with spans from 250 to 350 ft. in length running along roadways, or where space is limited. Their life is from 25 to 50 years, depending upon their upkeep.

For heavier circuits, they lack the necessary horizontal and torsional strength. The more common types are the tubular, made in sections, the diamond, the latticed-girder type, and the patented types, of which the tripartite is an example. Of these, the low weight efficiency of the first two and the difficulty with which the insides are protected from corrosion make them doubtful for high voltage transmission. The last two are extensively used. Steel poles have reached a much higher state of development abroad than in the United States.

160. The tripartite steel pole, shown in Fig. 78, consists of three continuous U parts, the dimensions of which are given in Par. 234. These are held together by "spreaders" and "collars" bolted together. The strength and rigidity of the pole can be increased by increasing the number of these members, and the pole is everywhere accessible, so that it can be readily painted and inspected. Tripartite poles may be shipped either assembled or "knocked down." They can be assembled by unskilled labor. In ordinary soil, and with a concrete foundation, it has been asserted that the poles need only be buried for one-tenth their length.

161. Steel poles should invariably have a concrete foundation, in order to obtain adequate bearing area. Steel-pole foundations are shown in Fig. 56.

162. Concrete poles are coming to be used for high-voltage transmission. Their first cost and maintenance are very low, they are not injured by the attacks of insects, fire, etc., and, apparently, are not damaged by lightning. They can be used in the most accessible places only, as they must be constructed, in most cases when erected. Their weight results in high transportation costs. Though there are as yet no data regarding their life, it is probably considerable. Two poles, 150 ft. (45.8 m.) high, 11 in. (28.0 cm.) square at the top, 31 in. (78.7 cm.) square at the bottom, and capable of withstanding, without guys, a 2,000-lb. horizontal pull at the top, have been successfully installed by the Hamilton Power, Light and Traction Co., at the Welland Canal Crossing.

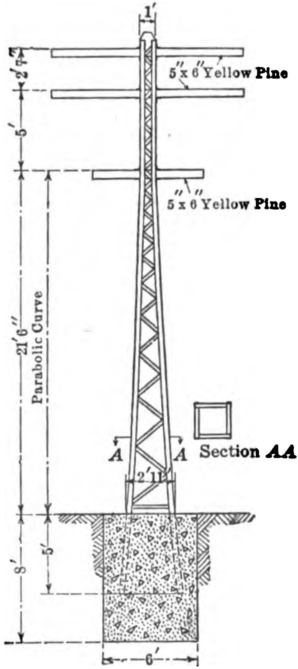


FIG. 56.—Typical steel pole.

STEEL TOWERS

163. Advantages. Steel towers in the open country, and for trunk lines of large capacity and long spans, are unquestionably the best type of construction. The two systems, the rigid and flexible, are both in general use, ard the latter is becoming more used. The flexible system compares favorably even with wooden poles, as far as first cost is concerned, since most of the work on it can be done by unskilled labor. The flexible towers as a rule come all assembled.

Towers are the strongest of all supports for their weight, not only under direct horizontal pull, but under torsion as well. They are free from injury by fire, attacks of insects, birds, etc., and are not wrecked by lightning. They have a life of from 25 to 50 years and possibly longer, when properly maintained.

164. The design of a steel tower is largely the work of the structural engineer, but the electrical engineer should be able to specify the various stresses that the tower must withstand, the height, length of cross arm, etc., and be able to check the design by calculating the stresses in the various members. Towers made with members which are too light, deteriorate very rapidly when corrosion once begins, and the cost of painting such towers, should this form of protection be found necessary, will be high. Members should never be much less than 3/16 in. (0.48 cm.) thick. Fig. 57 shows a standard tower, Ontario Hydroelectric Commission, and Fig. 58 shows a flexible tower.

165. Protection against corrosion is obtained by painting, galvanizing and sherardizing. For proper protection, paint must be applied every 2 or 3 years, and if the tower consists of a large number of small members, the expense of painting may be prohibitive. Where the structures consist of a few members, painting may be economically used. One coat of hot dip galvanizing well applied offers protection, for perhaps 30 years, except at the ground line. A shell of concrete at the ground line may increase the life of the tower materially. Sherardizing or "dry galvanizing," gives a uniform coating at a low cost, and offers a high resistance to wear and abrasion. If the zinc is removed by abrasion or bending, the zinc-iron alloy still offers protection.

166. Erection of the tower is ordinarily by gin poles or by shear poles. The former device consists of a wooden mast or a frame which must be set outside the tower base. The butt must be firmly anchored, and the pole strongly guyed, especially in the direction of the back line.

The shear pole supports the raising line and affords a means of raising the tower by a straight away pull. The straight shear pole has a groove at the top, over which the raising line passes. The shear pole may be lowered to the ground when the raising line clears the top.

Heavy towers must often be braced at the base by some form of strut, to reinforce the tower against the stresses due to erection.

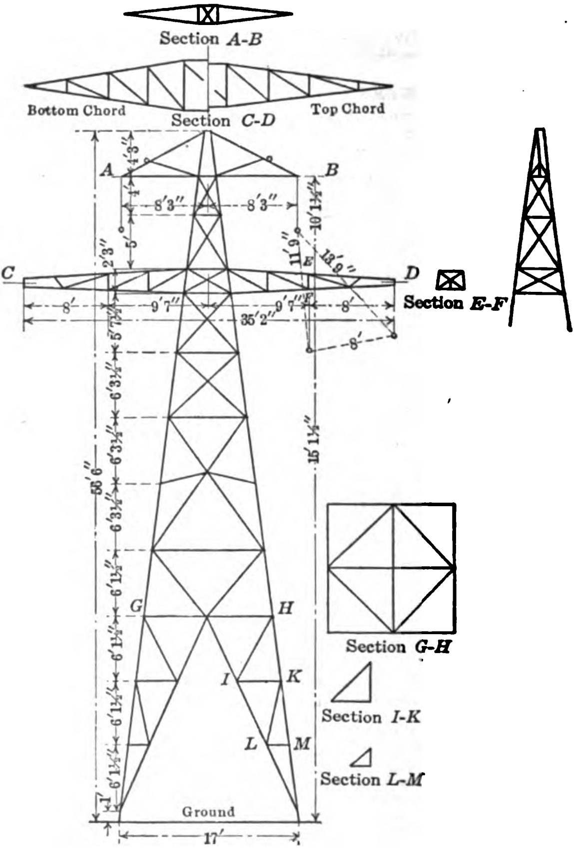


FIG. 57.—Rigid steel tower.

167. Special structures are often required for transpositions, and at points where the line crosses a river, a bay, or a railroad. They are also used where the line makes a sharp angle; where the line is dead-ended; and to allow the installation of line switches, protective apparatus, or outdoor substations or switching stations. Special structures are usually very expensive as compared with the standard towers, and where one of the latter will answer the purpose, it should be used.

168. Steel towers may be set directly in the ground, in which case, the steel should be well protected by galvanizing. The footings are usually made by bolting an angle or channel iron directly to the bases of the anchor stubs. For the heavier structures, a built-up grillage is necessary. Fig. 59 shows a concrete anchor.

POLE ACCESSORIES

169. Wooden cross arms may be of either Norway or yellow pine, long-leaf yellow pine, Washington fir, though other woods such as cypress, oak, spruce and cedar are used to a limited extent. Long-leaf yellow pine, and Washington fir are the best woods for high-class construction, the average life untreated being 8 and 11 years. Wooden cross arms are being used in connection with steel or concrete poles. In certain localities, cross arms are being treated to prevent decay. The full-cell treatment (see Par. 147) is usually employed, although the initial treatment by live steam is found unnecessary if the arms have been well seasoned. Cross arms should be seasoned for at least 3 months and painted with two coats of white lead paint, unless properly treated with a suitable preservative. For the voltages employed in transmission work, there has been no standard size of cross arm adopted. In the lighter construction, the standard electric light cross arm, 3¼ in.×4¼ in. (8.25 cm.×10.8 cm.) often answers the purpose. For heavier work, sizes ranging from 4 in.×5 in. (10.2 cm.×12.7 cm.) to 5 in. × 7 in. (12.7 cm.× 17.8 cm.) are used.

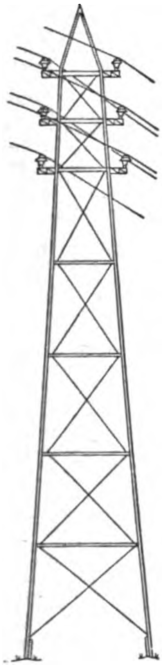


Fig. 58.—Flexible tower.

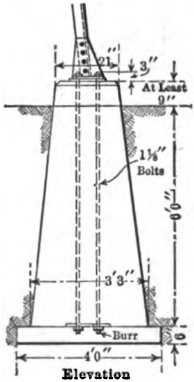


Fig. 59.—Concrete anchor for steel tower.

Cross arms should be snugly fitted into a 0.75-in. (1.9 cm.) gain. Unless the pole previous to erection has been treated by some preserving process, the gain should be given a good coat of mineral paint. Cross arms may be secured to the pole by two lag bolts, though in the best construction the cross arm is supported with a through bolt and braces. The cross arms on alternate poles should face in opposite directions.

170. Cross-arm braces are discussed in Sec. 12, Par. 179.

171. Double cross arms should be used where excessive stresses may occur such as at line terminals, corners, curves, and where extra precautions against life or property hazard are required, as at railroad, highway, or low-voltage line crossings. See Sec. 12, Par. 178.

172. The wish-bone and bo-arrow cross arms, made of angle iron, are used for wooden-pole, single-circuit construction. The ground wire is carried on the bayonet, at the tip of the pole. See Fig. 60.

173. Insulator pins are made of wood, of steel and of steel in combination with porcelain. Although the wooden pin adds to the insulation, the dielectric stress in the insulator is so localized, especially in wet weather, that little is gained; wood deteriorates rapidly, being carbonized by leakage currents, and eaten by nitric acid which forms in the presence of high voltages. Furthermore, a wooden pin is weaker mechanically than a steel pin, hence requires a larger hole in the cross arm, and thus decreases the mechanical strength of the arm. **Wooden pins** should be used only for the lightest construction, and with voltages not exceeding 20,000. They are made from locust, oak, maple, hickory and eucalyptus, and should have a fine straight grain, free from knots.

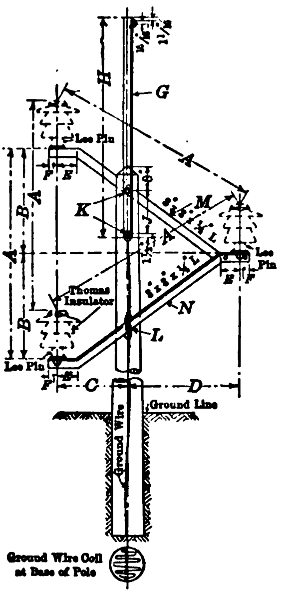


FIG. 60.—Wish-bone cross arm.

174. A wooden pin with a centre bolt is common. The bolt serves as a cross-arm fastening and the wooden portion holds the insulator. The advantage of this over a straight wooden pin is that a much smaller cross-arm hole is required.

175. Steel pins may be of steel, malleable iron, cast iron, cast steel, or combinations of these. They are much stronger than wood pins, and when well galvanized have a much longer life. They are either cemented directly into the insulator, with Portland cement, or capped with either a wooden or a lead thimble, which is screwed into the porcelain. The difficulty of replacing such insulators has been obviated by providing a steel thimble, threaded inside, which is cemented directly into the insulator, and to which the metal pin is screwed. A steel pin designed with a large shoulder which rests on the cross arm, decreases the size of cross-arm hole necessary.

176. Clamp pins are designed to eliminate the weakening of the cross arm due to removal of valuable material when holes are drilled for the insulator pins. Furthermore, they reduce the concentration of leakage current, and hence the burning and charring of the wood.

177. Insulator pins with a porcelain base (lead or wood thimble) prevent an arc from striking from the conductor to the pin, have a long life, and are mechanically strong. Even though the porcelain cracks, the pin will only bend and the insulator will not fall.

178. Method of hanging suspension insulators. When suspension insulators are used, the breaking of a conductor pulls the string into a nearly horizontal position. The tower connection at top of suspension string should be made as snug as possible to the under side of the cross arm, to avoid torsion on the arm.

179. A tie wire or a clamp may be used to fasten the conductor to the insulator. The main function of a tie is to hold the conductor securely to the insulator, and prevent it from creeping from one span to the next. Its form depends largely on the type of insulator used. Aluminum tie wires should be used with aluminum conductors, as contact with other metals may form a galvanic couple and produce corrosion. Furthermore, a harder metal will injure the soft aluminum. A large bearing area must be allowed where aluminum is used, as it is softer than iron or copper

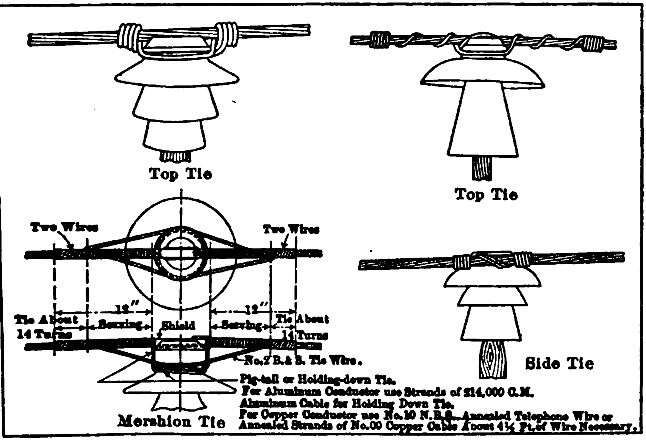


FIG. 61.—Insulator ties.

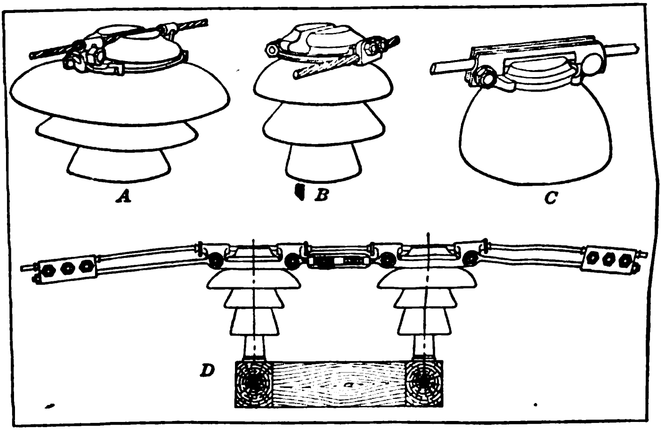


FIG. 62.—Insulator clamps.

No. 2, No. 3 and No. 4 A.W.G. have been found most satisfactory for aluminum ties. A few typical insulator ties are shown in Fig. 61, and Fig. 62 shows two Clarke insulator clamps.

180. Cable clamps for suspension insulators may be designed either to allow the cable to slip through and equalize the horizontal stresses in adjacent spans, or to hold the cable to approximately breaking loads, in case of a broken span. The clamp should be designed with a liberal cable seat and long, free, well-rounded approaches, so that the conductor will not be permanently injured if a span breaks, and the string is thus thrown temporarily into use as a strain insulator.

181. Suspension strain or anchorage clamps should admit the wire from the span without producing any kinks, or sharp bends, and should have a long, liberal bearing surface. The cable should not be held by such devices as U or J bolts, but rather by flat smooth surfaces.

POLE BRACES, GUYS, AND ANCHORS

182. Pole braces consist of shorter and lighter poles bolted against the main pole. They are sometimes preferable to guying, especially where a narrow right of way does not allow a guy wire to be used. The brace can be designed to take tension and compression; assist the main pole to resist the stresses in the direction of the line, and is not easily damaged maliciously. Owing to the increasing cost of poles, the cost of erection, and the liability of destruction by grass fires, guys are ordinarily to be preferred. Fig. 63 shows standard methods of bracing. The bearing area of

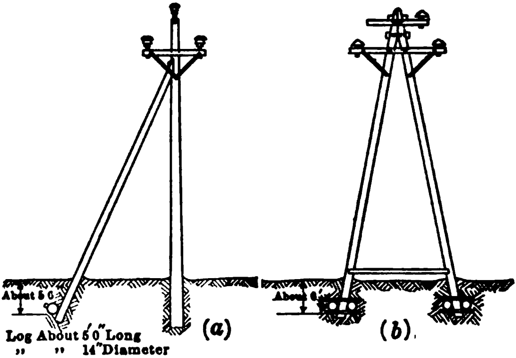


Fig. 63.—Pole brace. A-frame.

the soil can be increased by fastening planks to the base, or by placing a flat rock under the butt. A log bolted to the butt also permits the brace to take tension. An A frame, or double-pole shown in Fig. 63b may be substituted for the braced pole.

183. Guys are necessary to assist the supporting structure in resisting such unbalanced stresses as are produced at angles, terminals or on sloping ground. They are also used to give the line increased stability in places where a failure is very undesirable, where a hazard to life or property must be avoided, as at a railroad crossing, or where a line runs parallel to or crosses a highway. Steel towers are seldom guyed, their resistance to overturning being sufficiently large (also see Sec. 12, Par. 174, 175, 176).

Well-galvanized steel strand, a table concerning which is given in Sec. 4, should be used for guys.

184. Straight-line guying is used to give increased stability to the line. Approximately every twentieth pole should be guyed, in the direction of the line, either by head or anchor guys, and, if possible should be side guyed as well. Head guys should be used when a line runs over abruptly sloping ground, in order to give the line increased longitudinal stability.

185. Guy anchors are necessary where there are no trees, poles, or rocks to which the guy line may be conveniently attached. The simplest and most reliable form of anchor is the so-called "dead man" which consists of a log, 8 to 15 in. (20 to 38 cm.) diameter and 5 to 12 ft. (1.5 to 3.7 m.) long. A guy rod is passed through and held by a nut and washer. The log is buried to a depth of from 4 to 7 ft. (1.2 to 2.1 m.), depending on the load it must carry, and the character of the soil. Malleable iron plates may serve the same purpose.

186. Patent anchors. The many types of patent anchors depend for their holding power upon projections that are brought into play upon reversal of stress. The anchors are placed into position by being driven, screwed, or buried in the ground.

187. Rock anchors are often desirable where ledges or large boulders are encountered. They are made by setting an eye-bolt into the rock with or without cement, depending upon the character of the rock.

CONDUCTOR CONSTRUCTION

188. Wire stringing may be accomplished either by securing the end of the wire and carrying the reel forward, or by maintaining the reel stationary and carrying the end of the wire forward. The former method is best adapted to light construction and long lengths, whereas the fixed reel is best adapted to heavier and shorter lengths. The conductors are drawn up by means of a team, and when the proper sag and tension are obtained, the wires are attached to the cross arms by snub-grips, thus making temporary dead-ends which remain until the lineman can attach the clamps or make the tie. Where flexible or light structures are used, these must be guyed temporarily until a permanent line anchorage is made.

189. Phase wires may be arranged (Fig. 64) (a) in a horizontal plane; (b) in a vertical plane; (c) at the vertices of an equilateral triangle; (d) at the corners of a square (quarter-phase); and (e) at the corners of an isosceles triangle. Only in (c) are the conductors symmetrical with respect to one another. In the other cases except (d) the inductive drop and charging current are unbalanced, but these effects are so slight that they can be neglected. The arrangement of circuits on a pole will be determined by mechanical considerations and the type of construction employed. When making inductance and capacity calculations, the *average distance* between wires, or the cube root of the product of all three of the actual distances may be used. Either method introduces only a slight error. For spacing and clearances see Fig. 54.

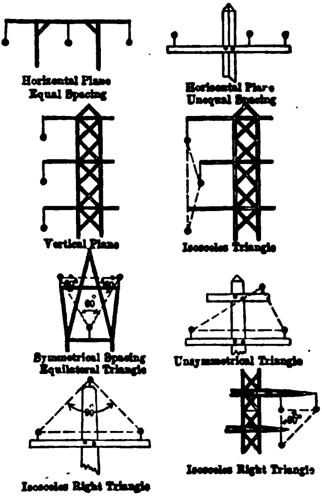


FIG. 64.—Grouping of phase wires.

190. Cable splicing. The insulation should be carefully removed from the ends of the cable to be spliced, close attention being given to getting the copper perfectly clean. A copper sleeve of the proper size may be used to make the joint. The joint should be left smooth and free from any little points of solder or sharp edges, as these factors tend to produce abnormal dielectric stress.

All burned or imperfect material in the insulation should be removed. The braid and tapes should be taken back far enough to allow the splices to be completed without touching them; this is very necessary owing to their low insulating properties.

The insulation should be beveled down to a very thin edge until it has the appearance of a well-sharpened lead pencil; this bevel or taper should be very gradual. If the taper is too short, it will be difficult to put the splicing compound on with sufficient density where the insulation stops at the joint, or at the end of the scarf. More high-tension joints break down at this point than at any other one place. The remedy is a very long gradual taper or scarf.

When possible, a good rubber cement should be used, smearing the taper as far up on the insulation as the splicing compound is to go, keeping it off the copper. The cement should be allowed to dry out until all moisture has disappeared, leaving it firm and sticky. Enough pure rubber should be put on to cover the copper, running about one-third of the way up on the taper. This should be covered with a good rubber splicing compound until it is somewhat larger than the rest of the cable. Care should be taken to put as much tension on the splicing compound as it will stand in order to get it on tight, to exclude all air and make the whole a solid, dense mass. In the case of submarine cables, the vulcanising of all patches and splices is recommended.

On small stranded joints which must be kept flexible and which cannot be soldered, a layer of tin-foil over the joint is recommended; this should be laid on before the rubber is applied, and will prevent any corrosive action of the sulphur in the rubber on the unsoldered joint. (Also see Sec. 12, Par. 219.)

191. Joints in transmission lines are seldom made up from the conductor itself but are almost entirely patented devices. Aluminum is not readily soldered and hard-drawn copper becomes annealed when soldered. The Western Union joint is used only for small wires. The so-called dovetail splice is made by fitting the strands of one cable between those of the other and wrapping one strand at a time tightly around the others and around the cable.

Patented joints that are satisfactory for inside wiring or short spans may give trouble when subject to the stresses incidental to the long spans employed in transmission work, unless installed with considerable care. The parallel-groove clamp is used where a jumper connection or station connection is to be made.

192. The McIntyre joint is used chiefly on small sizes of cable, although it has been used on sizes as large as 650,000 C.M. It is made of seamless copper or aluminum tubing, oval in section, into which each conductor is pushed from opposite ends, until the conductors project about 2 in. beyond the ends of the sleeve. The tube is then twisted three or four complete turns by special tools. This joint is efficient both electrically and mechanically.

193. Ground-wire construction. See Par. 80, 87. Ground wires are designed primarily to protect the line from lightning disturbances, hence should be placed well above the line conductors. With wooden poles, the so-called "bayonet" shown in Fig. 60 is commonly used. This may be a piece of angle iron or a pipe properly drilled and fitted to be fastened to the pole top to receive the ground wire. Where steel towers or poles, and consequently long spans, are used, the ground wire is often depended upon to take up some of the unbalanced stress due to the breakage of a line conductor. This is especially true when flexible towers with pin insulators are used. A ground wire is absolutely necessary to hold these towers in the correct longitudinal position, if suspension insulators are used. The ground wire should be held securely to the pole top by a clamp which is slightly flexible, has a grip of several inches, and flaring, well-rounded approaches. The use of J bolts or U bolts should not be allowed, as they will crush and weaken the cable at a point where mechanical strength is most necessary. Taps to ground connections for the same reason should not be soldered, but rather fastened by well-designed clamps. Some companies mount the ground wire on insulators as an extra conductor during the winter. The wire should be grounded at every steel pole or tower by contact with the metal work. If the metal work is completely imbedded in concrete at the base the ground should be made by driving an iron pipe, about 6 ft. (2 m.) long and 1 in. (2.5 cm.) diameter, into the ground, and connecting it to the metal work with a copper wire.* If the soil is dry, the ground can be made more permanent by pouring salt water around the pipe. When wooden poles are used, the ground connection should be made at every pole, by running a copper wire down the pole and grounding to a pipe driven in the ground, or by coiling the wire (bare) in a flat helix and placing it under the pole-butt.

194. Transpositions† are made to eliminate electrostatic and electromagnetic unbalancing of the various phases; to eliminate mutual induction between parallel lines; and to prevent disturbances in neighboring telephone and telegraph circuits. The distance between power-line transpositions is a matter of judgment, and may vary from 10 to 40 miles. Many engineers question the value of transpositions, and lines are operating satisfactorily without them. Fig. 65 shows the transposition of a section of three-phase line and a telephone circuit.

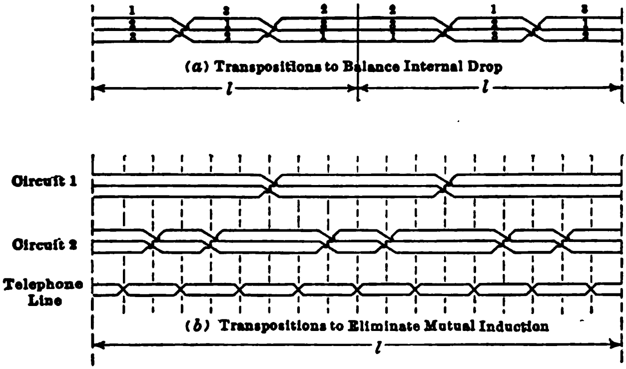


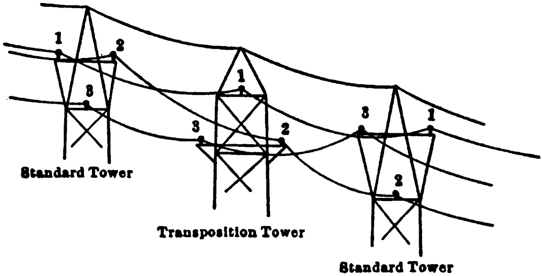
FIG. 65.—Transpositions.

195. Transpositions are commonly made by rotating the delta; by gradually changing the relative positions of the wires; by dead-ends and jumpers, similar to the method employed in telephone work. The first method requires special structures that are usually interspersed between the standard towers. When the wires are arranged at the corners of a triangle, the delta is rotated through 60 deg. in one span, and through the other 60 deg. in the next span. This is shown in Fig. 66 (*a*). When the wires all lie in the same plane, resort to an intermediate triangular arrangement must be made, as shown in Fig. 66 (*b*). Both of the above methods require special structures, and the transposition spans are usually about one-half the length of standard spans, in order that proper clearance between conductors may be maintained. The jumper method, shown in Fig. 66 (*c*), requires only a standard strain tower, which may be slightly modified if the conductors happen to lie in a vertical plane.

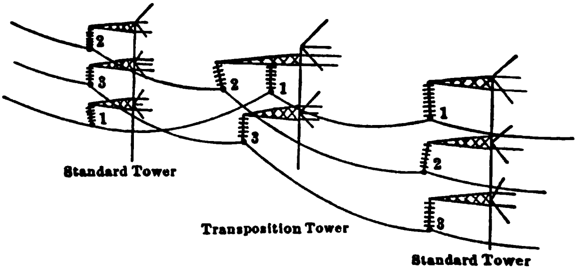
196. A telephone line is essential to the satisfactory operation of every transmission system, as a means of communication between generating stations, substations and patrolmen. When possible, the telephone wires should be run on a separate pole line to eliminate disturbances and trouble caused by the high-tension circuit. The cost of an extra pole line is often prohibitive, so it then becomes necessary to carry these wires on the power line poles or towers. In this case they should be at least 8 ft. (2.44 m.) beneath the nearest power wire, and in as protected a position as possible, otherwise the telephone may be rendered useless when trouble occurs on the power line—a time when the telephone is most needed. Small telephone

* See Bibliography 63. † Bibliography 69, 70.

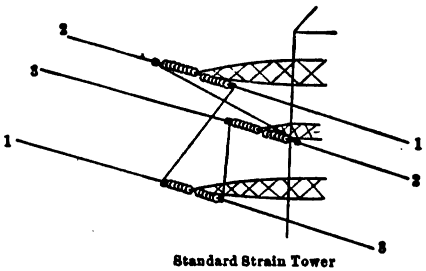
wires may be unable to withstand the stresses in occasional long spans. In this case they may be supported by a steel messenger wire, and if this latter is grounded, it helps to shield the telephone from inductive effects.



(*a*) Single Circuit Construction-Symmetrical Spacing



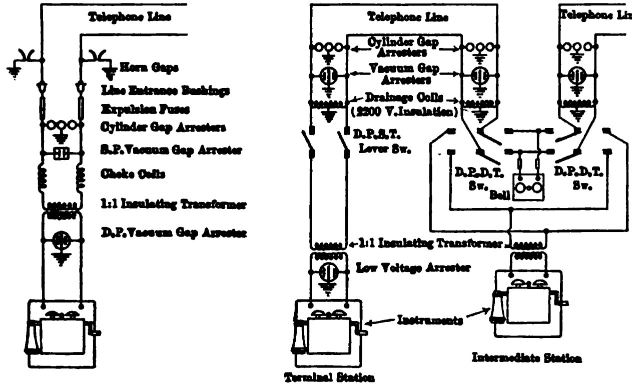
(*b*) Vertical Spacing



(*c*) Dead-end Jumper Method

Fig. 66.—Methods of transposition.

197. Induced electrostatic charge may raise the potential of the telephone circuit to a dangerous value. This potential can be greatly reduced by connecting coils of low reactance to ground, known as *drainage coils*, across the telephone line at intervals, and grounding their middle points. For further protection to the user, vacuum lightning arresters, horn-gaps, fuses and well-insulated transformers are used. Fig. 67 shows the connections ordinarily employed.



(*a*) Without Drainage Coils (*b*) With Drainage Coils

FIG. 67.—Telephone protection.

198. Where overhead crossings are made as over railroads or highways, extra precautions are necessary to protect life and property. In the past, a grounded cradle or basket-work beneath the lines, or some other grounding device, has been used to catch and ground the falling conductor. Patent wire clamps and hooks, out of which the conductor drops when broken, have been more or less used. Present-day practice rests on the principle that the less there is to come down, the better, and further assumes that there shall be no broken conductors. . Safety is now procured by the use of short well-supported spans, having a liberal factor of safety.

199. Extra precautions in overhead-crossing construction.* Long spans shall be avoided; the supports at the crossing and adjacent spans shall be in a straight line; the power wires shall cross *over* the telegraph and telephone wires, whenever practicable; cradles shall in general not be used; but where the power lines run beneath the others, a cradle or bridge of adequate strength may be required; a 12-ft. (3.66 m.) side clearance to the nearest rail, a 7-ft. (2.14 m.) clearance to siding rails, and a 30-ft. (9.15 m.) headroom to the top of the rail under the most unfavorable loading conditions, is allowable practice; the clearance above the other wires shall be not less than 8 ft. (2.44 m.).

When suspension insulators are used, the crossing span shall be dead-ended, or else the maximum sag in the crossing span shall not exceed 30 ft. (9.15 m.) in case of failure in the adjacent span; the normal tension shall be allowed in the crossing and adjacent spans (see Par. 99), and no splices or taps shall occur in these spans; the pins, insulators, and attachments shall be able to hold the conductor under the greatest stress with the designated factor of safety, and the insulators shall be such that if shattered the conductors will not fall.

Wooden poles supporting the crossing span shall be side-guyed in both

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A.

directions if practicable, and shall be head-guyed away from the crossing span; the next adjoining poles shall be guyed toward the crossing span.

Assumed loads shall be the resultant of dead-load, ½ in. of ice, and wind pressure of 8 lb. per sq. ft. on the ice-covered diameter at zero deg. fahr. The stresses and clearances shall be calculated for a temperature variation of from − 20 deg. fahr. to + 120 deg. fahr., except in those regions where this range is not representative. Towers or poles shall withstand a wind pressure of 13 lb. per sq. ft.

Factors of safety, or ultimate unit stress divided by allowable unit stress, shall be not less than the following:

Wire and cables	2
Pins	2
Insulators, conductor attachments, guys	3
Wooden poles and cross arms	6
Structural steel	3
Reinforced concrete poles and cross arms	4
Foundations	2

HIGH-TENSION CABLES

200. Underground and submarine cables are often used for transmission purposes and pressures up to 60,000 volts are successfully used.

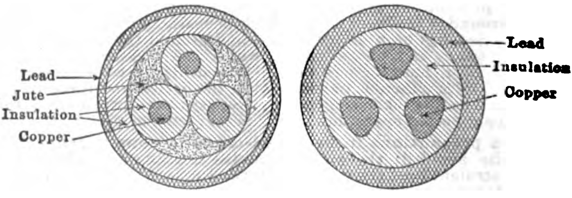
201. Three types of insulation are in common use, rubber compounds, varnished cambric, and impregnated paper.

(a) **Rubber compounds** consist of pure Para rubber and such mineral ingredients as sulphur, whiting, talc and litharge, which are thoroughly mixed together; the compounds are forced upon the conductors and then vulcanized.

(b) **Cambric insulation** consists of cotton cloth and a viscous filler. Each surface of the cloth is covered with multiple films of insulating varnish. The cloth is then applied to the conductor in the form of tape wound on spirally, the filler being applied between the successive layers.

(c) **Impregnated paper** insulation consists of Manila paper tapes applied spirally and evenly to the conductor, and then thoroughly impregnated with an insulating compound.

202. Cable insulation. In underground practice it has been found necessary to protect the insulation by a lead sheath. For submarine



(*a*) American Three-Phase Cable. (*b*) Clover Leaf Three-Phase Cable (English)

Fig. 68.—High-tension cables.

installations, cambric and paper-insulated cables have lead sheaths usually armored with steel for protection. When rubber is used, the lead sheath is unnecessary. Varnished cambric will resist water to a certain extent. Paper is worthless as an insulator if moisture is allowed to enter the cable.

Sometimes two or more of the insulations classified in Par. **201**, are used in the same cable to good advantage. For alternating-current transmission it is advisable to have all the conductors of the circuit in one cable, as the tendency to set up currents in the sheath is then practically neutralized. In all high-tension cables, the sheath should be well grounded to allow the high-voltage static charge to pass readily to earth. Where high-voltage conductors pass from the air into the cable, or from the cable into air, a large pot-head should be used, thus reducing to a minimum the high potential gradient that would otherwise occur at this point. Fig. 68 shows sections of three-conductor high-voltage cables; (*b*) is the clover-leaf type used in Europe.

203. Electrical disadvantages of a cable system. A cable system differs from an overhead system in that the electrostatic capacity is much greater while the linear inductance is negligible. Hence the charging current may be equal to or even greater than the load current itself. Surges* and transient phenomena are much more common than on an overhead line of the same length.

204. Underground cables for high-tension work are ordinarily installed in standard ducts (see Sec. 12). All underground cables should be **lead covered.** The rubber covering may last for years after the lead sheath has been eaten away by electrolysis or has been injured mechanically.

205. High-voltage cables† should be tested at a potential from 2 to 2.5 times their working pressure, depending upon the system to which they are connected.

The factory test voltage E, which should be applied between the core and sheath of a single conductor concentric cable, having homogeneous insulation, is

$$E = Kd \log_{10} D/d \tag{53}$$

where D is the diameter over insulation, d the diameter of the copper and K is a constant depending on the insulating material. If d is expressed in mils, K is about 250 for 30 per cent. Para rubber, cambric, and paper. From this formula the proper test voltage or the proper thickness of wall for a given test voltage may be determined.

SUBSTATIONS‡

206. The building is intended to shield the apparatus and equipment from the weather, as well as to furnish a shelter where repairs may be quickly made. A low-voltage station may have a fairly low initial cost. On the other hand, the large clearances required by overhead bus bars, connecting-leads, arrester equipment, etc., make the high-voltage substation a rather expensive affair.

207. The transformers should be installed in separate fireproof compartments which should be of such construction as to prevent burning oil from flooding the station, in case of trouble. Provision should be made for easily moving the units, so that repairs and replacements can be quickly made. Each transformer is often installed on wheels and rails, and trucks are provided in order that the large units may be readily moved.

208. Protective equipment is often placed indoors. The larger sizes of aluminum arresters and the large overhead clearances required for the horn-gaps often necessitate that these as well as the aluminum arresters, be placed out-of-doors. Where there are no overhead busses or inflammable material, the following clearances from the top of the horns should be allowed:§ for pressures up to 16,100 volts, 3 ft. (1 m.); from 16,101 to 37,900 volts, 4 ft. (1.2 m.); from 37,901 to 70,000 volts, 6 ft. (2 m.). At pressures above 70,000 volts, the horn-gaps should never be placed indoors. The auxiliary charging gaps for the aluminum arresters should always be in sight of the operator.

209. Choke coils are often mounted on post insulators on the outside of the building, especially where very high voltages are employed. For the lower voltages they may be conveniently installed on the inside wall, or directly in the switch leads.

210. High-tension bus bars are hung from the ceiling by suspension insulators, are suspended by ceiling insulators, or are mounted on post insulators. Owing to their low cost it is desirable to utilize suspension insulators whenever possible. Fig. 69 shows typical high-tension bus construction. (See Sec. 10, Par. **369.**)

* See Bibliography 45–55 incl.
† See Bibliography 33.
‡ See Sec. 12, Par. **51.**
§ See Bibliography 64.

211. Entrance and outlet for lower voltages are as shown in Fig. 70. Plate glass with a central hole, slightly larger than the conductor, is often used, as it keeps the weather out. Where high-voltage must be carried into a station, great care should be used in the design and selection of suitable bushings. A simple entrance for a 110,000-volt line consists of a 5-ft. (1.5 m.) slab of glass or marble, with a small hole sufficient to admit the conductor without undue corona discharge. In Fig. 71 are shown typical wall bushings.

The condenser type* **of bushing** is built up by placing thin layers of tin foil between concentric layers of insulation, and making the areas of the foil equal, irrespective of the diameter, thus giving uniform potential distribution. Such a bushing is shown in Fig. 70 (c).

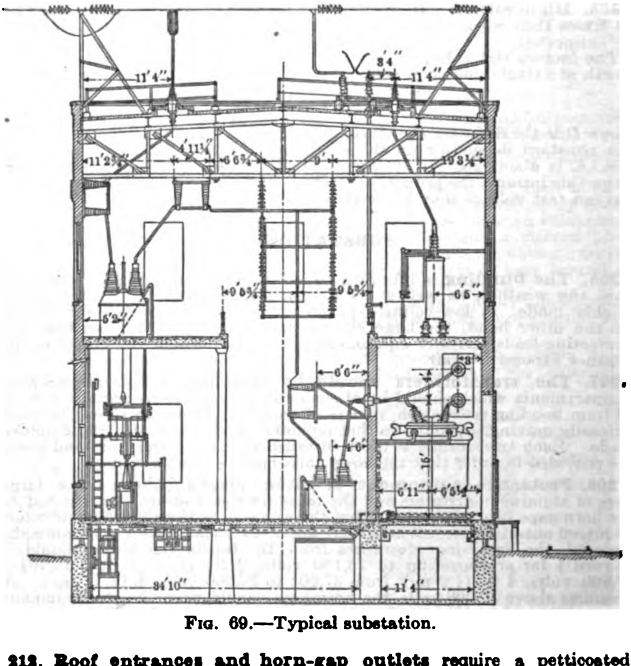


FIG. 69.—Typical substation.

212. Roof entrances and horn-gap outlets require a petticoated insulator in addition to a wall bushing in order to prevent trouble which might arise from rain and condensed moisture. The ratio of wet to dry flash-over should be very high. Fig. 138, Sec. 10, shows a typical roof insulator, and Fig. 72 shows standard roof construction.

213. A Substation wiring diagram is shown in Fig. 73, and Fig. 74 shows a typical meter panel. Meter leads A and B (Fig. 74) correspond to instrument transformer leads A and B (Fig. 73).

214. Outdoor switching stations are often installed at points where the amount of switching actually done does not warrant the expense of a building for housing the equipment. In such cases, a safe and economical

* Bibliography 44.

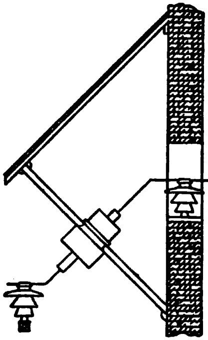
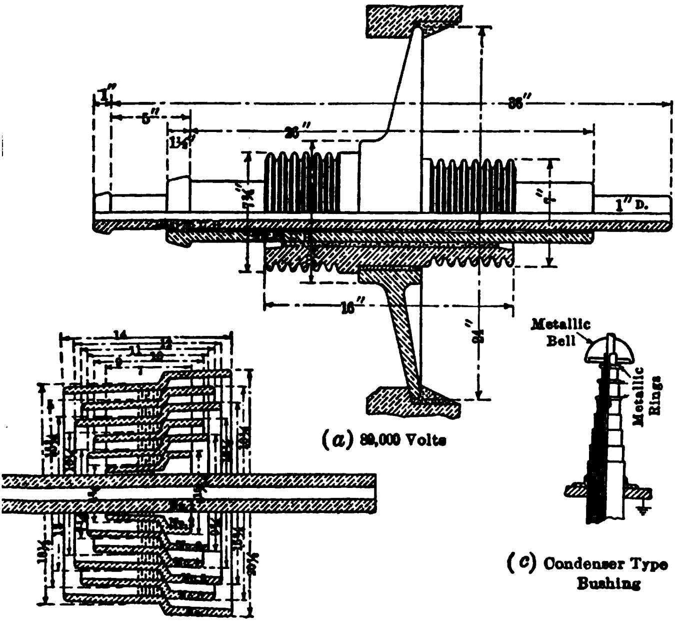


FIG. 70.—80,000 volt entrance.



(*a*) 80,000 Volts

(*b*) 90,000 Volts

(*c*) Condenser Type Bushing

FIG. 71.—High-tension bushings.

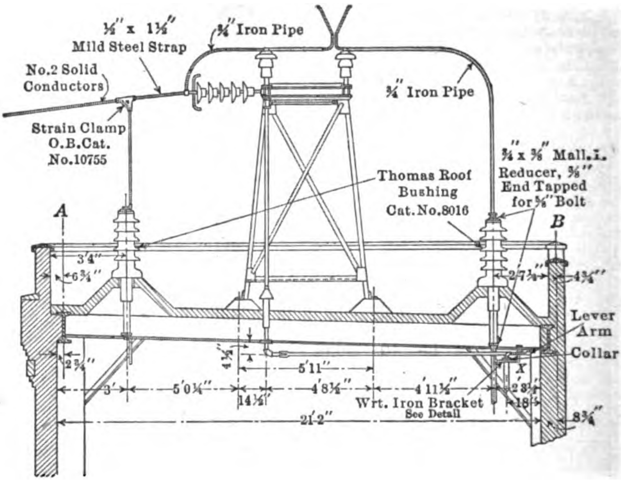


Fig. 72.—Typical roof construction showing horn gaps and roof insulators.

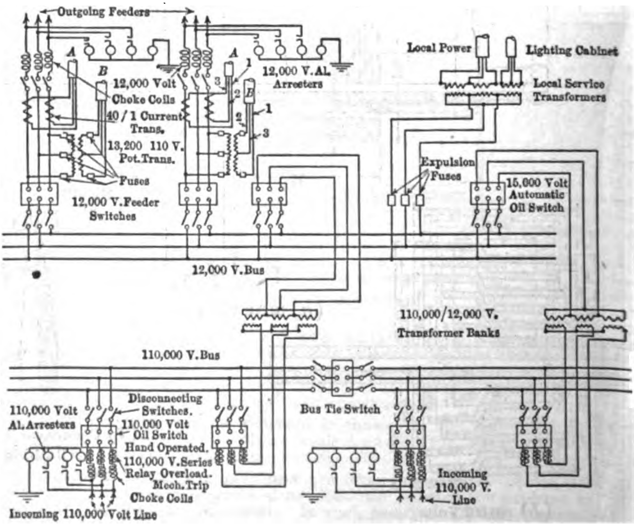
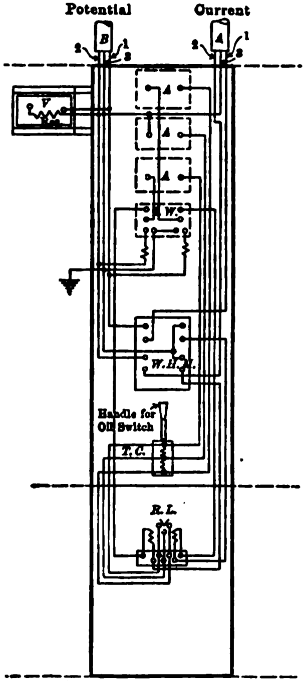


Fig. 73.—Substation wiring.

construction is to erect a platform on a special structure, upon which the switch-handles, transformers and other equipment are placed.

215. Outdoor substations* are rapidly coming into use, since the large clearance necessitated by high voltages would require a very large building. They are also used where small loads are tapped from the main line, requiring only one transformation from line to consumer. Switches, arrester equipment, power and instrument transformers have been developed to such a point that little deterioration occurs due to the weather. The outdoor equipment should be installed on paved, well-drained ground, and should be enclosed by a fence to exclude intruders. A small building may be necessary for making repairs, as well as to protect the operator and the switchboard and meter equipment. Climate, location, comparative costs of building and ground, the voltage and method of operation, are factors which largely determine the type of station. The transformers and arresters should be shielded from the hot sun and in winter the electrolytes and cooling water must be prevented from freezing. Painting the arrester tanks white tends to prevent the absorption of heat and cold. Transformer oil thickens and loses its insulating properties under extreme conditions of cold. An outdoor substation can be enlarged or modified with but little expense.



A Ammeter
V Voltmeter
I.W. Indicating Wattmeter
W.H.M. Watthour Meter
R.L. Inverse Time Limit Relays
T.C. Trip Coils

Fig. 74.—Instrument panel for substation.

OPERATION

216. A chief operator should be in absolute control of the system and should have direct telephone connection with every part of it, not only over the company's private line, but over a leased wire as well, as in times of emergency the private telephone line may be crippled. Likewise the chief operator and the substation operators should be in telephone connection with all linemen and patrolmen. In the chief operator's office there should be a dummy board showing the position of every line and switch on the system and whether each switch is opened or closed. No switch should be operated, no generator connected to or disconnected from the system, no water taken from a flume, unless the chief operator is notified and sanctions the operation. All communications should be repeated to the sender in order to prevent any misunderstandings and should be written in the log book to reduce mistakes to a minimum.

217. A complete log should be kept, not only by the chief operator, but by switchboard operators as well, of every transaction, loads carried, shutdowns, causes of trouble, and times of connecting or disconnecting motors and generators on the system.

* Bibliography 105, 106, 107.

A *multi recorder** for lightning and switching phenomena has been devised, whereby the exact time of switching, shut-downs and disturbances are automatically recorded.

218. A periodic line inspection should be maintained over all lines, the frequency of inspection depending on the country and the importance of the lines. A patrolman should be assigned to about 20 miles of line, as one man is then always within 10 miles of each section of the line. The patrolmen may cover the ground on foot, on horse-back, or with a horse and team, depending entirely upon the nature of the right of way, his duties and the distance he must travel. He should be furnished with a telephone test set and sundry tools and materials whereby he is able to make repairs, replace insulators, pins or cross arms. Some companies provide small booths every 2 or 3 miles along the line, where a small stock of insulators, pins, cross arms, wire and clamps is kept, so that material for repairs is always within a comparatively short distance. The pole switches and line sectionalising switches should be inspected at least once a month, to insure proper alignment of parts and proper operation in times of need. The patrolman should be held responsible for the proper operation of his particular section of the line.

Defective insulators which cannot be detected by inspection may be located by the use of a megger. A sound insulator should have a resistance greater than 1,000 megohms, whereas, if the porcelain or glass is injured or cracked, the resistance will drop below 500 megohms.

219. Line repairs and replacements should be made only after the line is "dead." The lineman or patrolman should notify the chief operator when a particular line or section is desired. The line should then be cleared, not merely through the oil switches, but should be opened by disconnecting switches as well. Before a lineman is allowed to work the line should be well grounded, in order to eliminate the electrostatic charge. If the line closely parallels another, both ends should be grounded to eliminate any dangerous induced potential.

220. Aluminum arresters† should ordinarily be charged at least once a day, under normal conditions of temperature. In hot weather, or if exposed to a higher temperature, they should be charged two or three times a day. After passing a heavy discharge, and undergoing a high temperature rise, they should be charged intermittently while cooling, in order to re-form the film, which dissolves very quickly when the temperature is above normal. The charging current should be about 0.4 amp. The auxiliary or charging gap should be closed three or four times or until the arc ceases to flare. Ammeter jacks are now available for convenience in measuring the charging current. An abnormal charging current may denote trouble within the arrester, such as carbonized oil between the cones. It is desirable to charge the arresters individually, not all at the same time. (Also see Sec. 10, Par. 362.)

221. Short circuits may open the line when a station is provided with automatic breakers. Where non-automatic switches are used, the operator should decrease the voltage, rather than open the circuit, waiting for the line to clear. If the line does not then clear, the load should be thrown over to a spare line until repairs can be made. Where it is essential that the service shall not be interrupted, resort may be had to such expedients as operating single phase, with a ground return, etc., until the line is again in its normal condition.

TRANSMISSION ECONOMICS

222. Value of continuity of service. No system should be equipped with expensive automatic control devices, duplicate lines, liberal protective equipment, and spare generating plants in order to insure continuity of service, unless the cost of an interruption or a shut-down justifies the expenditure of such capital. The line should be constructed as cheaply as is consistent with the required standard of service, without endangering life or property. Further, a system should not be extended to a distance greater than that at which there is a reasonable prospect of selling sufficient power to pay the development and operating costs of the extension.

223. The type of line must be decided upon after considering the reliability desired, the character of the country, transportation facilities, availability of timber, etc. Although steel construction, as an engineering

* Bibliography 58, 59.

† Bibliography 64, 65.

proposition, is far superior to wood, there are many instances where the low first cost of wood alone makes a transmission project economically feasible.

224. The length of span should be so chosen as to have the line cost a minimum. As the length of span increases, the number of supports and insulators decreases, but the height of the support and the conductor spacing must be increased to allow for the greater sag. The effect of these changes on cost is shown in Fig. 75 (see Bibliography 79). Under these conditions the most economical span for steel towers is about 700 ft. Other factors, such as the decreased cost for pole or tower rights on private right of way, the lesser number of insulators, with the decreased possibility of failure with the longer span, should receive due consideration.

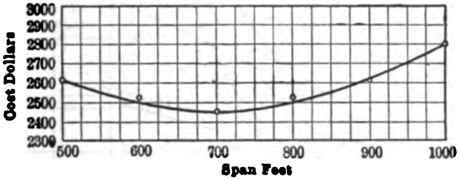


Fig. 75.—Span length and cost.

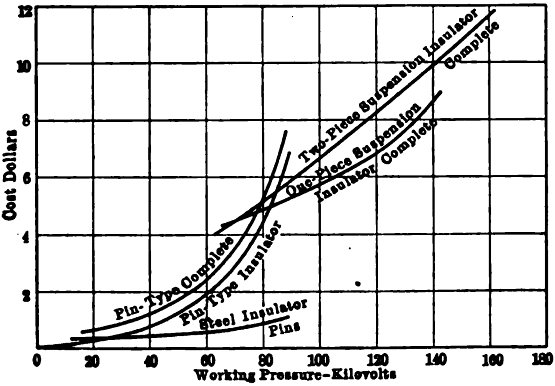


Fig. 76.—Cost of insulators.

225. The choice of conductor material lies between copper and aluminum, except for a few special spans. Although aluminum is about 10 per cent. cheaper than copper for the same conductance, its greater temperature coefficient of expansion and lower tensile strength demand greater sags, hence more expensive structures.

226. The size of conductor is influenced by mechanical considerations and by the amount of energy that it is permissible to waste in transmission. Line regulation may require a larger conductor than is economically demanded. When energy may be generated and sold at a low rate per kw-hr., a much smaller conductor is justified than if the reverse be true.

227. The choice of voltage is determined by the amount of power and the transmission distance. The conductor cross-section varies inversely as the square of the voltage, but the cost of insulators, supporting structures, stations, protective equipment and transformers increases as the voltage is increased. These last three items are independent of the length of the line, so would make a higher voltage on a long line economically desirable, neglecting other considerations. Roughly, a thousand volts per mile seems to be the criterion adopted by engineers. An 80,000-volt line presents no greater operating difficulties than a 30,000-volt line. Surge voltages are, however, dependent upon the current and systems have been designed to operate at a higher voltage than is economically demanded, in order to secure greater freedom from surges.

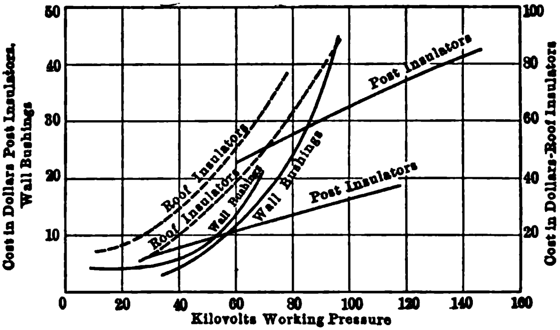


FIG. 77.—Cost of station insulators.

COST DATA†

228. Preliminary and right of way*

	Minimum cost per mile	Maximum cost per mile
Surveying....................................	$5.00	$10.00
Right of way, perpetual easement, 50 poles per mile.		
Along highways $0.50 to $2.00 per pole.......	25.00	100.00
Along section lines $0.50 to $5.00 per pole.....	25.00	250.00
Through fields, $2.00 to $10.00 per pole.......	100.00	500.00
Towers, 10 per mile, $9.00 to $20.00 per tower.	90.00	200.00

229. Cost of wooden poles

Length, ft.	Top diam., in.	Approx. butt diam., in.	No. per carload	*Cost Northern Cedar f.o.b., Minneapolis, per pole	*Cost Western Cedar, f.o.b., Spokane, per pole	Cost Chestnut f.o.b., Western Mass., per pole	*Cost Cypress f.o.b., St. Louis, per pole	Cost per pole unloading, cents
30	7	11	55–95	$4.60	$2.50	$3.25	$1.20	5–8
35	7	12	50–70	6.70	3.25	4.00	2.00	8–12
35	8	13	40–60	6.95	3.75	5.25	2.30	8–12
40	7	14	40–55	7.50	3.75	6.25	2.35	12–15
45	7	15	60–70	10.25	4.25	7.75	2.85	15–18
50	7	16	48–55	11.90	5.00	10.50	3.30	22–25
55	7	17	39–42	15.10	5.50	14.00	3.50	25–30
60	7–8	18	30–33	22.50	7.00	20.00	3.90	30–35
65	7–8	19	23–25	29.00	8.50	30.00		35–40

* Bibliography 78.

† Cost data should be used merely as suggestive, the data here given being without reference to special conditions.

230. Cost of Butt treatment by open-tank method*

Species	Size of pole		Amount creosote applied		Cost of treatment		Total
	Top diam., in.	Length, ft.	Lb. per cu. ft.	Lb. per pole	Preservative	Operation	
Chestnut	7	30	.....	25	$0.30	$0.45	$0.75
Northern white cedar	7	30	.....	50	0.60	0.45	1.05
Western yellow pine	8	40	6	37.5	0.90	0.45	1.35
Western yellow pine	7	40	10	62.5	1.45	0.45	1.90
Western red cedar	7	40	6	39	0.90	0.45	1.35
Lodge pole pin	7	35	.....	35	0.80	0.45	1.25

231. Unit labor costs

	Cost per mile	
	Minimum	Maximum
Cost of hauling, 10–20 cents per pole per mile of line per mile hauled	$5.00	$10.00
Cost of framing and attaching fittings $0.25 to $1.00 per pole	12.50	50.00
Cost of digging holes $0.50 to $2.50 each	25.00	125.00
Cost of rock holes, $2.00 to $4.50 each	100.00	225.00
Cost of raising and setting with pikes. $0.35 to $1.00 per pole	17.50	50.00
Cost of raising and setting with gin wagon $0.35 to $0.60 per pole	17.50	30.00

232. Cost of long-leaf, yellow-pine cross arms, middle west†

3.25 in. × 4.25 in. per lin. ft.	$0.0375
4 in. × 4 in. per lin. ft.	0.055
4 in. × 5 in. per lin. ft.	0.075
4 in × 6 in. per lin. ft.	0.0825
4.5 in. × 5.75 in. per lin. ft.	0.089
5 in. × 7 in. per lin. ft.	0.12

Fir 5 to 15 per cent. higher.
Cost of steel cross arms 2.5–3 cents per lb.

233. Approximate prices each of high-voltage insulator pins‡

Insulator voltage	Wood pins paraffined	Steel pins galvanized	Iron pins with separable thimble; galvd.	Steel pins with porcelain base; bolt galvd.
80,000	$0.65	$0.85	$0.80	$0.85
66,000	0.50	0.65	0.75	0.75
60,000	0.40	0.60	0.68	0.65
50,000	0.35	0.60	0.68	0.65
45,000	0.35	0.60	0.68	0.65
40,000	0.30	0.50	0.48	0.22

Wood pins with steel bolt not used for these high voltages.
* Steel pipe, forged.

* Abeles & Taussig, Spokane, Wash.
† Bibliography 78.
‡ Locke Insulator Mfg. Co.

234. Tripartite steel poles. (Fig. 78)

Length overall	Type of arming	U-bar section	Weight complete	Depth of set in concrete	Average cost of setting	Cost comp. at Franklin, Pa.
SINGLE CIRCUIT—NO GROUND WIRE Design used to carry three No. 4 A.W.G. H. D. copper conductors in 300-ft. spans						
30 ft.	Fig. A	No. 2	447 lb.	4 ft.	$5.00	$12.77
35 ft.	Fig. A	No. 2	508 lb.	4 ft.	5.25	14.07
40 ft.	Fig. A	No. 2	595 lb.	4 ft.	5.50	16.90
45 ft.	Fig. A	No. 2	675 lb.	4½ ft.	6.00	19.32
SINGLE CIRCUIT—WITH GROUND WIRE Design used to carry a ¼-in. steel strand ground wire three No. 4 A.W.G. H. D. copper conductors and a No. 10 steel phone circuit in 300-ft. spans						
32 ft.	Fig. B	No. 2	553 lb.	4 ft.	$5.25	$16.58
37 ft.	Fig. B	No. 2	631 lb.	4½ ft.	5.50	18.01
42 ft.	Fig. B	No. 2	714 lb.	5 ft.	5.75	21.65
47 ft.	Fig. B	No. 4	886 lb.	5½ ft.	6.25	24.16
SINGLE CIRCUIT—NO GROUND WIRE Design used to carry three No. 1 A.W.G. equivalent copper strand and 2 phone wires in 350-ft. spans						
41 ft.	Fig. C	No. 6	1,197 lb.	4 ft.	$7.10	$32.08
46 ft.	Fig. C	No. 6	1,372 lb.	4½ ft.	8.40	37.28
51 ft.	Fig. C	No. 6	1,548 lb.	5 ft.	10.95	42.68
SINGLE CIRCUIT—WITH GROUND WIRE Design used to carry a ⅜-in. steel strand ground wire three No. 0 conductors and a phone circuit in 350-ft. spans						
54 ft.	Fig. D	No. 6	1,757 lb.	5½ ft.	$13.97	$50.41
59 ft.	Fig. D	No. 6	2,012 lb.	6 ft.	16.00	58.71
65 ft.	Fig. D	No. 6	2,235 lb.	6½ ft.	18.20	65.86
DOUBLE CIRCUIT—WITH GROUND WIRE Design used to carry a ¼-in. steel strand ground wire and six No. 4 A.W.G. copper conductors in 300-ft. spans						
35 ft.	Fig. E	No. 4	853 lb.	4 ft.	$6.00	$24.28
40 ft.	Fig. E	No. 4	977 lb.	4½ ft.	7.05	28.41
45 ft.	Fig. E	No. 6	1,327 lb.	4¾ ft.	9.15	33.15
DOUBLE CIRCUIT—WITH GROUND WIRE Design used to carry a ⅜-in. steel strand ground wire, six No. 0 A.W.G. copper-clad conductors and a phone circuit in 440-ft. spans						
40 ft.	Fig. F	No. 6	1,800 lb.	4 ft.	$8.70	$50.64
50 ft.	Fig. F	No. 6	2,162 lb.	5 ft.	11.70	61.51
60 ft.	Fig. F	No. 6	2,529 lb.	7 ft.	16.85	72.33

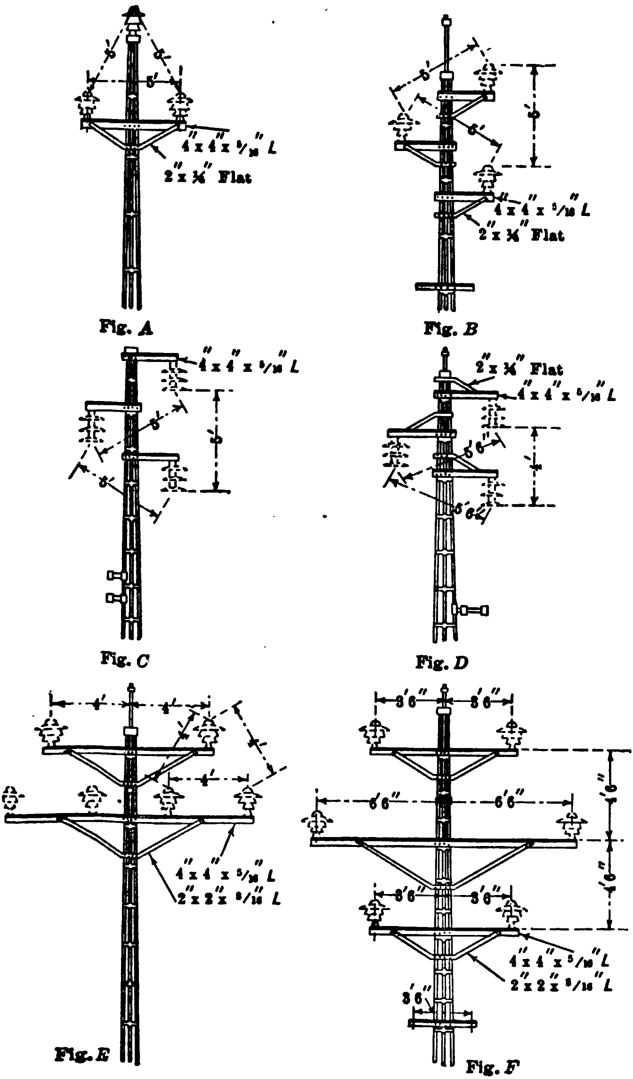


Fig. 78.—Tripartite pole.

235. Cost of steel towers

3.25 to 4.25 cents per lb. galvanized. 0.5 to 1 cent cheaper, painted

Height, ft.	Weight, lb.	Number per mile	Cost each at 4 cents, lb.		Cost per mile	
			Minimum	Maximum	Minimum	Maximum
Single circuit						
40	1600–2500	12	$64.00	$100.00	$768.00	$1200.00
50	1800–3000	9	72.00	120.00	648.00	1080.00
60	2200–3500	7	88.00	140.00	616.00	980.00
Double circuit						
40	2200–3500	12	$88.00	$140.00	$1056.00	$1680.00
50	2600–4200	9	104.00	168.00	936.00	1512.00
60	3200–5000	7.	128.00	200.00	1152.00	1800.00

236. Cost of placing steel towers in position, 8 and 12 towers per mile

	Per mile	
	Minimum	Maximum
Labor cost of distribution at $2.00 to $2.50 each..	$16.00	$30.00
Digging holes, earth setting at $4.00 to $6.00 each..	32.00	75.00
Digging holes, and concrete foundation at $10.00 to $20.00 each.	80.00	250.00
Digging holes and concrete foundation anchor towers (1 per mile)	30.00	90.00
Assembling at $7.50 to $25.00 each..............	60.00	300.00
Raising at $3.00 to $10.00 each.................	24.00	120.00
Total cost per mile of placing towers in position { earth setting	$162.00	$615.00
Total cost per mile of placing towers in position { concrete foundation	210.00	795.00

237. Semi-flexible steel towers vs. wooden poles*

Cost of transmission line per mile, wooden poles

Specifications:

33,000 volts working pressure, No. 2 B. & S. copper wire
120-ft. pole spacing, one pole line
44 poles per mile
Pin type insulators
"Bo-Arrow" cross arms
35-ft. poles, 7-in. top diameter
⅜-in. ground wire (standard galvanized wire)

Material, labor, etc.

44	Poles, 35-ft., 7-in. top diameter @ $8. f.o.b., Ohio	$ 352.00
44	Cross arms "Bo-Arrow" galvanized complete @ $3.79	166.76
44	Telephone brackets @ 10 cents	4.40
	Bog shoes @ 15 cents per pole, average	6.60
	Guying material @ 50 cents per pole	22.00
	Pole steps and hardware @ 75 cents	33.00
	Framing and trimming of poles @ 50 cents	22.00
	Creosoting of poles @ 20 cents	8.80
	Cartage @ 70 cents per pole	30.80
	Hauling (railway) @ $1.20 per pole	52.80
	Digging of holes @ 1.20 per pole	52.80
	Setting of poles @ $1.80 per pole	79.20
3	Miles hard drawn copper strand No. 2 B. & S. @ $181.20 per mile	543.60
1	Mile ⅜-in. Siemens-Martin steel strand wire	54.00
2	Miles Tel. wire No. 10 B. & S. copper clad 30 per cent. @ $25.00 per mile	50.00
44	Ground wire connections @ 35 cents per pole	15.40
132	Porcelain petticoat insulators @ 50 cents	66.00
	Tie wire	4.50
88	Telephone insulators @ 2 cents	1.76
	Stringing 3 miles No. 2 B. & S. strand @ $15.00	45.00
	Stringing 2 miles No. 10 copper clad wire @ $10.00	20.00
	Stringing ground wire	18.00
	Soldering materials	5.00
	Miscellaneous material	10.00
	Damage, expense to property of owners	5.00
	Clearing of branches and trees	4.50
	Tools	3.00
	Camp expenses	18.00
	Materials deposited along the lines for repairs	19.20
	Wasted materials	18.00
	Contingencies and incidentals, 7 per cent	121.25
	Supervision and inspection, 5 per cent	92.67
	Total construction cost per mile with wooden poles exclusive of right of way	$1,946.04
	Right of way @ $8.00 per pole	352.00
	Total cost including right of way	$2,298.04

*From *Lefax*, by Frank G. Nagele.

Cost of transmission line per mile, semi-flexible steel structures.

Specifications:

33,000 volts working pressure, No. 2 B. & S. copper wire
400-ft. pole spacing, one pole line
13 poles per mile
3-disc suspension type insulators
$\frac{7}{16}$-in. ground wire (standard galvanized wire)

Material, labor, etc.

13	Towers (steel frames) 43-ft. high with cross arms, telephone clips and pole steps, complete, f.o.b. Central Ohio @ $53.00 per tower	$ 689.00
	Cartage @ 80 cents per frame	10.40
	Hauling (railway) @ $1.25 per frame	16.25
	Digging of holes @ $1.50 per frame	19.50
	Erecting of frames, @ $2.00	26.00
	Concrete foundations for curve frames and frames in swampy ground	40.00
	Guying of poles	30.00
	Crushed stone for regular foundations	6.00
3	Miles No. 2 B. & S. copper wire @ $181.20	543.60
2	Miles No. 10 B. & S. copper clad @ $25.00	50.00
1	Mile $\frac{7}{16}$-in. S.-M. steel strand wire	75.00
39	Suspension insulators, porcelain 3-disc unit sets including suspension hooks and wire clamps @ $3.50	136.50
26	Telephone insulators and pins @ 20 cents	5.20
	Stringing 3 miles No. 2 B. & S. @ $18.00	54.00
	Stringing 2 miles No. 10 B. & S. @ $12.00	24.00
	Stringing ground wire	20.00
	Miscellaneous material	10.00
	Painting of structures @ $1.60 each	20.80
	Soldering material	5.00
	Clearing and trimming of trees	4.50
	Damage, expense to property owners	20.00
	Camp expenses	16.00
	Wasted materials	5.00
	Contingencies and incidentals, 6 per cent	109.61
	Supervision and inspection, 5 per cent	96.82

Total construction cost per mile with steel towers exclusive of right of way	**$2,033.18**
Right of way @ $15.00 per frame	**195.00**
Total cost including right of way	**$2,228.18**

238. Cost of galvanized steel wire (*Roebling*)

(7-*strand*)

Dollars per 1,000 ft.

Diam., in.	Single galvanized	Double galvanized	*Siemens-Martin	*High strength	*Extra high strength
$\frac{5}{8}$	....	....	$32.60	$46.90	$65.60
$\frac{1}{2}$	$18.00	$22.50	21.00	29.60	41.25
$\frac{7}{16}$	15.00	18.75	17.25	25.90	34.50
$\frac{3}{8}$	11.00	13.75	13.50	20.25	26.60
$\frac{5}{16}$	9.00	11.25	11.10	15.75	20.25
$\frac{9}{32}$	....	....	8.25	13.10	15.75
$\frac{1}{4}$	7.00	8.75	7.50	11.25	14.25
$\frac{7}{32}$	6.00	7.50	....	....	....
$\frac{3}{16}$	5.00	6.25	6.38	9.75	12.00
$\frac{5}{32}$	4.60	5.75	....	....	....
$\frac{1}{8}$	4.00	5.00	4.13	6.00	7.88
$\frac{3}{32}$	3.20	4.00	....	....	....

* Double galvanized.

239. Cost of substations*

Kw. capacity		Water cooled				
†Oil cooled	Water cooled	Cost of building		Cost of equipment		Total cost per kw.
		Total	Per kw.	Total	Per kw.	
3,650	4,325	$12,490	$2.89	$29,670	$6.87	$9.76
2,400	3,075	9,152	2.97	30,534	9.92	12.89
1,500	1,875	10,979	5.85	23,774	12.65	18.50
1,500	1,875	7,236	3.86	19,023	10.15	14.01
1,500	1,875	7,344	3.92	14,732	7.87	11.79

240. Comparison costs of indoor and outdoor types of substation‡

Transformer substation			600-volt motor-generator substation		
2,000 kva., 25,000-volt, 60 cycles			3,000 kva., 22,000–3,000-volt, transformers 25 cycles		
	Indoor	Outdoor		Indoor	Outdoor
Building	$ 5,400	$ 1,020	Building	$ 21,835	$ 7,480
Transformers	7,200	7,800	Transformers	15,000	16,000
Switchboard	2,500	2,625	Motor-generators	48,000	48,000
			Exciters	4,500	4,500
Total	$15,100	$11,445	Switchboard	20,000	20,200
				$109,335	$96,180
Per kva	$7.55	$5.72	Per kva	$36.45	$32.00

241. Cost of cables per 1,000 ft.

2/0 stranded, 3-conductor, lead-covered						
	Underground			Submarine		
Volts	Insulation			Insulation		
	Rubber	Cambric	Paper	Rubber	Cambric	Paper
6,600	$1,040	$ 700	$ 620	$1,110	$1,180	$ 920
13,000	1,840	1,150	780	1,810	1,490	1,220
25,000	2,210	1,520	1,090	2,740	2,180	1,690

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* From "Data."
† Capacity of same station, oil cooled.
‡ Bibliography 105.
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SECTION 12

DISTRIBUTION SYSTEMS

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Author of "Electric Central Station Distributing Systems"

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SECTION 12

DISTRIBUTION SYSTEMS

CLASSIFICATION OF SYSTEMS

1. Distributing circuits may be classified as to the nature of the current—direct or alternating; as to method of connection—series or multiple; and further as to phase, number of conductors, voltage and frequency. The following is a statement of the field of application of the principal kinds of distributing circuits.

2. Direct current is best adapted to use: (a) where the distances are small, (b) where there is variable-speed machinery, and (c) where there is an area of congested load for which storage-battery reserve is necessary to insure continuous service.

3. Alternating current is best adapted to use where the distances are greater and the density of the load not sufficient to justify low-tension distribution without transformation from a higher voltage.

4. The use of series systems is limited almost entirely to street and other lighting which is all in use at the same time. These systems are inherently high-tension in character and are, therefore, not suitable for general purposes. They are operated by direct current or alternating current at a constant current of 5 amp. to 10 amp. in American practice. In Europe there are several direct-current series power transmission systems in operation utilising a series of motor generators as the converting medium (Sec. 11).

5. Multiple or parallel systems are used for general purposes almost exclusively. When **direct current** is used a nominal voltage of 110, 220. or 550 is employed, the last named being used only for power distribution. The Edison three-wire system at 220 and 110 volts is common in large installations.

When **alternating current** is used, the primary mains are operated at a nominal voltage of 2,200. Single-phase, two-phase, and three-phase circuits are in general use, with frequencies of 25 or 60 cycles. In general, single-phase distribution is used for lighting and small power service, and two-phase or three-phase distribution is used for larger power loads.

6. Frequency. Twenty-five cycles is standard where most of the energy is converted to direct current for lighting and railway service or other purposes. Sixty cycles is standard where the energy is delivered for retail consumption as alternating current. Other frequencies such as 30, 33, 40, 50 and 133 cycles are in use in some of the older installations in America and in Europe. Sixty-two and one-half cycles is used in some modern systems where the supply is derived from a 25-cycle system, this frequency giving a better design of frequency-changer apparatus.

GENERAL APPLICATIONS

7. The single-phase system, requiring only the simplest form of electric circuit, has the advantage of a minimum number of conductors, and hence the minimum first cost for distributing mains. The feeders, however, require 33 per cent. more copper than equivalent three-phase feeders. Single-phase motors are more complicated and cost more than polyphase motors, and usually produce more disturbance of pressure, in starting, than three-phase machines. The distribution of energy by single-phase circuits is, therefore, usually limited to motor units of less than 10 h.p., although motors up to 35 h.p. are used in single-phase systems with good success. This system is used very generally for lighting circuits, in both single-phase and polyphase systems.

8. Two-phase systems. Two-phase distribution is effected by the use of two single-phase circuits in a quarter-phase relation, making a **four-wire** system; or by means of a **three-wire** system in which one conductor of each phase is common.

The four-wire system is substantially the same as a single-phase system, except that two-phase motors may be used. The principal advantages of two-phase systems are that there are only two phases to keep balanced and only two transformers are required to supply polyphase energy to motors.

In a three-wire, two-phase system, the current in the common or neutral conductor is 1.414 times the current in the outer conductors, with balanced load. When all conductors are the same size, the copper required is 75 per cent. of that needed for a four-wire system. When the neutral is 40 per cent. larger than the outer conductors, the amount of copper required is 85 per cent. of that needed for a single-phase system or a four-wire, two-phase system. In the primary mains, which are all the same size, the three-wire two-phase system is as economical of copper as the three-wire, three-phase system. The line drop in this system is such that even with balanced load the drop in the two phases is not the same, making voltage regulation difficult, unless line-drop compensators are employed. The three-wire circuit cannot be used where the mid-points of the quarter-phase generator windings are tied together, as is the case in some machines.

9. Three-phase, three-wire system. This system is commonly employed for general distribution, since it is readily derived from a three-phase transmission system; it is also well suited to power distribution, and requires but 75 per cent. as much copper in the feeder system as an equivalent single-phase system. The three-wire distributing mains are usually carried only where motor service is required, the lighting service being taken on single-phase branches from the three-phase main. Users of small motors, up to about 5 h.p., are generally supplied from a single phase; while the larger motors, up to 30 h.p. or 40 h.p., are supplied from two phases with the open-delta connection.

10. Three-phase four-wire system. In primary distribution this system is usually operated at 3,800 volts between phase wires and 2,200 volts between any phase wire and neutral. This gives the advantage of 3,800-volt distribution in the feeder system and permits the supply of energy over a radius about twice as great as with 2,200-volt systems, with the same regulation. Standard 2,200-volt transformers and other accessories are used, and the lighting branches are single-phase. The unbalanced load is carried by the neutral wire, and with the use of line-drop apparatus, good pressure regulation is possible with any proportion of unbalanced load.

The four-wire distributing mains are carried only where there are motors or large loads to be served, and but three wires are needed for installations of less than 30 to 40 h.p., which may be served by two transformers connected in open delta. The wide range permissible has led to the adoption of this system in many of the larger cities of the United States. It is also well suited to the supply of suburban districts and rural communities, where double-voltage, 4,400–7,600 volts may be used to supply a group of towns and villages, the pressure being regulated independently on each phase at the source of supply.

11. Direct-current low-tension systems find their principal field of application in important parts of cities where the protection of the storage battery reserve is of great value, and where there are many elevators, printing presses and other variable-speed machines, and where space for transformers would be difficult to secure in public thoroughfares. The principal limitations of direct-current distribution are the small radius of distribution, and the necessity for rotating machinery to transform the energy from an alternating-current source of supply. This requires a greater number of substations to cover a given area, and these are more expensive both in first cost and operation than alternating-current substations.

12. Two-wire, 500-volt, direct-current systems are operated in some cities where they were originated to supplement single-phase systems in the early period of development. The duplication of mains necessitated by a separate power-service results in an excessive investment and 500-volt systems are being eliminated wherever possible.

13. Combination systems. Various combinations of alternating-current, and direct-current, or 25-cycle and 60-cycle systems, are necessary in the larger cities. The direct-current supply is usually derived through synchronous converters or motor-generators from an alternating-current generating system. The 60-cycle supply is sometimes derived from a 25-cycle system by the use of synchronous motor-generators called frequency changers. In some cases both 25-cycle and 60-cycle generating systems are maintained, and the frequency changers are used as a connecting link between the two systems.

TYPES OF CIRCUITS

14. Series circuits. Two general types of arrangement are employed in laying out series circuits, the "open loop," and the "parallel loop." In the **open-loop** circuit (Fig. 1) the lamps are connected by following the shortest available route, without reference to the separation from the return conductor. This permits a minimum length of circuit, but makes it difficult to test for a break, or open circuit in the line. In alternating-current circuits it also tends to increase interference with telephone systems.

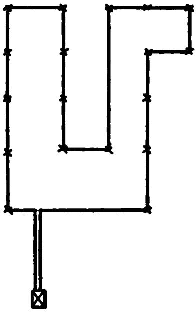


FIG. 1.—Open-loop series circuit.

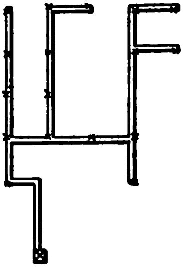


FIG 2.—Parallel-loop series circuit.

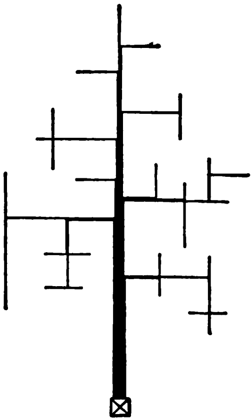


FIG. 3.—Tree-system of distribution.

The **parallel-loop** circuit (Fig. 2) is laid out in such a way as to be near the return conductor at many points. This affords frequent opportunity for test and minimizes inductive disturbances, but usually requires a greater mileage of conductor than the open-loop circuit. A combination of parallel loops with small open loops may often be used to advantage.

15. Multiple circuits. The arrangement of multiple circuits may take any one of a number of forms as conditions require. The simplest and least expensive circuit is that commonly known as the "tree" circuit (Fig. 3); it is thus named because it is branched off in various ways, and has its heaviest branches nearest the source of supply. The tree system is not adapted to supplying a uniform distribution pressure and is only suited to short branches and those branches in which the current values are small as compared with the conductor capacity.

16. A system of feeders and mains is the arrangement most commonly employed in city distribution for lighting and power-service. This takes the form of a network in low-tension systems (Fig. 4), and an isolated or dead-ended main system in primary distribution (Fig. 5). In the low-tension network the system of mains is designed to be of such capacity as to carry the load units which are tapped off from house to house, and the feeders are provided in such number, of such size and at such points as will maintain an even distribution of pressure, within a few per cent., over the entire system of mains.

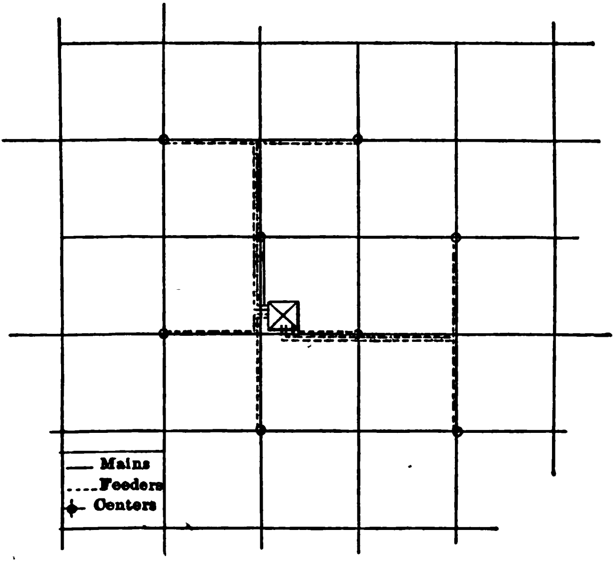


FIG. 4.—Feeders and mains in a direct-current network.

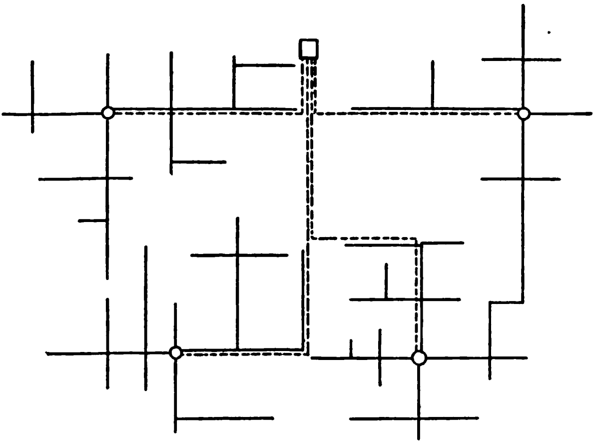


FIG. 5.—Feeders and mains in alternating-current distribution.

17. Primary-main systems are usually supplied by a feeder at a **centre of distribution,** this point being a junction from which the load is distributed in four or more directions. These mains are not interconnected, because it is not practicable to provide fuse protection, and in most cases not much is to be gained by such connection.

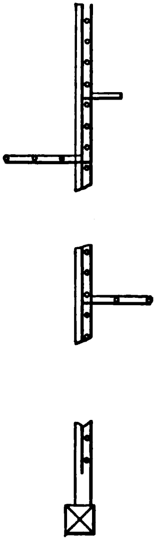


FIG. 6.—Loop feeder.

18. The loop feeder (Fig. 6), is used where the load is distributed in a long continuous line with few side branches. This arrangement distributes the pressure more evenly along the line than is possible with other types of circuit.

19. Ring feeders. Where it is desired to provide emergency supply to units of load in one general direction from the point of supply, the most economical means often consists of the type of feeder known as a ring circuit (Fig. 7). The capacity of the ring must be sufficient to carry the combined load of all the units, in case either of the links adjacent to the point of supply should fail.

20. Urban transmission systems. In cities having too large an area to permit an economical distribution of electrical energy from a single point, it becomes necessary to transmit energy from a generating station (located at a point convenient to coal and water supply) to substations centrally located with reference to the districts served. This transmission system, in the larger cities, becomes practically a bulk-supply distribution system. The same condition exists where hydroelectric energy is brought from a distance for distribution in a large city. These urban transmission systems are universally three-phase; where two-phase energy is generated, it is converted to three-phase energy for transmission.

21. Pressures and frequencies in urban transmission. The pressures in common use are 6,600, 9,000, 12,000, and 13,200 volts, and the standard frequencies are 25 and 60 cycles. The use of 25 cycles is preferable where the principal portion of the energy is converted to direct current for lighting and railway service, because the synchronous converter is more economical in operation and in first cost, at 25 cycles, than at 60 cycles. The use of 25-cycle energy for general lighting purposes is not satisfactory, and the transformers, motors, etc., are more expensive; hence it is necessary to convert the retail supply of alternating current to 60 cycles, to put it into form which is readily saleable.

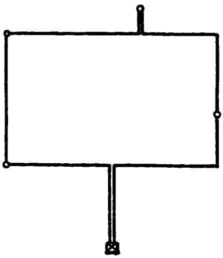


FIG. 7.—Ring feeder.

The use of 60 cycles is desirable where the major part of the energy is to be distributed as alternating current. This permits the use of transformer substations, instead of frequency-changing motor-generators which are necessary for securing 60-cycle energy from a 25-cycle supply.

22. Underground urban transmission. Urban transmission lines are necessarily placed underground to a large extent. This involves the use of paper-insulated lead-sheathed cables, which are made up with the three conductors of the circuit under one sheath. With standard 3.5-in. ducts, the largest size of cable which can be drawn into the duct is about 3 in. outside diameter, and this limits the maximum size of the conductor which can be used with a given thickness of insulation. At pressures of 6,600 volts, 400,000-cir. mil sector-shaped conductors are the largest in use. At 9,000 to 13,000 volts, about 300,000 cir. mils is the maximum size. This fixes the maximum load which can be carried continuously on such cables at from 4,500 to 6,000 kv-a.

In the larger cities where certain substations distribute loads of 8,000 to 15,000 kw., several cables are required to supply each substation, and it is desirable to have cables of the maximum size.

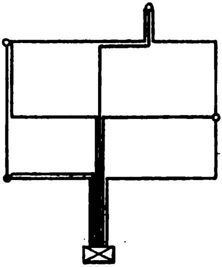


FIG. 8.—Radial feeders.

23. Reserve cables. A reserve cable must be provided for use in case of the failure of any of the cables which normally carry the load. This reserve may be secured by having a spare cable direct from the power-station, or by means of a **tie line** from a neighboring substation, or by the use of a ring system. When substation loads are small as compared with the cable capacity, the ring system is often found to be the most economical (Fig. 7). After the combined loads of the substations exceed the capacity of one side of the ring, additional capacity may be secured by adding **radial** feeders (Fig. 8). This is the situation in the larger cities where substation loads run from 2,000 kw. upward.

DESIGN OF CIRCUITS

24. General. The function of a conductor being to convey electrical energy from the source of supply to the consuming device, it must be of such size that it will not absorb too great a percentage of the energy or become overheated. The problem of designing a circuit is, therefore, one of determining what size of conductor should be used to limit the loss of voltage to a specified amount, when distance and current-strength are known, and also determining whether the size needed for the specified voltage drop is sufficient to carry the current safely.

25. Direct-current circuits. In direct-current circuits the current and the resistance are the only factors affecting the drop in voltage. The resistance of a mil-foot of pure annealed copper at 68 deg. fahr. being 10.4 ohms, that of a conductor D ft. long and M cir. mils in area is $R=(D\times 10.4)/M$. The drop with current I, therefore, is

$$E=IR=\frac{I\times D\times 10.4}{M}\ \text{(volts) or } M=\frac{I\times D\times 10.4}{E}\quad \text{(cir. mils)} \qquad (1)$$

If both conductors are of the same size the total drop is twice the drop in one conductor, as found by Eq. 1; if they are not of the same size, the drops in the different sizes must be computed separately and added together.

Example. A two-wire circuit is to carry a load of 100 amp. a distance of 300 ft. with a drop of 5 volts. What size of conductor must be used?

$$M=\frac{2D\times I\times 10.4}{E}=\frac{2\times 300\times 100\times 10.4}{5}=124{,}800 \text{ cir. mils.}$$

The nearest size is No. 2/0, A.W.G., which should be used.

26. The calculation of direct-current drop at any load is readily determined, where the size of the conductor is already fixed, by the use of the formula, $E=2IDR/1{,}000$, in which R is the resistance per 1,000 ft. of conductor, the formula gives the total drop in the two wires of the circuit.

Example. A circuit of 4/0 cable, 500 ft. in length, is to carry a load of 190 amp.; what will be the line drop? The resistance of No. 4/0 conductor is 0.049 ohm per 1,000 ft. (Par. **31**); $D=500$ ft. The drop is

$$E=\frac{2\times 190\times 500\times 0.049}{1{,}000}=9.3 \text{ volts.}$$

27. Three-wire direct-current circuits. In making calculations for a **three-wire Edison circuit,** separate computations are made for each conductor if the load is appreciably unbalanced.

Example. A circuit having two No. 4/0 A. W. G. outer wires and a No. 0 neutral, 1,000 ft. long, carries a load of 150 amp. on the positive side and 110 amp. on the negative side; what is the drop on each side of the circuit?

The resistance of 1,000 ft. of No. 4/0 = 0.049 ohm, and that of No. 0 = 0.098 ohm, per 1,000 ft. (Par. 31).

$E = IR = 150 \times 0.049 = 7.35$ volts drop on positive wire;
$E = IR = 110 \times 0.049 = 5.4$ volts drop on negative wire;
$E = IR = 40 \times 0.098 = 3.92$ volts drop on neutral wire.

The drop in the neutral wire is added to the drop on the "heavy" side and subtracted from that on the "lighter" side, making the total drop $7.35 + 3.92 = 11.27$ volts on the "heavy" side, and $5.4 - 3.92 = 1.48$ volts on the other side.

28. Alternating-current circuits. In an alternating-current circuit, voltage drop is caused by the combined effect of (a) resistance, (b) inductance, and (c) capacity. **The component of drop due to resistance** is governed by the same laws which govern direct-current circuits, and is in phase with the current. **The component due to inductance** (reactance drop) is a counter e.m.f. set up by the magnetic field as it reverses with each alternation; this back e.m.f. is a quarter cycle behind the current wave, and the component of impressed e.m.f. required to overcome it is a quarter cycle ahead of the current. The resistance drop and the reactance drop may be represented, therefore, by two sides of a right triangle.

The reactance of a circuit is ωL, where $\omega = 2\pi n$ and n = frequency in cycles per second; L = inductance in henrys. The inductance is a measure of the number of lines of force per ampere linked with the circuit; it increases, therefore, as the separation of the conductors of the circuit is increased, or with the introduction of iron into the magnetic field, since either of these increases the number of lines of force linked with the circuit.

29. Table of wire resistance and reactance. The table in Par. 31 gives the reactance drop in volts per ampere, for 1,000 ft. of conductor, for the distances of separation and sizes of wire commonly used in transmission and distribution work. It should be noted that the *reactance increases as the separation is increased.*

30. Example of calculation of resistance and reactance drops. A single-phase circuit 10,000 ft. long operates at 60 cycles and carries a load of 100 amp., with No. 0 wires 12 in. apart. What are the values of the inductive and the ohmic components of drop, and the impedance drop? The reactance per 1,000 ft., per amp. per wire, for No. 0 wires 12 in. apart is $X = 0.1043$. The resistance is 0.098 ohm. per 1,000 ft. The inductive component of the impedance of the circuit is

$X = 2D \times I \times 0.1043/1{,}000 = 2 \times 10{,}000 \times 100 \times 0.1043/1{,}000 = 208.6$ volts.

The ohmic component is $R = 2 \times 10{,}000 \times 100 \times 0.0981/1{,}000 = 196.2$ volts.

The impedance drop in the circuit is

$$\sqrt{(209)^2 + (196)^2} = 286 \text{ volts.}$$

The length of the line OA in Fig. 9 is proportional to the resistance component, that of AB represents the inductive component and OB the resultant of the two. If the circuit consisted of two No. 6 wires the resistance component would be 788 volts, the inductive component 241 volts, and the impedance drop would be

$$\sqrt{(788)^2 + (241)^2} = 824 \text{ volts.}$$

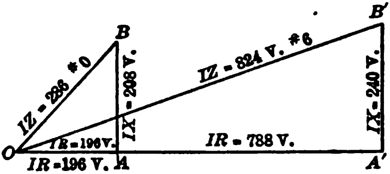


Fig. 9.—Resolution of ohmic drop and inductive drop to obtain total or impedance drop.

The e.m.f. diagram for the latter case, in Fig. 9, is $OA'B'$. It is apparent that the ratio of resistance to inductance decreases as the size of wire is increased, so that increasing the size for the purpose of reducing the pressure-drop becomes less effective in the larger sizes. It is preferable to install an additional circuit if facilities will permit.

31. Table of Resistance Drop and Reactance Drop in Volts per Amp., per 1,000 ft., per Wire, at 60 Cycles

Size in cir. mils or A.W.G.	Lb. per 1,000 ft. bare.	Lb. per 1,000 ft. T. B. weatherproof.	Resistance, ohms per 1,000 ft. at 68 deg. fahr.	Volts drop per amp. per 1,000 ft. of (one) wire at 60 cycles										
				Distance between centres										
				¾ in.	1 in.	2 in.	3 in.	6 in.	12 in.	18 in.	24 in.	36 in.	48 in.	60 in.
1,000,000	3,050	3,610	0.01035	......	......	......	......	0.063	0.0784	0.0877	0.0943	0.1036	0.1102	0.1153
500,000	1,525	1,870	0.0207	......	......	......	......	0.071	0.0864	0.0957	0.1023	0.1116	0.1182	0.1233
350,000	1,068	1,320	0.0296	......	......	......	......	0.0746	0.0905	0.0998	0.1064	0.1157	0.1223	0.1274
0000	640.5	754	0.0489	0.0328	0.0394	0.0553	0.0646	0.0805	0.0964	0.1057	0.1123	0.1216	0.1282	0.1333
000	508	614	0.0617	0.0355	0.0421	0.058	0.067	0.0832	0.0991	0.1084	0.1150	0.1242	0.1308	0.1360
00	402.8	486	0.0778	0.0381	0.0447	0.060	0.070	0.0858	0.1017	0.1110	0.1176	0.1269	0.1335	0.1386
0	319.5	388	0.0981	0.0408	0.0474	0.0633	0.0726	0.0885	0.1043	0.1136	0.1202	0.1295	0.1361	0.1412
1	253.3	312	0.1237	0.0435	0.0501	0.0659	0.0752	0.0911	0.1070	0.1163	0.1229	0.1322	0.1388	0.1439
2	200.9	254	0.156	0.0461	0.0527	0.0686	0.0779	0.0938	0.1097	0.1190	0.1256	0.1348	0.1414	0.1466
4	126.4	163	0.248	0.0514	0.0580	0.0739	0.0832	0.0991	0.1150	0.1243	0.1309	0.1402	0.1468	0.1519
6	79.46	112	0.394	0.0567	0.0633	0.0792	0.0885	0.1044	0.1203	0.1296	0.1362	0.1455	0.1521	0.1572
8	49.98	73.8	0.627	0.0621	0.0687	0.0845	0.0938	0.1097	0.1256	0.1349	0.1415	0.1508	0.1574	0.1625
10	31.43	50.2	0.997	0.0674	0.074	0.0898	0.0991	0.1151	0.1309	0.1402	0.1468	0.1561	0.1627	0.1678

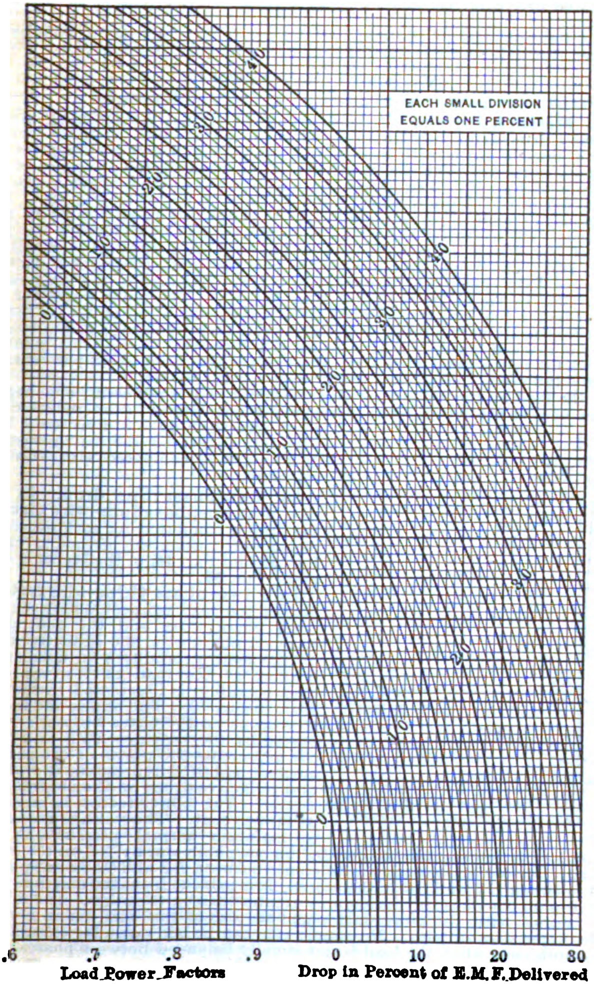


Fig. 11.—Mershon chart for calculating drop in alternating-current lines.

The net line drop is, therefore, 127 volts or 5.8 per cent. of the receiver voltage.

If a lighting load of 100 amp. at 100 per cent. power-factor were being carried, the inductance factor *ER* would be zero and *ON* would be

$$\sqrt{(2{,}288)^2 + (94)^2} = 2{,}290 \text{ volts.}$$

At 100 per cent. power-factor, therefore, the drop is 90 volts.

35. Mershon diagram. R. D. Mershon has devised a diagram by means of which **line-drop calculations,** which do not involve charging-current effects, may be made with facility and yet with sufficient accuracy for all ordinary purposes. This diagram,* Fig. 11, is based on the principles of the diagram of Fig. 10. The concentric circles are described about a centre, to the left of the diagram, which corresponds to the point *O* in Fig. 10. The divisions are made in percentages so that the scale may be applicable to any voltage. The use of the chart may be illustrated by the example of the circuit of No. 0 wire carrying a load of 100 amp. at a distance of 4,500 ft. (Par. 34). The ohmic drop is 88 volts, or 4 per cent., while the inductive drop is 4.3 per cent. The power-factor is 0.8. The base of the 0.8 power-factor line in Fig. 11 is the point *R* in Fig. 10. The point where the 0.8 power-factor line intersects the first circle is the point *E* in Fig. 11. Passing from this point to the right, 4 divisions, and then upward, 4.3 divisions, a point is reached which is a little below the 6-per-cent. circle; this point is equivalent to the point *P* in Fig. 10. The net line drop is 5.8 per cent. of 2,200 = 128 volts, compared with 127 volts by calculation.

If the load on the circuit has a power-factor of 100 per cent., one begins at the base of the 100-per-cent. power-factor line, passes to the right 4 divisions and then up 4.3 divisions. The drop is found to be about 4.1 per cent., or 90 volts, as compared with 90 volts calculated.

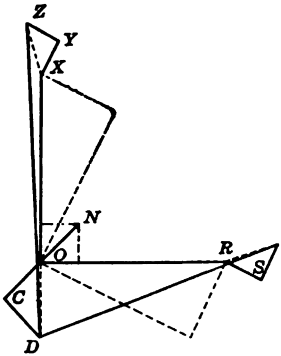


Fig. 12.—Diagram of potential drop on two-phase three-wire circuit.

36. Two-phase line drop. In the case of a **two-phase four-wire circuit** the drop is computed for each phase independently, using the method given in Par. 33 and Par. 34, or the Mershon diagram, Par. 35.

In a two-phase three-wire system having the load connected between the outer phase wires and the neutral or common phase wire, the inductive drop on the neutral produces an unbalanced pressure at the load or receiver end. This condition is illustrated in the diagram in Fig. 12. The ohmic and inductive drops on the outer wires are represented by the triangles *XYZ* and *RST*. *ON* represents the phase of the neutral current and *OCD* represents the ohmic and inductive drops on the neutral conductor. The power-factor is assumed at 90 per cent. The voltage necessary to maintain normal pressure at the feeder end is represented by line *DZ* on one phase and by *DT* on the other phase. The net line drop is the difference between *DZ* and *OX* in one phase, and between *DT* and *OR* in the other. It is evident from the diagram that the drop on one phase is considerably greater than on the other. The difference varies with the power-factor and the size of the wire, being greater with larger sizes of wire. No simple rule can be laid down for calculating such problems, when the load is not equally balanced between phases, and a graphical solution is usually the most practical.

37. Drop in three-phase three-wire symmetrical circuits. In a three-phase three-wire circuit with conductors symmetrically arranged and carrying a balanced load, the inductive effect is the same in each wire and

* *American Electrician,* June, 1897.

the calculation of drop may be made exactly as it would be for a single-phase circuit carrying one-half the load.

As the currents in the three wires are 120 deg. apart in time phase, the ohmic drop for the two wires making up any one phase is not twice that of one wire, as it is in a single-phase two-wire circuit, but is 1.73 times this drop. The inductive component of drop is also 1.73 times that of a single wire, for the loop. If the load on a three-phase circuit were the same as on the single-phase circuit in the previous example (Par. 34), the current per wire in the three-phase circuit would be

$$\frac{100\times1.732}{3}=57.7 \text{ amp.}$$

The drop at 100 amp. on the three-phase circuit would be $(5.8/2)\times1.73=5.0$ per cent., and at 58 amp. the drop would be 58/100 of 5 per cent., or 2.9 per cent. The single-phase drop at the same load was found to be 5.8 per cent., or twice the three-phase drop.

Therefore, for the same load and equal line drop, the size of the conductor in a three-phase circuit may be one-half that of a single-phase circuit. There being three wires in the three-phase circuit, it follows that the *weight of copper which is required for a three-phase circuit is three-quarters of that required for single-phase* transmission, with equal pressures between phase-wires, equal loads and equal line drops.

38. Drop in three-phase three-wire unsymmetrical circuits. When the arrangement of conductors is not symmetrical, the inductive component of drop is different among the different pairs of wires, on account of the different distances between centres. The most common case is that in which the wires are arranged on a cross-arm in the same horizontal plane. In such cases the equivalent of a symmetrical arrangement can be secured by **transposing** the conductors at proper intervals. This is not necessary in 2,200-volt distributing feeders which are equipped with line-drop compensators, as they can easily be adjusted to correct the unbalanced conditions.

The calculation of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Loads which are not unbalanced more than 10 per cent. to 15 per cent. may usually be averaged and considered as balanced for practical purposes. In systems where the lighting service is all on one phase, and the third phase wire carries a small scattered load of three-phase motors, the lighting phase may be considered as a single-phase circuit in computing the drop. However, as the motor load increases, the drop in the lighting phase becomes less for a given current value, until, when the current in the other phases equals that in the lighting phase, the drop in the latter is but 86.6 per cent. of what it would be with the same current carried for lighting service only.

39. Drop in three-phase four-wire circuits. The pressure at the transformer, on such systems, is the pressure between phase wires and neutral; when the latter is 2,200 volts, the pressure across phase wires is $2,200\times1.732=3,810$ volts. With **balanced load** the neutral conductor carries no current and the drop is that in the phase wires only. The resistance drop at 100 amp. on a No. 0 circuit 9,000 ft. long is $100\times9\times0.0981=88$ volts. This is 4 per cent. of 2,200 volts. Assuming a 12-in. spacing, single-phase, the inductive component of drop is $100\times9\times0.1043=94$ volts, or 4.3 per cent. At 80 per cent. power-factor, by the Mershon diagram (Fig. 11), the total drop is 5.8 per cent. The size of wire for a given load and drop, three-phase, is one-half what it would be for a single-phase circuit, or, assuming wires of equal size, the distance may be doubled for the same drop as compared with a single-phase circuit.

In the case of an **unbalanced four-wire circuit**, which is the more usual condition, the effect of the drop on the neutral wire must be taken into consideration. In general, the effect of the unbalance is to increase the drop on the more heavily loaded phases and decrease it on the lightly loaded phases, in comparison with the drops at balanced load, as shown in the case of the three-wire two-phase circuit above. A graphical solution of the problem of determining line drop in unbalanced three-phase four-wire circuits is shown in Fig. 13. This diagram is constructed on a principle similar to that used in Fig. 12 for a two-phase circuit.

The load on A phase is heavier than that on B and C, and the drop OB due to the neutral current is added almost directly to the drop *XZ* on the *A*-phase conductor.

The net drop on *A* phase is *EZ–OX*, that on *B* phase is *ET–OR* and on *C* phase it is *EW–OU*.

Where line-drop compensators are employed in each conductor, only the individual calculations for the four conductors are required, as the compensator corrects for the effect of the neutral drop.

40. Skin effect is an alternating-current phenomenon (Sec. 2, and Sec. 4, which materially affects cables of large cross-section, due to the fact that the currents passing through the strands around the outer surface of the cable encounter less inductance and impedance than the strands near the centre, thus causing the outer strands to carry more current, proportionately, than the inner strands. It is desirable, therefore, to build up large cables about a core of non-conducting material. Cables of over 500,000 cir. mils are often made in this manner where they are to be used in 60-cycle systems, and cables of more than 1,000,000 cir. mils for 25-cycle systems.

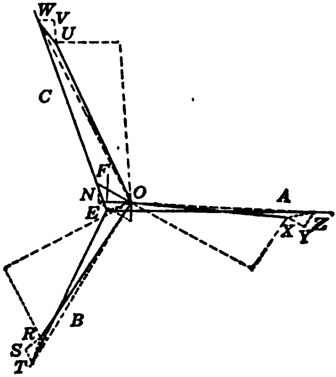


FIG. 13.—Diagram of drops in a three-phase four-wire circuit.

The increase in effective resistance due to skin effect is approximately proportional to the product of the frequency and the circular mils, as shown in the following table in Par. 41.

41. Table of Skin-effect Coefficients

Cir. mils × frequency	Coefficient	
	Copper	Aluminum
10,000,000	1.000	1.000
20,000,000	1.008	1.000
30,000,000	1.025	1.006
40,000,000	1.045	1.015
50,000,000	1.07	1.026
60,000,000	1.096	1.04
70,000,000	1.126	1.053
80,000,000	1.158	1.069
90,000,000	1.195	1.085
100,000,000	1.23	1.104
125,000,000	1.332	1.151
150,000,000	1.433	1.206
175,000,000	1.53	1.266
200,000,000	1.622	1.33

To determine the skin effect of a copper cable having an area of 1,000,000 cir. mils, carrying current at 60 cycles, refer to the table, opposite the product 60,000,000. The coefficient is 1.096. The resistance of a 1,000,000-cir. mils cable per 1,000 ft. being 0.01035, the effective resistance at 60 cycles is $0.01035 \times 1.096 = 0.01134$, or 9.6 per cent. more than with continuous current. The resistance of a 1,500,000-cir. mils cable is increased 19.5 per cent. at 60 cycles. The current-carrying capacity of large cables is reduced in proportion to the reciprocal of the skin-effect coefficient; that is, if the coefficient is 1.096, the capacity is only $1/1.096 = 91.2$ per cent. of that with continuous currents.

42. Effect of electrostatic capacity. At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered. At transmission voltages it is a matter of considerable importance in many cases (Sec. 11). The electrostatic capacity of an overhead circuit is fixed by the distance between the conductors and by their size; with insulated conductors (aerial or in cable), the capacity is further affected by the dielectric constant (Sec. 4), of the insulating material. The mutual capacity of a single-phase uninsulated circuit strung in the open air, per 1,000 ft. of circuit, is given by

$$C = \frac{0.003677}{\log \frac{d}{r}} \quad \text{(microfarads)} \qquad (2)$$

where d is the distance between centres of conductors and r is half the diameter (radius) of the conductor. The logarithm used is the *common logarithm.*

43. Charging current. The charging current of a single-phase circuit is given by

$$I = \frac{6.284 DnCE}{1{,}000{,}000} \quad \text{(amp.)} \qquad (3)$$

where D is the length of circuit in thousands of feet, n is the frequency, C is the capacity in microfarads, and E is the effective voltage between conductors. The charging current of a symmetrical three-phase circuit, between phase wires, is $2/\sqrt{3} = 1.155$ times that of a single-phase circuit with equal spacing between phase wires.

When an inductive load is carried on the line, the lagging component of the load current tends to offset the leading current required to charge the line. The tendency of the charging current to raise the power-factor of the line current thus results in a corresponding tendency to reduce the line drop where the load is of an inductive character. (For full treatment of the effect of capacity on line drop, see Sec. 11.)

44. Electrostatic capacity of cables. In underground cable work the effect of charging current is greatly increased by the reduced separation of the conductors. The charging current cannot be determined so easily, however, since the dielectric constant of the insulation must be taken into account. The mutual capacity of a three-phase three-conductor cable between conductors, per 1,000 ft., is given by

$$C = \frac{0.00735\ K}{\log \frac{3a^2\ (R^2 - a^2)^3}{r^2\ (R^6 - a^6)}} \quad \text{(microfarads)} \qquad (4)$$

When K is the dielectric constant, a is the distance from the centre of the cross-section of the cable to the centre of the conductors, R is the radius of the inside of the lead sheath, and r is the radius of the conductors. The *common logarithm* should be used.

45. Dielectric constants of cable insulation. The value of K, the dielectric constant, is determined by tests on samples of cable. It varies with different materials, and with variation of temperature with the same material. The general effect of increase in temperature is to decrease the dielectric constant, and increase the dielectric loss. The length and the voltage of cable systems are usually such that the charging current is not sufficient to cause any operating inconvenience.

46. Current-carrying capacity of conductors. The energy absorbed by a circuit, I^2R, is dissipated in the form of heat, and tends to raise the temperature of the conductor. The maximum current-carrying capacity of a conductor is dependent upon whether it is installed in open air, in conduit or underground. The character of the insulation is also a factor, since certain kinds of insulation may be safely operated at higher temperatures than others.

The insulation of rubber-covered conductors should not be operated regularly at temperatures above about 50 deg. cent. (122 deg. fahr.). Weatherproof and other fibrous types of insulation may be operated at temperatures as high as 65 deg. to 70 deg. cent. (149 deg. to 158 deg. fahr.). Conductors used inside of buildings are subject to the requirements of the National

Electrical Code, which limits the current in rubber-covered cables to values such that the temperature rise will not exceed about 15 deg. cent. (59 deg. fahr.). This represents a temperature of about 40 deg. cent. (104 deg. fahr.) during summer months, or in parts of buildings such as engine rooms which are normally above outside air temperature. Slow-burning insulation is accordingly required in places where the temperature is likely to be above 45 deg. cent. (113 deg. fahr.).

47. Table of Current-carrying Capacity of Wires and Cables Under Various Conditions

Size, A.W.G. or cir. mils	National electrical code		Lead-covered cables		
			Single conductor		
	Rubber ins. (amp.)	Slow-burning ins. (amp.)	Rubber 30 deg. cent. rise (amp.)	Paper or cambric, 40 deg. cent. rise (amp.)	Three conductor paper ins. 45 deg. cent. rise. (amp.)
14	15	20	....	....	....
12	20	25	....	....	....
10	25	30	20	22	....
8	35	50	30	34	26
6	50	70	50	56	48
4	70	90	78	87	68
3	80	100	98	110	81
2	90	125	121	134	93
1	100	150	145	160	110
0	125	200	169	187	132
00	150	225	192	210	150
000	175	275	245	270	190
0000	225	325	285	315	225
250,000	235	350	320	360	255
300,000	275	400	370	415	300
400,000	325	500	460	515	370
500,000	400	600	550	605	....
750,000	525	800	750	830	....
1,000,000	650	1,000	900	1,030	....
1,500,000	850	1,360	1,200	1,450	....
2,000,000	1,050	1,670	1,400	1,590	....

48. Current-carrying capacity of underground cables. The rise of temperature of underground cables depends upon the amount of energy liberated by all the cables in the duct line, and upon the ability of the cables and ducts to radiate the heat to the surrounding earth. The laws governing the radiation of heat from cable conductor to lead sheath and thence to earth have been studied by various investigators. S. Dushman* has derived a formula by which the temperature of the copper may be calculated from observations taken on the lead sheath, as follows:

$$t = K \log \frac{D}{d} \frac{(I^2 \times 1{,}000)}{(\text{cir. mils})} \text{ (deg. cent.)} \qquad (5)$$

in which t is the fall of temperature in deg. cent. from copper to sheath, D is the inside diameter of sheath in inches, d is the diameter of the conductor (inches), I is the current (amperes) and K is a constant varying with the type of cable. For single-conductor cable, $K = 0.27$; for two-conductor cables $K = 0.6$; and for three-conductor cable, $K = 0.9$. The *common logarithm* is used.

The temperature of the conductor may thus be calculated from sheath

* Dushman, S. *Trans.* A. I. E. E.; Vol. XXXII, 1913, p. 165.

measurements without taking resistance measurements of the copper. This formula is of great practical value where cables cannot be taken out of service to make resistance measurements. Tests made on cables in service verify Dushman's formula with sufficient accuracy for practical purposes.

49. The radiating capacity of cables in the central ducts of a large underground line is less than that of the cables in the peripheral ducts, and the temperature of the former tends to become higher when the ducts are well filled. The effect of the position of cables in a duct line has been studied by H. W. Fisher.* The results of his tests indicate that with a nine-duct line the rating of a cable should be reduced about 15 per cent. from its capacity in a four-duct line; while in a sixteen-duct line it should be reduced about 40 per cent. This is true only when there are working cables in all the ducts of the line.

50. The carrying capacity of multiple-conductor cables is less than single-conductor cables of the same size, because of the larger energy loss in proportion to the radiating surface. Duplex cable has about 90 per cent. of the carrying capacity of single-conductor cable; concentric cable, 80 per cent.; and three-conductor cables, 75 per cent. The maximum temperature at which paper or cambric should be operated is about 65 deg. cent. (149 deg. fahr.). The temperature may be pushed above this figure occasionally for a short time, but if operated continuously above 65 deg. cent. the paper will be injured.

SUBSTATIONS

51. The function of a substation is to convert energy received from a bulk-supply system, at the transmission voltage and frequency, to energy suitable for distributing purposes. The energy distributed may be in the form of direct current at the voltage at which it is utilized, or in the form of alternating current at a voltage suitable for general distribution through step-down transformers located at suitable points in the district served. The expense of installing and operating a substation must be justified by the saving made by the shortening of distributing feeders and the reduction in feeder losses incident thereto.

52. Substation location. The distance between substations depends upon the voltage of distribution and the density of the load. The average length of the distributing feeders should be such that the total investment in feeder conductors and substation equipment is a minimum.

In low-tension systems it is usually found desirable to locate substations approximately 1 mile apart, except in very congested districts where they are sometimes located less than 0.5 mile apart, on account of the very large loads to be carried.

In 2200-volt alternating-current distribution, substations may be spaced from 2 to 3 miles; in four-wire systems operating at 2,300–4,000 volts, they may be located from 4 to 6 miles apart, in scattered districts. In the outlying parts of the larger cities they are usually found from 2 to 3 miles apart on account of the density of the load.

53. Substation classification. Substations may be divided into three principal classes: (a) those in which transformers change the pressure from that used in transmission to the distribution voltage; (b) those in which frequency changers convert energy from one frequency to another and from the transmission voltage to the distributing voltage; and (c) those in which the transmitted energy is converted by synchronous converters to continuous current at low voltage.

54. General features. Each of these classes of substations (Par. 53) has certain elements which are common to all. Each is served by incoming transmission lines which are terminated in oil switches and connected thence to a high-tension bus system. One side of the converting apparatus is connected to the high-tension bus and the other side to two or more distributing busses. From these busses the outgoing feeders are taken off through suitable feeder switches, in conjunction with regulating apparatus.

55. Substation building. The size of the lot and the dimensions of the building should be such as to permit an arrangement of apparatus which will not be unduly crowded, and which will permit the installation,

* Fisher, H. W. *Trans.* A. I. E. E.; Vol. XXII, 1903, p. 440.

repair and maintenance of the equipment at minimum cost. Where further growth is probable, due regard must be had for subsequent extensions of building and equipment. Fireproof construction is warranted where continuous service is important.

56. Bus-bar arrangement. Fig. 14 shows a simple arrangement for a substation having one main line and one reserve line. Where the load is such that several direct lines are required, a **transfer bus** (Fig. 15) is very desirable. This permits the operation of any machine from any line and makes the reserve line available in case of the failure of any of the main lines.

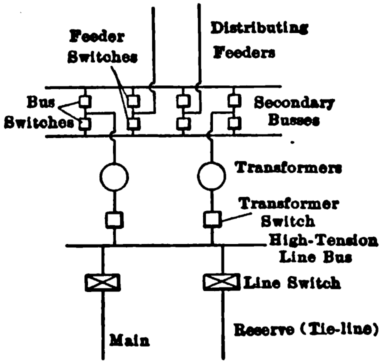


Fig. 14.—High-tension bus arrangement in a small substation.

57. Duplicate distributing busses are provided both as a means of operating the longer feeders at a higher bus pressure, and as a means of facilitating repair and maintenance work without interrupting service.

58. In continuous-current systems, two busses are required in practically all cases for **pressure control** during the heavy-load period, and in the larger substations it is sometimes necessary to provide **three busses** to take care of certain feeders which are exceptionally long or very short.

59. Transformer substations. The simplest type of substation is that which transforms alternating-current energy from one voltage to another

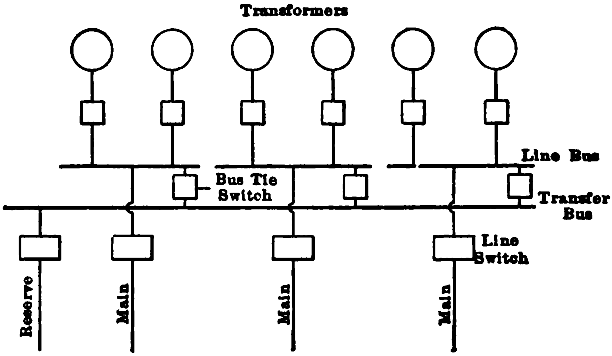


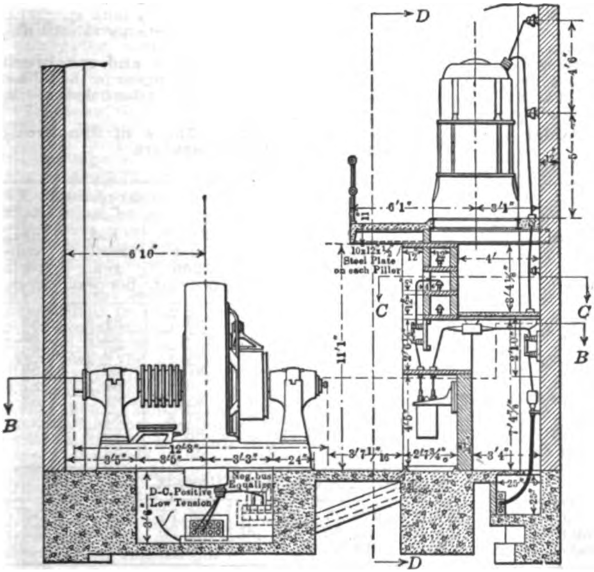
Fig. 15.—Bus arrangement in a large substation.

and requires, therefore, only transformers for the converting equipment. Both oil-cooled and air-cooled types of transformers are used for this purpose, with either single-phase or three-phase units. Oil-cooled units are preferable where the substation may be left without attendance during certain hours of the day. Oil-insulated, water-cooled transformers are used quite generally where there is an ample supply of cooling water.

Single-phase units are commonly employed where capacities of less than 1,000 kw. are required, although there is no settled practice in this regard.

Three-phase units are less expensive than single-phase units, particularly in the larger sizes, and require considerably less floor space.

60. Frequency-changer substations. Where the transmitted energy is converted to another frequency, the equipment consists of a motor generator, usually of the synchronous type; the motor is usually wound for the transmission voltage, to avoid the investment in transformers, where the voltage is less than 15,000 volts. This type of apparatus requires an exciter equipment, which may be driven by the machine itself, or by a separate motor. There should be at least one separately driven exciter equipment in a station where the exciters are direct connected.



Section *A-A* Incoming Line

FIG. 16.—Synchronous converter substation.

61. The synchronizing equipment of frequency-changer sets must be so arranged that synchronising can be done at both frequencies. When the machine is brought into step on the transmission side, the arrangement of the poles is such that the generator end is held with a fixed angle of phase displacement from the supply system, except for one particular (and correct) position of the motor fields. In a 25-cycle to 60-cycle frequency changer having ten and twenty-four poles respectively, there are *five* positions in which the 25-cycle machine may come into synchronism, only *one* of which will permit the 60-cycle (generator) end to be synchronised with another frequency changer already in operation. The 60-cycle end must be synchronized by slipping poles until it comes into phase. Where the frequency changer is being synchronized with a generating system, it is necessary to advance or retard the phase of the 60-cycle generators.

62. Continuous-current substations. A continuous-current supply is usually derived from transmission systems by the use of synchronous converters, or motor-generators. The synchronous converter is universally employed where the transmission system is operated at 25 cycles, as the converter is less expensive in first cost and more efficient in operation than a motor-generator. Converters have been little used in 60-cycle systems until recent years. The development of the interpole converter has minimised the tendency of 60-cycle converters to hunt and flash over.

Where motor-generators are employed both synchronous and induction types of motors are in use. The induction motor has the advantage of greater stability than the synchronous motor in times of disturbance to the frequency or the voltage of the system. The induction motor, however, has a power-factor (lagging) of about 85 per cent., whereas the synchronous motor has an adjustable field and may be operated (overexcited) with a leading power-factor, thus raising the power-factor of the generating system. It has become customary, therefore, to employ both synchronous and induction types of motors in converting 60-cycle energy to continuous-current energy, in order to secure the advantages of both.

Efficiencies and first costs of motor-generators and synchronous converters at one-half, three-quarters, and full load appear in the following table (Par. 63), compiled from a paper read by E. W. Allen before the Association of Edison Illuminating Companies, 1908.

63. Tables of Efficiencies, Cost and Floor Space of Synchronous Converters and Motor-generators

Efficiencies

Rating, kw.	Per cent. load	25 cycles			60 cycles		
		Syn. mot.-gen. per cent.	Ind. mot.-gen., per cent.	Syn. converter, per cent.	Syn. mot.-gen., per cent.	Ind. mot.-gen., per cent.	Syn. converter, per cent.
300	100	84	85.3	89.5	86.7	84.8	88
300	75	82.3	83.3	88.5	85	82.3	86.7
300	50	77	79.8	86.5	81.7	79	82.5
500	100	85.5	86.8	90.8	87.8	86.3	89
500	75	83.7	84.8	90.3	86	84.3	87
500	50	79.5	82	88.3	83	81	83
1000	100	87.5	87	91.8	87.8	87	....
1000	75	86	85.8	90.5	86	85.3	....
1000	50	82.2	82.3	90	83	82	....

Approximate Cost per Kilowatt

300	......	$26.20	$26.35	$25.15	$25.75	$25.85	$25.00
500	......	24.70	24.35	22.00	23.20	23.40	22.70
1000	......	20.25	19.85	19.80	19.45	19.50	....

Floor Space, Square Feet

300	......	80	80	91	67	67	96
500	......	122	122	131	110	110	150
1000	......	136	136	170	140	140	.....

64. Motor-generator sets are commonly wound for the transmission voltage, and are started by the use of a compensator at fractional voltage. A single compensator is sufficient for a substation if a starting bus is provided, through which the same compensator can be used to start any of the units; a spare compensator should be in reserve.

65. The synchronous-converter substation, Fig. 16, is provided with transformers stepping down to the proper voltage for the alternating-current side of the converter. The transformers are commonly of the air-blast, three-phase type, as this form of equipment can be placed in a minimum of space.

66. Connection of neutral for three-wire continuous-current system.—The six-phase type of converter, wound for 250 volts, with a diametrical connection in order to provide for the neutral conductor, Fig. 17, is commonly employed for machines of 1,000 kw. and larger. Motor-generators are also designed for 250 volts, a small **balancer-set** being used to take care of the unbalanced load.

67. The regulation of pressure on the bus supplied by a synchronous converter is accomplished by the use of an induction regulator placed between the transformers and the converter. Some variation in pressure can be secured by manipulation of the converter field-rheostat, but this affects the power-factor and it is not depended upon for pressure control.

68. In the split-pole type of converter, which has been introduced in recent years, considerable range of **pressure regulation may be secured** by variation of the field rheostat without serious interference with the power-factor, and with this type of machine regulators are sometimes omitted.

69. Synchronous converters may be started in various ways, and it is usual to provide for at least one method of starting from both the alternating-current and the continuous-current sides. The converter may be started from the continuous-current side by the use of a starting rheostat in practically the same manner as that used in starting a continuous-current motor.

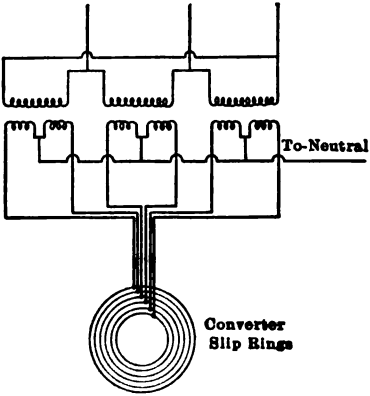


Fig. 17.—Six-phase diametrical connection for synchronous converter.

The converter may be started from the alternating-current side with the field open, by impressing approximately half the normal pressure, derived from a starting compensator or half-taps on the secondary of the transformer. The latter method is usually preferable. After the machine has come up to speed, the fields are excited and the polarity corrected, if necessary, by reversing the field, and slipping back one pole.

The current required in starting from the alternating-current side is from one and one-half to twice full-load current, while 25 per cent. to 30 per cent. of full-load current is sufficient for starting from the continuous-current side. The normal method of starting is, therefore, preferably from the continuous-current side.

70. Low-tension switchboards. The operation of distributing systems at low pressure involves very large currents and for that reason the most important part of a low-tension switchboard is the arrangement of heavy bars of copper, 3 in. to 6 in. wide and 0.25 in. to 0.5 in. thick, required for the safe handling of such currents. The important features of the design are to maintain sufficient clearance between bars of opposite polarity and to make the connections as short as possible consistent with accessibility for repair and maintenance work.

71. Feeder panels. The switchboard shown in Fig. 18 is based upon a vertical arrangement which permits ample separation of opposite polarities and minimum length of the bus-bar copper per feeder. Each vertical section comprises a set of switches and instruments for one three-wire feeder, the neutral not being brought into the main board. The neutrals are commonly carried to a separate bus in the basement, where they are connected without disconnecting switches other than removable copper links.

72. Switchboard voltmeters. It is customary to provide a single voltmeter with a multiple-point switch so arranged that one voltmeter can

79. End-cell switches for battery reserve. The tendency of the battery pressure to fall off at the time of discharge is provided for by the use of end-cell switches which are under the control of the operator, so that additional cells can be connected in series in sufficient number to hold the pressure up to the desired value. Normally, the end-cell switches are set so that the battery floats on the system. In any emergency which causes the bus pressure to drop, the battery immediately begins to supply energy, thus tending to maintain the bus pressure. A diagram of a battery, equipped to act as a reserve on two sets of busses, is shown in Fig. 19.

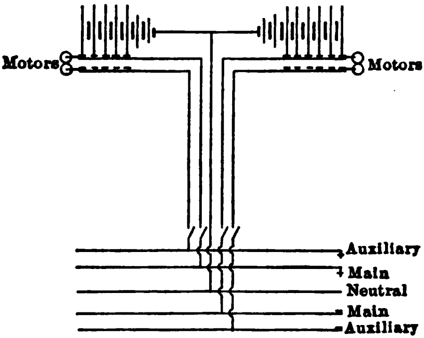


FIG. 19.—Arrangement of battery end-cells.

80. High-tension switchboards (up to 15,000 volts). In the design of high-tension switchboards, the space required for proper separation and insulation of the bus bars, and for the installation of oil-switches, necessitates an arrangement in which the busses and oil-switches are installed in some remote location such as a basement, the control panels being located at a point convenient to the operator.

Ammeters, voltmeters and wattmeters are operated with series (current) and shunt (potential) transformers, and oil-switches are usually of the remote-control type, so that the switchboard panel carries only low-tension apparatus. In smaller substations and in cases where only a few switches are installed, hand control is sometimes employed for the oil-switches on outgoing feeders.

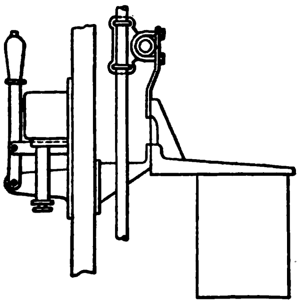


FIG. 20.—Tank-type of oil-switch.

81. High-tension bus bars commonly consist of cable or copper tubing mounted on suitable insulating supports, carried on a skeleton frame of pipe or angle iron. Oil-switches for distributing feeders are commonly mounted on the same framework in such a way as to provide an orderly system of connections from the busses to the switch terminals. Bus bars operating at voltages of 6,600 and upward are commonly installed in compartments, so arranged as to reduce to a minimum the probability of an arc between conductors of opposite polarity; this is very important where large amounts of energy are available to supply a short-circuit in case it should occur.

82. Disconnect-switches should be provided to permit oil-switches to be taken out of service during repair and maintenance work.

83. Two general types of oil-switches are employed, the **tank type** (Par. 84) for distributing-feeders and for the control of converters or transformers, and the **compartment type** (Par. 85) which is used for the control of transmission lines and at other points in the transmission system where the switch may be called upon to open automatically under short-circuit.

tive section *B* and the non-inductive section *A* in proportion to the load on the feeder. The secondary winding is divided into four sections of 5 volts each, and four sections of 1 volt each. The 5-volt terminals are connected to the contacts numbered 1, 2, 3, 4, and 5, and the one-volt terminals to the contacts numbered 6, 7, 8, 9, and 10. The arms may be independently adjusted, thus permitting any setting from 1 volt to 24 volts. The current from the shunt (potential) transformer *C* passes through the feeder voltmeter and the two movable arms to 3, thence through the portion of the non-inductive section, which is included between 3 and 5, and the portions of the inductive section between 6 and 9 and between 4 and 5, back to the transformer *C*. In completing this circuit, the impressed pressure has been opposed by a counter-e.m.f. of 10 volts in the non-inductive section and by 8 volts in the inductive section. The reading of the voltmeter is thus made

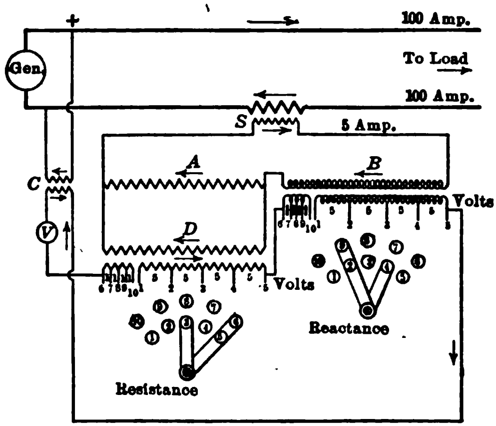


FIG. 22.—Circuits of Westinghouse line-drop compensator.

the same as it would be at the end of a feeder (in the secondary) having a resistance-drop of 10 volts (secondary) and a reactance-drop of 8 volts (secondary) at 100-amp. load.

89. In the General Electric line-drop compensator, Fig. 23, there is but one movable arm on each section, with eight points per section. Each point represents 3 volts when 1 amp. is flowing in the compensator circuit. The compensator shown (Fig. 23) is set so as to introduce in the voltmeter circuit an inductive counter-e.m.f. of 9 volts and a non-inductive counter-e.m.f. of 12 volts, when the feeder is carrying 100 amp.

90. Calculation of compensator setting for a single-phase feeder. Given a 60-cycle feeder of No. 0 A.W.G. copper wire, 5,000 ft. long, single-phase, wires 12 in. apart, series (current) transformer ratio 100 amp. to 5 amp., shunt (potential) transformer ratio 2,200 volts to 110 volts, how should the compensator be set?

The resistance drop on No. 0 wire, from Par. **31**, is 0.0981 volt per amp. per 1,000 ft.; hence the drop at 100 amp., for 5,000 ft., will be $2 \times 100 \times 5 \times 0.0981 = 98$ volts $= 4.5$ per cent. The inductive drop of No. 0, at 12-in. spacing, being 0.1043 volt per amp. per 1,000 ft., the drop at 100 amp. will be $2 \times 100 \times 5 \times 0.1043 = 104$ volts $= 4.7$ per cent. The resistance and the reactance should each be set at 5 volts ($= 0.045 \times 110$), to give constant pressure at the end of the feeder at all loads.

91. Calculation of compensator setting for two-phase feeders. In the case of **a two-phase, four-wire feeder**, the method of connection is similar to that used for a single-phase feeder, except that separate equipment is required for each phase, and hence the calculations are similar.

A **two-phase, three-wire feeder**, with unbalanced load requires one compensator in each wire, with connections as shown in Fig. 24. The values of resistance and inductance per 1,000 ft. used in the case of a single-phase feeder are based on the use of two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only.

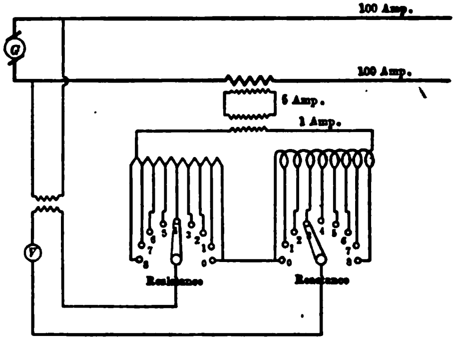


Fig. 23.—Circuits of General Electric line-drop compensator.

92. Calculation of compensator setting for three-phase feeders. In the case of a **three-phase, three-wire feeder** carrying unbalanced load, a compensator is required in each wire. For instance, if the feeder previously used for illustration were a three-phase, three-wire feeder (with symmetrical spacing of phase wires) carrying 100 amp. per wire, the ohmic drop in each wire would be $5 \times 100 \times 0.0981 = 49$ volts, and the inductive drop 52 volts.

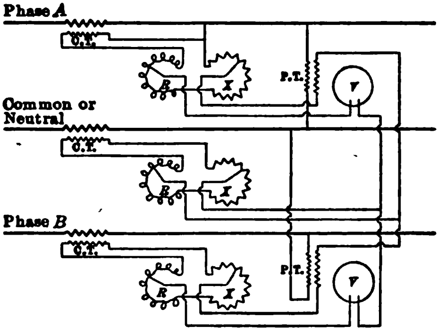


Fig. 24.—Compensator connections for two-phase three-wire system.

These values are respectively 3.8 per cent. and 4.1 per cent. of the pressure to neutral, 1.270 volts ($= 0.577 \times 2,200$).

In a **three-phase, four-wire feeder** operating at 2,200 volts between phase wires and neutral, the method of calculating the drop is as follows: Given a feeder of four No. 0 wires (12-in. spacing) running 5,000 ft. from the station as a three-phase feeder, the drop in each phase wire at 100 amp.

will be 49 volts, ohmic, and 52 volts, inductive. The working pressure being 2,200 volts, this is about 2.5 per cent. If the entire load of the feeder is delivered from this centre of distribution, the compensator on each phase wire

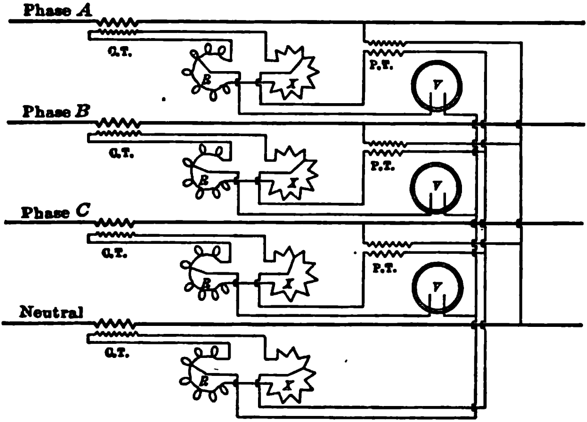


FIG. 25.—Compensator connections for three-phase four-wire system.

should be set at 2.5 per cent. on each dial; that on the neutral should be set at 2 per cent. on each dial, to take care of unbalanced load. If, however, the A-phase branches off with a neutral to a single-phase centre of a distribution 2,500 ft. beyond, there must be added to the A-phase setting, $2 \times 100 \times 2.5 \times 0.098 = 49$ volts $= 2.2$ per cent., making the new setting $2.5 + 2.2 = 4.7$ per cent. If the other phases branch to similar centres of distribution, at different distances, the drops must be computed similarly, and added to the three-phase drop. The connections of the compensators for a three-phase, four-wire feeder are shown in Fig. 25.

93. Automatic regulation of feeder voltage. In connection with automatic regulation the General Electric Co. has developed a device which serves as a line-drop compensator combined with a relay. This device, known as a "**contact-making voltmeter**," is shown in Fig. 26. It consists of a solenoid having windings which are tapped at various points and brought out to adjustable switches, as in the line-drop compensator. One winding produces a magnetic flux proportional to the pressure; another carries current in proportion to the load and opposes the flux due to the feeder pressure. This counter-

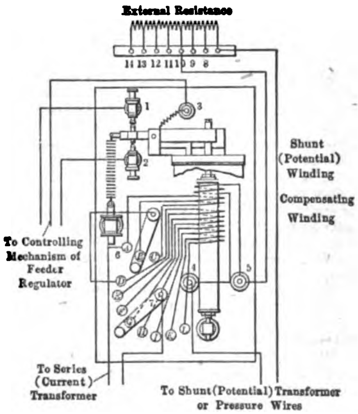


FIG. 26.—Automatic regulators for controlling feeder voltage.

magnetomotive force may be adjusted roughly by setting the proper switch on the points *A*, *B*, or *C*, and the finer adjustments are made by the points *D* to *L*. The pivoted bar carries the contacts which control the supply of energy to the feeder regulator.

As the load increases, the plunger falls until the contact is made which raises the pressure on the feeder. This increases the flux due to the pressure and the plunger rises sufficiently to stop the movement of the regulator until a further change in load or bus pressure occurs. This device gives very satisfactory results at all power-factors from 75 per cent. to 100 per cent.

94. Bus-bar voltage regulation. Where there is a variable motor load supplied by motor-generator converting equipment, it is desirable to maintain a constant bus pressure, in order to prevent the load variations from affecting the bus pressure and thus impairing the steadiness of voltage on the feeders supplying the lighting service. The automatic regulator devised by Tirrill has been successful in accomplishing this purpose.

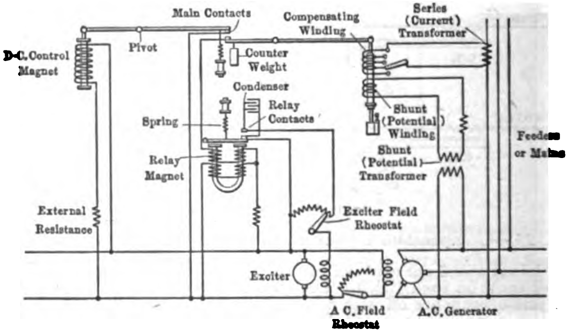


FIG. 27.—Connections of Tirrill regulator.

95. Tirrill regulator. The general scheme of connections is shown in Fig. 27. The secondary circuits of the shunt (potential) and series (current) transformers in the generator leads are connected through a solenoid in a compounding relation. The series section is subdivided so that different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other contact terminal of this relay circuit is carried on a similar lever which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main generator terminals tends to close it.

This closing of the circuit demagnetizes the relay, which is differentially wound, and its armature is withdrawn by a spring. This shunts the field rheostat of the exciter, increases its terminal pressure, and opens the relay circuit, thus weakening its pull.

Where there are several units in parallel in a station, the regulator may be applied to the exciter for a portion of them and the bus regulated for constant pressure with the series coil of the alternating solenoid cut out. With this arrangement, the bus pressure may be maintained constant at any desired value by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

SECONDARY DISTRIBUTION

96. The secondary mains of an alternating-current system serve users in a local area, while the primary mains supply larger areas. The standard system of secondary distribution in America is the **single-phase**,

three-wire Edison system at approximately 110–220 volts for lighting and small motor service, and 220-volt two-phase or three-phase for general motor service; 440 volts and 550 volts are also used to some extent for power systems in industrial plants. For the supply of mixed service of lighting and motors from a secondary network, the **four-wire, three-phase system** at 115–200 volts or 120–208 volts, approximately, is sometimes used.

97. The voltage of general distribution systems must be low enough to be adapted to incandescent lamps, fans, heating devices and other small accessories, which are preferably made for the voltages around 110. Motor voltages are higher in order to secure economy of conductor investment; this is especially true with large installations.

98. Transformers are usually wound for a ratio of 2,200 to 110–220 volts, though some of the systems where 115–230 volts are standard are using a ratio of 2,080 to 115–230 volts. This secondary voltage permits a spacing between transformers of 600 ft. to 800 ft.

99. In laying out secondary systems for lighting service, it is usual to limit the drop from transformer to consumer to about 2 per cent. where first-class service is required. In scattered districts where secondaries are too small and remote to warrant interconnection, the problem of design consists in striking a balance between the cost of conductors, and the cost of transformers and their losses.

By reaching out farther from the transformer with the secondary mains, the number of transformers is reduced, and, their average size being larger, their total cost is smaller. This is true because the cost per kilowatt is less for the larger sizes, and because the kilowatt capacity required per kilowatt connected is less for a large number of users than for a few.

100. Minimum annual cost. As the radius of distribution from the transformer becomes more than 500 to 600 ft., the cost of conductors increases very rapidly, and it becomes more economical to provide additional transformers. On the other hand, if too many transformers are used, the iron loss which goes on 24 hr. a day becomes excessive, and the investment per kilowatt in transformers is high. The minimum annual cost of a secondary system is that at which the fixed charges on conductors and transformers, plus the value of the iron loss, is a minimum. The iron and copper losses of standard American transformers appear in the table in Par. **101** (also see Sec. 6).

101. Losses and Efficiencies of Standard Transformers for Alternating-current Distribution

2,200 to 110–220 volts, 60 cycles

Rating kv-a.	Watts loss		Per cent. efficiency, full load	Per cent. regulation		Per cent. charging current.
	Core	Copper at 125 deg. fahr.		100 per cent. p-f.	80 per cent. p-f.	
1	20	26	95.8	2.61	3.18	5.5
1 1/2	25	37	96.2	2.47	3.10	4.0
2	30	46	96.5	2.33	3.00	3.6
3	34	70	96.8	2.36	3.01	3.0
5	40	82	97.2	2.08	3.12	2.5
5	45	102	97.3	2.08	3.10	2.3
7 1/2	62	137	97.6	1.84	2.93	2.2
10	80	163	97.8	1.66	2.85	1.9
15	105	233	97.9	1.58	2.80	1.6
20	131	295	98.0	1.52	2.96	1.5
25	147	351	98.2	1.47	2.90	1.3
30	163	411	98.2	1.46	2.90	1.2
40	205	476	98.3	1.30	2.80	1.2
50	240	605	98.4	1.20	2.70	1.0

Also see Sec. 6.

102. All-day efficiency of transformers. In a distribution transformer, the iron loss may reach a considerable percentage of the daily consumption of energy. A 5-kw. transformer which carries full-load 4 hr. a day delivers 20 kw-hr. per day, and has a copper loss of about 102 watts at full-load, while the iron loss would be about 45 watts. The copper loss per day would be about 410 watt-hr., while the iron loss would be 24×45 = 1,080 watt-hr. The total loss being 1.5 kw-hr., the all-day efficiency is 20/21.5 = 93.0 per cent., and the full-load efficiency is 5,000/5,150 = 97.1 per cent. It is apparent that the all-day efficiency varies with the **load factor** or hours' use of the maximum load.

103. Calculation of secondary mains. The most economica size of conductor and spacing between transformers for secondary mains may be determined approximately as follows:* assuming a load density per 1,000 ft. and an allowable pressure drop, determine the distance between transformers which will result in that drop with several sizes of conductor.

The investment in wire and transformers may then be found. The fixed changes in the investment plus the annual value of the iron losses in the transformer constitute the annual cost of this secondary main (exclusive of pole line or conduit). The minimum annual cost will be found to work out approximately as in the curves shown in Fig. 28.

104. Curves of cost variation, overhead distribution. The variation of the elements of cost as the spacings between transformers and the size of wire are changed, is illustrated by the curves in Fig. 28, which are based upon a load density of 50 kw. per 1,000 ft., with overhead lines. It is apparent from this curve that the minimum cost is found with No. 2 wire at a spacing of 600 ft. between transformers. The curves of total cost at other load densities are shown in Fig. 29.

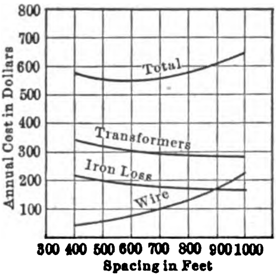


Fig. 28.—Elements of cost of secondary main.

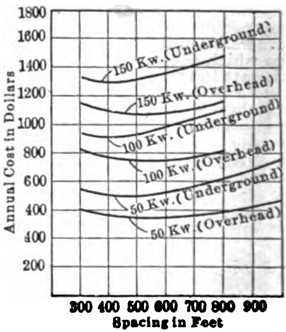


Fig. 29.—Economical spacing of transformers.

Where energy may be charged at less than 1 cent per kw-hr., or with water power, the decreased value of core loss tends to permit the use of smaller transformers, shorter spacings and a smaller size of wire.

105. Curves of cost variation, underground distribution. The curves for underground lines also appear in Fig. 29. The spacing for minimum cost is not materially changed, being about 500 ft. for each load density.

The flatness of the curve of total cost allows considerable flexibility in spacing, and it is generally preferable to use as few transformers as possi-

*Gear and Williams. "Electric Central Station Distributing System," '08.

ble with the larger sizes of conductor, so as to reduce the number of units to a minimum. Furthermore, it is usually desirable to **anticipate an increase in load** by installing a larger conductor than is required for immediate needs. The size of transformers is then gradually increased, from time to time, as the load increases.

106. Uneven load density. The curves (Figs. 28 and 29) are based on an assumption that the load is uniformly evenly distributed along the line throughout its length, but such is rarely the case in practice. At occasional intervals, department stores, churches or other large customers of energy throw heavy loads upon the line. It is necessary, therefore, to locate transformers near such large consumers' premises and design the mains between them to carry the scattered load.

107. Secondary networks. The gradual extension of mains on all streets results in a system of lines which is interconnected and becomes a network. **Transformers are preferably located** at intersections where they feed in all directions with the best economy of copper. In the design of such networks the sizes of secondary cable are fixed by the local conditions. The smaller consumers distributed along the routes are carried from mains of proper size, and the larger consumers such as theatres and department stores are cared for by a separate installation of transformers in the immediate vicinity of the consumers' premises.

108. Underground construction is often required in networks and this necessitates **manholes** of ample size for large transformers and such junction boxes as are necessary for operation. The space required is somewhat difficult to secure on account of pipes and other underground systems which limit the available space. In some cases it has been found desirable to install the transformers in a substation, supplying the network through low-tension feeders; this arrangement permits a saving in transformer investment and iron losses, as the diversity factor is better and the units are larger, but the cable investment is considerably greater.

109. Separate transformers for large motor loads. The design of secondary systems is subject to restrictions when **inductive loads**, such as arc lamps and motors, must be served along with incandescent lighting. The heavy starting-current required by induction motors may momentarily overload the transformer and the secondary main. This causes a flickering of incandescent lamps served in the vicinity. It is necessary, therefore, to install separate transformers for installations of motors if the best regulation is required for incandescent lighting. Motors larger than 10 h.p. can not usually be supplied from a lighting network without interfering with the service.

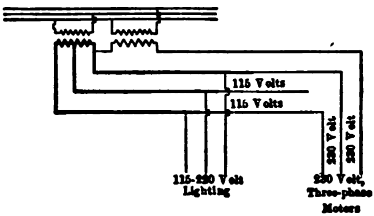


FIG. 30.—Three-phase secondary system, with single-phase lighting service.

110. Three-phase supply for mixed loads. In three-phase systems several methods of carrying mixed lighting and motor loads are in use. The most common method consists of **star-connected transformers supplying a four-wire main** operated at about 115 volts from phase to neutral and 200 volts across phase wires. The smaller lighting services are made three-wire and connected to two phases and neutral, and large services are balanced on three phases. Four-wire service is required wherever both lighting and motor service are supplied.

In another method, illustrated in Fig. 30, all the lighting is carried single-phase from a three-wire Edison main. Motors are served by the installation of additional smaller transformers and a fourth secondary (phase) wire. The lighting load is easier to keep balanced, and the higher diversity factor requires somewhat less transformer capacity for lighting.

111. Determination of transformer capacity. The selection of the size of transformers for various classes of consumers is important, since excess capacity involves idle investment and unnecessary core losses. Very few consumers use their entire connected loads at any one time. Where a number of consumers are served by one transformer, the various *maximum demands do not occur simultaneously* and therefore the resultant maximum demand is less than the sum of the individual demands. The demand must be ascertained by measurements which may be made by means of an ammeter or by a **Wright demand** indicator (Sec. 3).

Certain **ratios of maximum demand to connected load** may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These ratios or **demand factors** (Par. **112** to **118**) may then be applied with reasonable accuracy to the transformers for new consumers. The results of tests made on various groups of consumers in Chicago appear in Par. **112**.

112. Table of Demand Factors in Lighting Service
(Based on Chicago Experience)

Description of load	Number of customers	Kilowatts connected	Kilowatts demand	Demand factor (%)
Residence	137	84.7	18.9	22.3
Residence	68	126.6	15.75	12.4
Residence (119 kw.; stores 11 kw.)	196	129.5	28.85	22.3
Residence (1 customer, 7.5 kw.)	5	10.3	9.45	92.0
Residence 70 kw.; stores 7 kw.	77	77.0	21.0	27.3
Residence (59.7 kw.; hotel 48 kw.)	66	107.7	26.25	24.3
Residence (1 30-amp. rectifier)	121	183.5	30.5	16.6
Residence	34	47.5	10.5	22.2
Residence (2 30-amp. rectifiers)	19	79.2	15.7	19.8
Residence (1 30-amp. rectifier)	21	67.7	13.6	20.2
Residence (1 30-amp. rectifier)	21	54.1	13.1	24.3
Residence	47	68.7	8.4	12.2
Residence	144	129.95	22.6	17.4
Residence (4 30-amp. rectifiers)	43	59.0	26.6	42.0
Residence	85	99.65	16.1	16.1
Residence	84	112.5	14.7	13.2
Residence, 20 kw.; Stores 15.7 (hotel 25 kw.)	38	60.7	27.3	45.0
Residence	99	59.0	8.4	14.2
Residence	89	100.45	13.7	13.6

113. In store lighting the maximum demand for window lighting, signs and other display lighting is from 90 per cent. to 100 per cent. of the connected load. The demand on interior store lighting is from 50 per cent. to 70 per cent.

114. In residence lighting where the connected load is fifty lamps or less, the average demand factor of a group of residences is from 15 per cent. to 20 per cent. of the connected load; small residences and apartments having connected loads of forty lamps or less, average about 20 per cent. of the connected load.

115. In theatre lighting the border lamps and foot lamps, of several colors, are not used simultaneously; and the stage and the auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theatre the demand factor may be from 70 per cent. to 85 per cent., while in a large theatre it frequently runs as low as 50 per cent.

116. Influence of number of consumers on demand factor. In general, a higher ratio must be used where but few consumers are served from one transformer, than where there are more, as the occasional maximum demands of individual consumers are proportionately much larger.

117. The selection of transformers for motor loads is more difficult, as the maximum load may vary greatly from day to day or from month to month. Elevator and crane motors require transformers having 100 per cent. to 125 per cent. of the rated motor capacity, unless there are several motors supplied by one unit. This is necessary in order to hold up the pressure in starting. The average demand factors in motor service in Chicago are given in Par. **118.** These figures were made up from several thousand installations of continuous-current motors in Chicago, which were equipped with maximum-demand meters.

118. Table of Demand Factors in Motor Service
(Based on Chicago Experience)

Total installation in h.p.	Number of customers	Total h.p. connected	Average maximum h.p.	Ratio of max. to conn. h.p.
1 motor,				
1 to 5........	1177	2165	1862	86.1
6 to 10........	124	1036	676	65.3
11 to 20........	32	492	303	61.6
above 20.......	17	686	366	53.2
Total........	1350	4379	3207	73.3
2 motors,				
1 to 5........	177	412	285	69.1
6 to 10........	51	387	261	67.4
11 to 20........	30	438	288	65.9
above 20.......	6	203	74	36.5
Total........	264	1440	908	63.0
3 to 5 motors,				
1 to 5........	150	381	314	82.5
6 to 10........	42	290	238	82.1
11 to 20........	33	475	329	69.3
above 20.......	14	1245	657	52.7
Total........	239	2391	1538	64.3
6 to 10 motors,				
1 to 5.........	42	121	80	66.0
6 to 10........	21	157	98	62.4
11 to 20........	10	155	98	63.1
above 20.......	19	931	417	44.7
Total........	92	1364	693	50.8

SPECIAL METHODS OF TRANSFORMATION

119. General. The use of various primary and secondary voltages and systems gives rise to situations, at times, which require the distribution engineer to make use of special methods of transformation. Some of the combinations of apparatus and connections which are most likely to be used are presented herewith.

120. The connections of standard transformers are made with two primary and two secondary coils, which permits their use on 2,200-volt or 1,100-volt circuits. The secondary may be connected for 110 volts or 220 volts, or on the three-wire Edison system at 110–220 volts. Some systems use a transformer having windings for 1,040–2,080 to 115–230 volts.

121. Booster transformers. Where it is desired to raise or lower the pressure by a fixed percentage, as when line drop is excessive, this may be accomplished by a transformer used as a booster. This is a transformer so connected that the secondary is in series and in phase with the main line and thus the primary pressure is raised by the amount of the secondary voltage, as shown in Fig. 31.

When the secondary is reversed, the transformer becomes a "choke," or **negative booster** depressing the line pressure instead of raising it. The connections for 5 per cent. and 10 per cent. "boost" are shown in Fig.

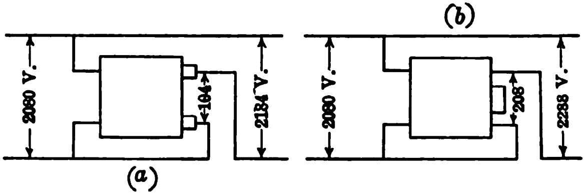


FIG. 31.—Booster transformer connection for positive boost.

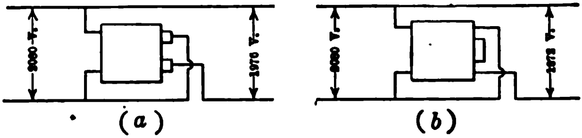


FIG. 32.—Booster transformer connections for negative boost or choking.

31, at *a* and *b* respectively. The corresponding connections for 5 per cent. and 10 per cent. choke (negative boost) are shown in Fig. 32.

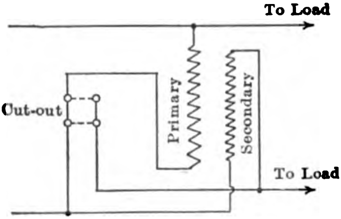


FIG. 33.—Connections of booster cut-out.

It is to be noted that the transformers used in these illustrations have a ratio of 10 to 1 or 20 to 1, and these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2,080 to 115–230 are used, the percentages are increased to about 5.5 per cent. and 11 per cent., respectively.

122. Precautions when installing boosters. If the primary of the booster is opened while the secondary is carrying the line current, the booster acts as a series transformer. The primary coils then generate a potential of 10,000 volts to 20,000 volts, or more, depending upon the load carried by the main circuit at the time. If a fuse is used in the primary, the blowing of the fuse will create this condition and the arc will hold across the terminals of the block, and is quite sure to break down the insulation of the primary coil.

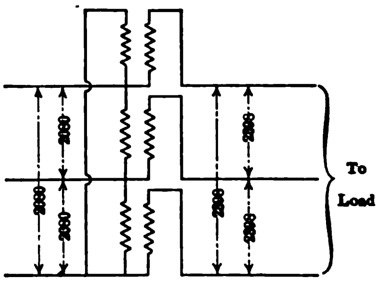


FIG. 34.—Connections of boosters in three-phase circuit.

The safest method of connecting or disconnecting a booster is to have the main line open while connecting it in or out of circuit. If the service cannot be interrupted, or if it is desired to switch the booster in or out at certain times, this may be accomplished by the use of a **series cut-out,** connected as shown in Fig. 33. The cut-out simultaneously opens the primary and short-circuits the secondary of the booster. Standard series-arc cut-outs should not be used where the line current is likely to be over 25 amp.

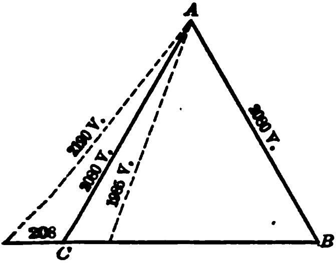


FIG. 35.—Effect of booster in one phase of three-phase circuit.

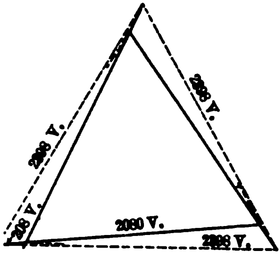


FIG. 36.—Effect of boosters in each phase of a three-phase circuit.

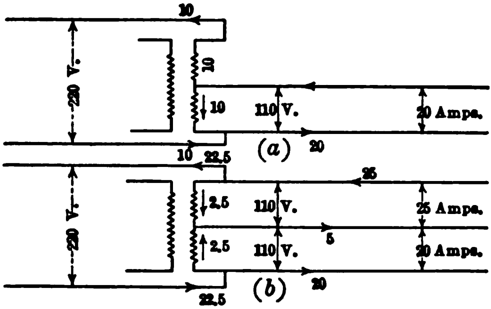


FIG. 37.—Connections of auto-transformers for 110-volt lighting.

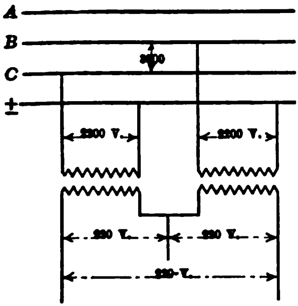


FIG. 38.—Open-delta connection of two transformers supplied from a three-phase four-wire system.

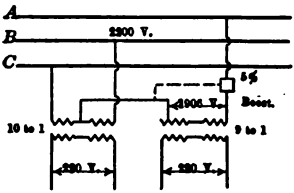


FIG. 39.—Transformation from three-phase to two-phase, or *vice versa*, with tee-connection.

123. The use of boosters in a delta-connected three-phase system is not so simple as in single-phase circuits. The booster secondary is looped into the line and pressure is taken for the primary from an adjoining phase, as in Fig. 34. The insertion of a booster on one phase affects the pressure on two phases, as shown diagrammatically in Fig. 35. The effect of a booster in each phase is shown in Fig. 36. Three boosters are required, therefore, to keep conditions in balance, in a three-phase three-wire circuit.

124. Auto-transformers. The use of 110-volt incandescent lamps in a 220-volt or 440-volt alternating-current system may be accomplished quite readily by the use of standard transformers used as auto-transformers. The connections in Fig. 37 show the methods of deriving two-wire and three-wire 110-volt distribution from a 220-volt system. When the lighting service is handled on a three-wire basis at 110-220 volts, the transformer carries only the unbalance of current; the primary winding is not used. Where 110-volt service is desired from a 440-volt plant, it may be secured from two transformers connected in series on the 220-volt side and in parallel on the primary side.

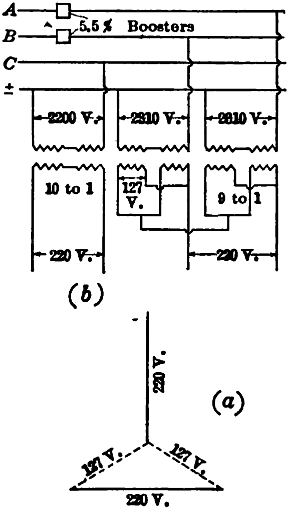


Fig. 40.—Two-phase service derived from a three-phase four-wire system with three transformers.

125. Three-phase conversion with two transformers. The cost of transformers for small three-phase motor service makes desirable the use of schemes of connections by which the three-phase secondary service may be derived from two transformers. Two schemes of connections are possible for this purpose, one known as the open delta and the other as the tee-connection.

The **open-delta connection** is merely an ordinary delta connection with one transformer left out (Sec. 6). Fig. 38 shows the open-delta connection supplied from a **three-phase four-wire** system. In this case the primaries are connected to two-phase wires and the neutral wire. In the open-delta connection the current in the transformer coils is 15.4 per cent. larger than with three transformers.

In the **three-phase three-wire** system, service may be given from two transformers with the **tee (T) connection** (Sec. 6). The current overload is 15.4 per cent.; as with the open-delta connection. This scheme cannot be used with standard 2,200-volt transformers on a four-wire system, as the principle of operation requires that the current divide and pass each way from the midpoint of the winding of one of the transformers, so that the magnetic field of one part balances the other.

126. Conversion from three-phase to two-phase, or vice versa. The **tee-connection** may be used in transforming from three-phase to two-phase, or *vice versa*, as shown in Fig. 39. with standard transformers having ratios of 9 to 1 and 10 to 1 respectively. If transformers having a ratio of 10 to 1 are available only, the right-hand transformer (Fig. 39) should be given a positive boost of 15 per cent. instead of 5 per cent. When using transformers having ratios of 9 to 1, the left-hand unit should be given a 10 per cent. negative boost, and the right-hand unit a 5 per cent. positive boost, in order to give 220-volt two-phase service from 2,200-volt primary mains.

127. Two-phase 220-volt service from a three-phase four-wire system may be secured with three standard transformers, connected as shown in Fig. 40. The unit at the left has a ratio of 10 to 1, and is connected from phase to neutral. The other two have ratios of 9 to 1, with their secondary coils in multiple, and are arranged as two limbs of a star-connection (Y), to give 220 volts across the outer wires. The three-phase system is therefore unbalanced by this arrangement, since half the energy is taken from one phase. The capacities of the transformers should be selected accordingly.

It is possible to use transformers with ratios of 10 to 1, but if this is done each of the phases supplying the right-hand transformer must be provided with a boost of 15 per cent.

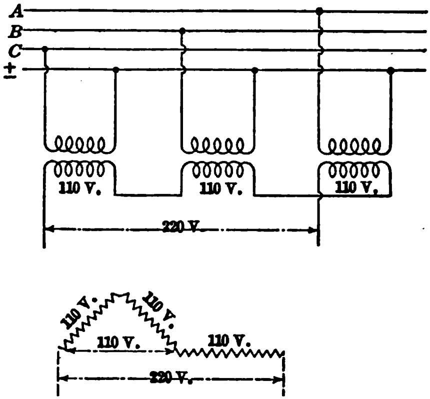


FIG. 41.—Conversion from three-phase to single-phase, with balanced load.

128. Conversion from three-phase to single-phase. In connection with electric welding and other work requiring single-phase energy in amounts so large that the unbalanced load is serious, the load may be equally distributed among the three phases by the scheme of connections shown in Fig. 41. Equal currents are drawn from the three phases to supply 220-volt single-phase energy. Each transformer must have capacity to carry the entire secondary single-phase current, so that the total transformer capacity must be 1.5 times the load.

PROTECTIVE APPARATUS

129. The insertion of fuses for protection in low-tension lighting systems has become universal, because of the low cost of fuses as compared with circuit breakers. In power systems where the circuits are opened frequently, the circuit-breaker is found preferable.

130. Plug-fuses. The fire hazard from the flash which occurs at the melting of a fuse led to the development of **enclosed fuses**, the earliest of which was the Edison plug-fuse, which is used very generally on circuits up to 20 amp.

131. Cartridge fuses. Cartridge fuses, consisting of a tube of fibrous material in which the fuse is mounted, with a filler of fire-resisting powders are used largely on circuit operating at 250 to 600 volts. Cartridge fuses have been fully standardized by the National Electrical Code as to voltage and current as follows: 250-volt: 0–30 amp., 31–60 amp., 61–100 amp., 101–200 amp., and 201–500 amp.; 600-volt: 0–30 amp., 31–60 amp., 61–100 amp., and 101–200 amp.

132. The law of the operation of fuses was discovered by Preece in 1888. It may be stated in the form,

$$\text{Current} = a\sqrt{d^3} \qquad (6)$$

On low-potential circuits the circuit-breaker consists of a switch of suitable design, with which is combined a series coil so arranged that it lifts a movable core and releases a spring-actuated mechanism which opens the switch. Circuit-breakers are designed so that they may be adjusted to operate at any point between 80 per cent. and 150 per cent. of their rated capacity.

In **high-potential systems** a series transformer may be installed at a convenient point to operate the tripping-coil of the circuit-breaker. On circuits operating at pressures above 600 volts the switch is designed to break in oil.

141. The operating mechanism of the circuit-breaker may be controlled by hand, or electrically by means of solenoids. In **hand-operated breakers** the energy required to open the circuit is stored in springs compressed during the act of closing. In **electrically operated breakers** the power for both closing and opening the circuit is supplied through solenoids or motors.

The larger sizes of circuit-breakers and those operating at the higher voltages are usually controlled electrically, on account of the power required, and because of the greater facility of operation. Continuous current is usually available in generating stations and substations, from the exciter system, and is therefore used for the operation of solenoid-controlled breakers where possible. Motor-operated breakers are often equipped with alternating-current motors.

142. Relays. It is usual to design relays for operation with an **inverse time element**; that is, with a relay set to operate at 100 amp. after 10 sec., it will operate at about 300 amp. in 5 sec. and almost instantaneously at 1,000 amp. This characteristic gives prompt action in opening the line under short-circuit, while reducing the likelihood of unnecessary interruption under brief overloads.

143. The arrangement of relays must be such that a short-circuit between any two wires will operate the breaker. On single-phase circuits

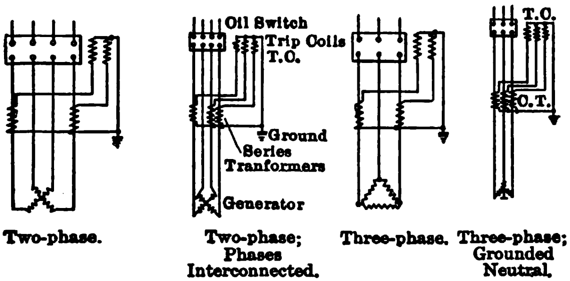


FIG. 42.—Relay arrangements for two-phase and three-phase circuits.

one relay is sufficient to accomplish this. On two-phase systems supplying lighting and motor service it is desirable to provide separate relays and circuit-breakers for each phase. In the three-phase, three-wire system without grounded neutral, relays are required in two of the three wires; the three-pole type of circuit-breaker is used. In the three-phase, four-wire system having the neutral point grounded, it is essential that relays be installed in each phase wire, with single-pole breakers; in case of a ground on one phase the corresponding circuit-breaker opens without interrupting the lighting service on the other phases (Fig. 42).

144. Relays on three-phase transmission lines. It is customary to provide relays at the point of supply, commonly called **overload relays**. Where several lines are operated in parallel, further protection is necessary. When the lines are connected to the same bus at each end, a short-circuit will draw energy from both ends and circuit-breakers must be provided at both busses. The relays at the receiving end must, however, be of a type which will operate only on reversal of the flow of energy. The converting equipment is provided with reverse-power relays on the secondary side.

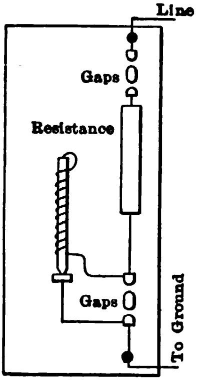


FIG. 43.—Solenoid type of lightning-arrester.

145. Speed-limiting devices. It is important that synchronous converters be protected by speed-limiting devices designed to operate the direct-current circuit-breaker when the speed exceeds a safe value.

146. Lightning Protection. Overhead distributing lines are susceptible to the effects of lightning. A discharge among the clouds causes an abrupt discharge of potential on the wires, which must be given an opportunity to escape to earth without injuring the insulation of the apparatus.

147. The function of lightning-arresters is to protect apparatus by passing the discharge of lightning to ground, without permitting the arc thus established to be maintained. This may be accomplished on potentials up to 600 volts by a short gap of non-arcing metal. At 2,200 volts or higher, several gaps in series are necessary, with a resistance to limit the current. Since each wire of the circuit is affected, discharge gaps must be provided between each wire and ground.

In systems having one side grounded, every discharge is likely to be followed by the generator current, as there is a fixed difference of potential between the circuit and earth. Arresters on grounded systems must, therefore, meet more severe requirements than those on ungrounded systems.

The problem of protection of transmission lines becomes more complex as the voltage is increased, and the study of protective methods for lines operating at 20,000 volts and upward is leading to new developments every year. The discussion in this Section will be restricted to alternating-current distributing systems operating at less than 5,000 volts.

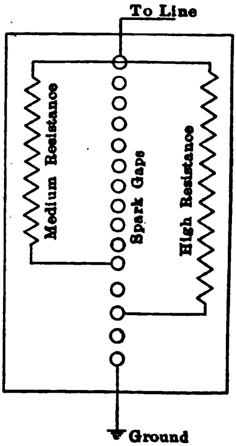


FIG. 44.—Multi-gap lightning-arrester.

148. Types of Arresters. The wide range in severity of lightning flashes makes it well-nigh impossible to design an arrester which will protect apparatus and yet withstand the effects of a direct stroke at any point nearby. The arresters described in the succeeding paragraphs (Par. **149** to **152**) include the leading commercial types which have been used in distribution work.

149. The Garton-Daniels arrester, Fig. 43, consists of air gaps and resistances, with a solenoid so arranged that the plunger is raised by the passage of the generator current, thus placing additional gaps in series and rapidly diminishing or stopping the flow of energy. The lightning discharge passes across the shunted gaps to ground owing to the inductance of the solenoid.

150. Multi-gap arrester. A modification of the spark-gap and resistance type of arrester has been employed quite extensively. This is illustrated in Fig. 44, as made for 2,300 volts, and consists of three paths of discharge, one of which has a high resistance (100,000 ohms), another a resistance of about 300 ohms, and a third which consists of 13 or 14 gaps without resistance. The impedance of the unit is such that discharges of very high frequency pass over the 13 gaps, while those of lower frequency pass over the smaller number of gaps through one of the resistances. A slightly modified form is shown in Fig. 45.

151. The aluminum-cell arrester has given good results because of its ability to stop the flow of current promptly and safely. It has been found especially valuable at transmission voltages where its expense is justified by the importance of the service. It is not suited for outdoor distribution work, since it requires daily charging and supervision and cannot be left continuously in circuit.

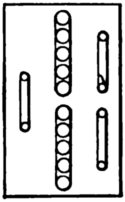


Fig. 45.—Westinghouse low equivalent arrester.

152. The compression type of arrester, Fig. 46, consists of a series resistance with air-gaps, assembled inside of a porcelain tube, the top of which is capped and sealed. The air-gaps are surrounded by a grounded strip of iron outside of the tube, which acts as a means of equalizing the potential gradient. The discharge of the arrester expands the air and compresses it, since the tube is sealed; hence the name compression type. This arrester, having but one path to ground, is of limited capacity.

153. Location of arresters. All of the above-described types of arresters are in general use on distributing systems in America, and each gives reasonably good protection to apparatus when placed in its immediate vicinity. Experience has fully demonstrated that lightning discharges do not travel any great distance along a line, owing to the very high frequencies of this form of energy. The arrester must, then, be located as near the apparatus as practicable, and preferably on the same pole. Complete protection of distributing transformers would require that an arrester be placed on every transformer pole.

The experience of large companies, however, has been that the cost of the damage to apparatus from lightning is not as large as the fixed charges on the arrester equipment, when complete protection is provided. The exact point at which these two elements of cost become a minimum varies with the value and the size of the transformers, since it costs as much to protect a 1-kw. unit as a 50-kw. unit. Practice has not yet become standardized, as the subject is still being studied and reliable conclusions can be reached only after a number of years' further experience.

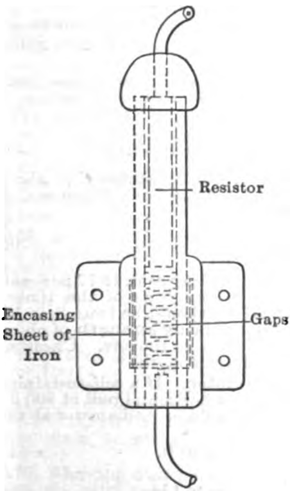


Fig. 46.—Compression lightning-arrester.

154. The use of lightning-arresters on transformer poles has been found to materially diminish the number of interruptions of service due to blowing of transformer fuses, and this tends to make the more liberal use of arresters desirable.

OVERHEAD CONSTRUCTION

155. General. Overhead construction is an economic necessity in a large part of every city. The **investment** for overhead lines in outlying districts usually is from 15 per cent. to 30 per cent. of that required for underground construction, and it is obvious that overhead construction must be used wherever feasible, to keep the investment within profitable limits.

In many cases the objection to overhead lines is minimized by locating them in alleys.

156. Poles. Distribution lines are necessarily carried on wooden poles. Iron poles are objectionable on account of the risk to linemen in handling "live" primary circuits. Iron poles are used in some cases for street-lighting circuits which are so operated that it is not necessary to do any work on them while they are "alive." The cost of iron poles is about twice that of wooden poles.

157. Concrete poles are being used increasingly in sections where the ravages of insects and the nature of the soil make the life of wooden poles very short. They are also being introduced for transmission work in places where iron poles would otherwise be required.

158. The woods which are best suited for pole work are Michigan cedar, Western cedar, chestnut, pine, and cypress.

159. The Michigan cedar grows with a natural taper of about 1 in. in diameter to every 5 ft. or 6 ft. of length, making a very substantial and rigid pole.

160. The Western cedar, which grows in Idaho and Oregon, has a natural taper of about 1 in. in 8 ft. to 10 ft. of length. For the same size of top the diameter of the butt is, therefore, smaller than that of the Michigan cedar. The surface of Western cedar is smoother than that of the Michigan cedar and the poles are very straight and neat in appearance. It is necessary on important lines to use nothing smaller than 8-in. tops with these poles, in order to secure adequate diameter at the ground line.

161. The chestnut pole is quite different from the cedar poles. The specific gravity of the wood is high and the surface is irregular and knotted, making the appearance of the chestnut pole not as good as that of cedar.

162. Pine and cypress poles are more like cedar in their general characteristics of weight and strength. Their use is limited to sections of the country where the timber is native, as their life is comparatively short.

163. On the Pacific coast, California redwood and some other native woods are used very generally.

164. Pole stresses. The stress acting on a pole at the top causes a tension in the fibre of the wood on one side of the pole and a compression on the opposite side. For a round pole the maximum fibre stress is:

$$f = \frac{384\,PL}{3.14\,(d)^3} \qquad \text{(lb. per sq. in.)} \qquad (7)$$

in which P is the pull at right angles, in pounds, at the distance L ft. above ground, and d is the diameter at the ground line, in inches. Expressed in another form, Eq. 7 becomes,

$$d = \sqrt[3]{\frac{384PL}{3.14f}} \qquad \text{(in.)} \qquad (8)$$

The unit stress f should be taken at not more than 10 per cent. to 12 per cent. of the ultimate breaking strength, as determined by tests of the timber in the form of poles; that is, the **factor of safety** should be from 8 to 10. Cedar, redwood and pine have an **ultimate breaking strength** of about 7,000 lb. per sq. in. when tested in the form of large timbers. Chestnut is slightly stronger, having a strength of 8,000 lb. per sq. in.

165. Example of calculation of pole diameter. If a self-sustaining (unguyed) pole is to support a line which exerts a horizontal pull of 800 lb. at a height of 30 ft. above the ground, what should be its diameter at the ground line to safely carry the load?

$$f = \tfrac{1}{10} \text{ of } 7{,}000 = 700;\ P = 800,\ L = 30 \text{ ft.}$$

$$d = \sqrt[3]{\frac{384 \times 800 \times 30}{3.14 \times 700}} = \sqrt[3]{4{,}193} = 16.1 \text{ in.}$$

This would call for the use of a 35-ft. pole with a butt-diameter of 16 in. at the ground line. The top-diameter of a Michigan cedar pole of this size would be from 8 in. to 9 in. In city practice where turns are made at right angles, which cannot be supported by a guy, the use of such poles is often necessary.

166. Wind pressure. The design of pole lines to withstand wind pressure must be considered where they are exposed, though the average pole-line distribution is so protected by buildings and trees that it is not subject to the full force of windstorms. The wind pressure on a normal flat surface is

$$p = 0.004\ V^2 \qquad \text{(lb. per sq. ft.)} \qquad (9)$$

where V is the velocity in miles per hr.; if Weather-Bureau observed velocities are used, they should be corrected.* Thus $p = 40$ lb. per sq. ft. at 100 miles per hr., 22.5 lb. at 75 miles, 10 lb. at 50 miles, and 2.5 lb. at 25 miles. The pressure on a cylindrical surface whose axis is normal to the wind is one-half that on a plane surface equal in area to the projected area of the cylinder. Thus for round smooth wires:

$$p = 0.002\ V^2 \qquad \text{(lb. per sq. ft.)} \qquad (10)$$

For bare concentric strands H. W. Buck† found that the constant in Eq. 10 is 0.0025.

The wind pressure on a 40-ft. pole, of which 34 ft. is above ground, with 7-in. top and 14-in. butt, would be calculated as follows. Projected area $= \{(7+14)/2\} \times 34 \times 12 = 4{,}284$ sq. in. $= 29.75$ sq. ft. Assuming a wind velocity of 60 miles per hr., $p = 0.002 \times (60)^2 = 7.2$ lb. per sq. ft. Total pressure on pole $= 29.75 \times 7.2 = 214$ lb. This force acts at the centre of gravity of the projected area, which is a long narrow trapezoid; or 15.1 ft. from the ground-line. The moment of this force about the ground-line is therefore $214 \times 15.1 = 3{,}230$ lb-ft. Taking the diameter of No. 6 A.W.G. triple-braid weather-proof wire as 0.32 in., the total wind pressure at 60 miles per hr., on a 120-ft. span, would be 23 lb. and on twenty wires it would be 460 lb.; this resultant force would act at a point about 3 ft. below the top of the pole, or 31 ft. from the ground-line. The resulting moment would be 14,260 lb-ft. The sum of the wind pressures on pole and wires would be $3{,}230 + 14{,}260 = 17{,}490$ lb-ft. A rough-and-ready rule is sometimes used that the wind pressure on the pole itself is about equal to that on five No. 6 A.W.G. weather-proof wires.

High wind velocities are attained at times in nearly all parts of North America, and it is advisable, therefore, to provide pole braces or guys on exposed lines.

167. Selection of poles. It is usual to select poles with 7-in. tops for important distributing lines.

The **height** of the poles selected for distribution purposes must be governed by the clearance over local obstructions and also by the number of cross-arms to be carried on the poles. Clearance over trees is especially troublesome in residence sections where trimming will not be permitted. In general it is desirable to use poles not less than 30 ft. long where primary lines are carried, and in built-up sections a minimum size of 35 ft. is preferable.

168. Poles for joint-line construction. Where joint-line construction with standard cross-arms is used, it is not usually possible to employ poles shorter than 35 ft. In a few cases the lines have been placed in cable and carried on 25-ft. poles on rear-lot lines. The use of poles over 40 ft. long is to be avoided wherever possible, on account of the cost, the increased danger in storms and the difficulty of handling transformers and service connections.

169. Poles should be spaced in approximately equal span lengths of about 100 ft. to 125 ft., to keep the sag within safe limits and to provide a sufficient number of points at which service drops may be taken off. The spans near self-supporting corner poles should be about 75 ft. long in order to relieve the strain on the corner pole. **The poles should be placed** opposite lot-lines to avoid interference with the rights of abutting-property owners.

170. Shaving and painting. It is considered good policy to carefully shave all poles, trim the knots, and give them two coats of paint. A dark green color is very commonly used because of its harmony with foliage in residence districts.

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* Fowle, F. F. "A Study of Sleet Loads and Wind Velocities;" *Electrical World*, Vol. LVI, 1910, p. 995.

† Buck, H. W. "The Use of Aluminum as an Electrical Conductor;" *Trans.* International Electrical Congress, St. Louis, 1904.

171. Stepping. Transformer poles and others which are climbed at frequent intervals should be provided with pole steps. It is the practice in many of the large city systems to provide steps on all poles.

172. Gaining. The gains should be cut for the cross-arms before the poles are erected. The **distance between cross-arm centres** must be sufficient to give clearance for service drops and allow a safe working **space** for linemen. The space usually allowed is about 24 in.

173. Pole setting. Experience has proven that the following practice is conservative, as regards the depth of setting.

Size pole (ft.)...............	30	35	40	45	50	55	60	70
Depth (ft.)................	5	5.5	6	6.5	6.5	7	7	7.5

Corner poles should be set about 6 in. deeper than the above. In rocky soil where boulders may be tamped about the poles, they need not be set as deep.

The poles should be placed so as to bring their natural curvature into the plane of the line. At corners a slight **rake** may be given in a direction opposite to the pull of the load. Several tampers should be employed to one shoveler, in **back-filling**, in order to insure the stability of the pole. Water may be used to advantage, where available, in settling the back-fill. In swampy soil, the digging of holes is greatly facilitated by the use of a **sand-barrel.** This consists of a sheet-iron cylinder about 30 in. in diameter and 3 ft. long, which is separable into two parts lengthwise, and is readily removed after the pole is in place. Various methods of setting are shown in Fig. 47.

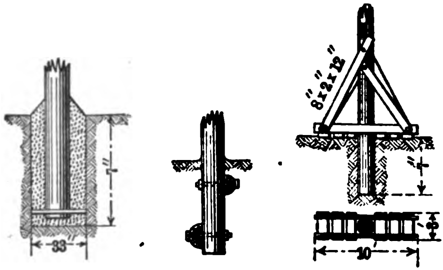

FIG. 47.—Methods of setting self-sustained poles.

174. Guying and bracing. Where the direction of a line changes, the tension of the wire should be supported by guying or bracing. The bracing method requires considerable space, and is more unsightly than a guy. Guys are secured in various ways, depending upon the space and the clearance required. Where nothing prevents, the guy cable may be secured to an **anchor** of timber or some form of patent anchor (Fig. 48). On public thoroughfares guys cannot be run directly to anchors without interfering with traffic, and the guys must be run to **stubs** at such height as to permit free passage of traffic beneath. Guys over roadways should clear about 25 ft., and those over pathways about 12 ft. (Fig. 48).

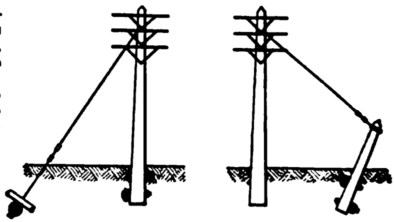

FIG. 48.—Anchor and stub guy.

Where side-arm construction is used it is necessary at corners to guy the cross-arms as well as the poles. At heavy corners a "head" guy is run from the base of the corner pole to the upper part of the next pole in the line.

The tension in the corner spans may thus be reduced, relieving the strain on the corner pole. In straight-away lines the head guy is used to limit the extent of damage in case several poles go down; this is sometimes called "storm guying."

175. Galvanized steel cable is generally employed for guying purposes because of its high tensile strength. Such cable is made in sizes varying in diameter by steps of $\frac{1}{16}$-in., from $\frac{1}{4}$-in. up. The **ultimate breaking strength of $\frac{1}{4}$-in. cable** is about 3,000 lb.; $\frac{5}{16}$-in., 4,500 lb.; $\frac{3}{8}$-in., 6,000 lb.; and $\frac{1}{2}$-in., 12,000 lb. Having calculated the tension, the size of guy cables should be such that the strain will be from one-fourth to one-fifth the ultimate breaking strength of the cable, or the **factor of safety of the steel cable,** from 4 to 5. Anchors should be placed at a distance from the pole not less than one-quarter the height of the guy attachment. In general, $\frac{1}{4}$-in. cable is used for the smaller loads, while the $\frac{3}{8}$-in. size is standard for corner poles where the load of the ordinary two-arm to three-arm distribution line is to be supported.

176. Strain insulators. It is important that guy cables attached to stubs be equipped with strain insulators not less than 8 ft. from the ground. This precaution is advisable for the protection of the public and of linemen.

177. Cross-arms. Southern pine and **Oregon fir** are the best woods for cross-arms because of their straight grain, high tensile strength, and durability. The **cross-section** should be such that the arm will safely bear

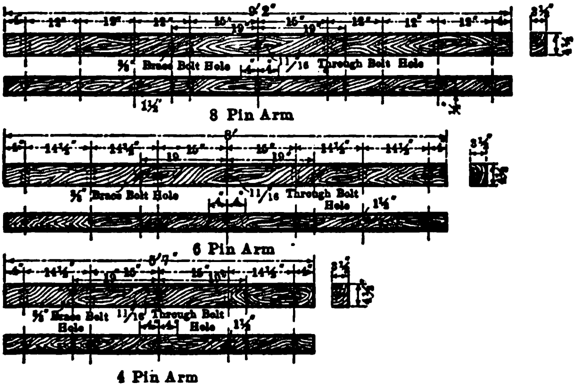

FIG. 49.—Dimensions of standard cross-arms.

the weight of a lineman in addition to that of the wires. Experience indicates that a cross-section 3.5 in. wide by 4.5 in. high is ample for the average requirements of distributing lines. For transformers of 20 kw. and larger it is usual to provide arms of a larger cross-section. Main lines are commonly built of six-pin arms, with four-pin arms on the smaller distributing lines. Where secondaries for both lighting and motor service must be carried on the same arm, it is usually necessary to employ six-pin arms.

The **spacing of pins** should provide safe working room for linemen and should take into account the average sag of the wires. Under the usual working conditions of distributing lines, it is not safe to attempt to use spacings less than 12 in. The spacing of the pole pins must give sufficient room for the men to climb to the upper arms, at least 30 in. being required for safety. The dimensions and spacings of standard cross-arms are shown in Fig. 49.

178. Double cross-arms. At corners, terminals, and other points where any unusual load is to be supported, the poles should be fitted with double arms. In turning corners on a single pole, the double-arming of in which T is the tension in pounds, L is the span length in feet, w is the weight per foot of conductor and S is the sag in feet at the centre of a horizontal span. If the span length is doubled, the tension must be quadrupled in order to keep the sag the same. If the tension is the same on several spans of different lengths, the sag is different in each span. The sag of any span when the tension is known is found by changing Eq. 11 to the form, $s = L^2w/8T$.

183. The maximum tension in a span is limited by the strength of the wire and supports. The **ultimate breaking strength of annealed copper wire** is about 34,000 lb. per sq. in., but the working stress should not be over one-fourth of this. The **ultimate tensile strength of hard-drawn wire** is about 60,000 lb. per sq. in. Such wire is left in the hardened condition in which it comes from the wire-drawing dies, which gives it greater strength and stiffness. The hard-drawn wire, however, should not be scratched in handling, as any injury to the surface increases the likelihood of fracture. If it is heated for soldering, its strength is reduced. Hard-drawn wire, therefore, is not adapted to general distribution work where taps must be made with soldered connections at frequent intervals, but for transmission lines and series-arc circuits it has advantages which are generally recognised.

184. The sag and tension of weather-proof, annealed wire and bare, hard-drawn wire may be readily determined from the tables in Par. **185** and Par. **186**.

185. Sag Table for Weather-proof Annealed Copper Wire

Size A.W.G.	10	8	6	4	2	1	0	2/0	3/0	4/0
Tension at 1 ft. sag (lb.)	62	92	140	204	318	390	486	607	767	942
Sag at 100 lb. tension (ft.)	0.62	0.92	1.40	2.04	3.18	3.9	4.86	6.07	7.67	9.42
Weight of wire, lb. per 1,000 ft.	50	74	112	163	254	312	388	486	614	754
Breaking stress (lb.)	283	440	700	1114	1772	2234	2818	3553	4480	5650

186. Sag Table for Bare Hard-drawn Copper Wire

Size A.W.G.	10	8	6	4	2	1	0	2/0	3/0	4/0
Tension at 1 ft. sag (lb.)	39.3	62	99	157	161	202	400	505	636	800
Sag at 100 lb. tension (ft.)	0.393	0.62	0.99	1.57	1.61	2.02	4.0	5.05	6.36	7.80
Weight of wire, lb. per 1,000 ft.	31.4	50	79.5	126	201	253	320	403	508	640
Breaking stress (lb.)	500	778	1240	1960	3120	3743	4560	5271	6590	8310

187. Use of sag tables. The tension at any other sag, or the sag at any other tension, or the sag or tension in any other length of span, may be readily found from the Tables (Par. **185** and **186**) as follows:

The tension at any other sag is $T' = T/S$, in which S is the sag in feet at which the tension is desired and T is the value at 1-ft. sag in the table. For example, the tension in a 100-ft. span of No. 0 weather-proof wire at a deflection of 2 ft. is

$$T' = \frac{T}{S} = \frac{486}{2} = 243 \text{ lb.}$$

Similarly, the sag at any other tension is $S^1 = S \times 100/T$, in which T is the assumed tension and S is the value of sag at 100 lb. tension in the table. For example, with No. 0 weather-proof wire the sag at 300 lb. is

$$S' = \frac{S \times 100}{T} = \frac{4.86 \times 100}{300} = 1.62 \text{ ft.}$$

For spans of other lengths, the sag or tension varies in proportion to the square of the length of the assumed span. That is,

$$S' = \left(\frac{L'}{100}\right)^2 S, \text{ and } T' = \left(\frac{L'}{100}\right)^2 T. \qquad (12)$$

For example, with No. 4/0 bare wire the tension with a span of 150 ft., at 1-ft. sag, would be

$$T' = \left(\frac{150}{100}\right)^2 \times 800 = 1{,}800 \text{ lb.}$$

Or if the tension of the line were 100 lb. in all the spans, the sag in a 150-ft. span would be

$$S' = \left(\frac{150}{100}\right)^2 \times 8 = 18 \text{ ft.}$$

188. Expansion and contraction of spans with temperature changes. The changes in sag due to expansion and contraction under varying temperatures are of much importance in the erection of the conductors. Lines erected during the winter months are likely to be too slack during the summer, and allowance should be made accordingly. The length of wire in a span, disregarding the elastic stretching due to the load, varies in proportion to the coefficient of expansion and the range of temperature:

$$L_t = L_o(1 + \alpha_o t) \qquad (13)$$

in which α is the coefficient of expansion, t is the temperature in deg. fahr. and L_o is the length of wire at zero temperature. When the length L_{t1} is known at some other temperature t_1, the formula becomes

$$L_t = L_{t1}\left(\frac{1 + \alpha_o t}{1 + \alpha_o t_1}\right) \qquad (14)$$

The linear coefficient of expansion of copper is 0.000017 per deg. cent. or 0.0000094 per deg. fahr. P. H. Thomas has worked out a graphical solution[*] of sag problems which is very useful where accurate results, with considerable variation of temperature and load, are required.

In practice the pole supports have a certain degree of flexibility which tends to take up part of the slack caused by expansion and to prevent excessive strains being placed on the wires by contraction during cold weather.

189. Table of sags recommended by National Electric Light Association. The following table, adopted by the N. E. L. A., represents good practice in wire-stringing at various temperatures, the deflection at the centre of the (horizontal) span being given in inches.

190. Table of Standard Sags Recommended by the National Electric Light Association

Deflection (sag) in inches

Span in feet	Temperature in deg. fahr.						
	30	40	50	60	70	80	90
50	8	9	9	10	11	11	12
60	10	11	11	12	13	14	14
70	11	12	13	14	15	16	17
80	13	14	15	16	17	18	19
90	14	16	17	18	19	20	21
100	16	17	19	20	21	23	24
110	18	19	21	22	24	25	26
120	19	21	23	24	26	27	28
130	22	24	26	28	30	32	33

191. Transformer installations. Transformers are usually supported on cross-arms by means of iron hangers. This class of construction is suitable for transformers of capacities up to 20 kw. For larger units the cross-arms should be double, and heavier than the standard arm. Large transformers which cannot be placed inside the building are often installed on a platform between two poles.

192. Grounded secondaries. To protect life and property in case a primary circuit becomes crossed with a secondary, it is very important

* Thomas, P. H. "Sag Calculations for Suspended Wires;" *Trans.* Amer. Inst. of Elec. Eng.; Vol. XXX, 1911; p. 2229.

that the secondary be grounded. This is preferably done by connecting the secondary circuit to **water pipes** where these are accessible. Where the ground must be made outdoors, the most practicable method is to drive a galvanized **iron pipe** into the ground to a depth of about 8 ft. The points to be grounded in various kinds of secondary mains are indicated in Fig. 52.

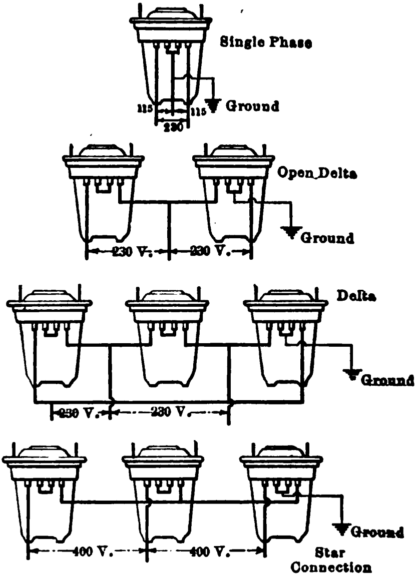

Fig. 52.—Connections for grounded secondary.

193. The grounding of secondaries up to 150 volts has been required by the National Electrical Code since 1913. There is some doubt as to the advisability of grounding secondaries when the difference of potential between any wire and ground is higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal.

194. When the ground connection is made to a pipe at the pole, the ground-wire is preferably brought down the pole in half-round wooden moulding. The ground-wire may be soldered to the pipe about a foot above the ground, or may be attached by means of a pipe cap as shown in Fig. 53.

195. Arrangement of wires. The position of wires on the cross-arms should be assigned according to a systematic plan. Circuits should be kept on the same pins throughout their course, to facilitate maintenance work. In general, through lines should be carried on the upper arms and local distributing lines at the bottom. All the wires of a circuit should be carried on adjacent pins. Connections carried across the pole for transformers or service drops should leave one side of the pole free for climbing.

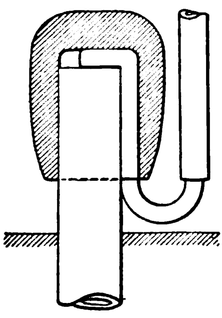

Fig. 53.—Ground-pipe cap.

196. Joint occupancy of pole lines. The use of a joint line of poles is preferable to separate lines, on thoroughfares where there are many service drops, as it avoids much confusion. Where poles are occupied jointly by both electric-light and telephone companies, *the lighting wires should always occupy the upper position.* A clearance of about 4 ft. should be maintained between the lower lighting wires and the telephone wires. Joint-line construction is the rule in most of the larger cities. For details of recommended forms of joint-line construction, see the "Report of Committee on Overhead Line Construction," *Trans.* N. E. L. A., 1911.

UNDERGROUND CONSTRUCTION

197. Edison tube system. The underground system devised by Edison consisted of 20-ft. lengths of iron pipe inside of which were copper rods imbedded in compound to exclude moisture. These lengths were made with various sizes of conductor from No. 4 A.W.G. up to 500,000 cir. mils for mains and up to 1,000,000 cir. mils for feeders. Feeder tubes were provided with three pressure wires to indicate at the station the pressure at the end of the feeder.

198. Arrangement of Edison tube system. Edison tube is joined by stranded connectors enclosed in cast-iron couplings which are filled with hot compound. At intersections the tubes are interconnected through fused junction boxes. Such tube lines are carried along each side of the street near the curb except where consumers are scattered or where an alley is used. The Edison tube system was the standard method of distributing low-tension energy underground until about the year 1897. The change to cable was made on account of the inability of the tube feeders to carry overloads without causing burn-outs. The necessity of opening street pavements in each case where repairs were made, also involved considerable expense.

199. Conduit systems. The early alternating-current and series-arc systems which were installed underground were unable to use a system similar to the Edison tubes because of the higher voltages employed. They were compelled to devise a drawn-in conduit system with manholes for handling the cables. Creosoted wooden pump log was tried and was satisfactory for some classes of work, but was too short-lived and inflammable.

Other systems were devised in which the ducts were intended to provide insulation, but experience proved that it was not practicable to maintain such a system. This led to the development of methods in which the insulation was applied to the conductor and the conduit was of some durable fire-proof material.

200. Modern standard conduit systems. Various forms of duct were tried out, but the most suitable were found to be those of fire-proof material such as terra cotta and clay tile.

A conduit made entirely of concrete and known as **stone pipe** has been used to some extent instead of clay tile. This is made in 5-ft. lengths and jointed with metal ferrules to preserve the alignment, single duct only being used. The conduit is laid in concrete, making a solid and durable duct system. The concrete pipe is fragile, however, and the breakage is likely to be greater than with the tile duct, if not carefully handled.

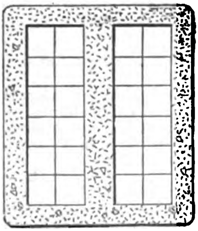

Fig. 54.—Arrangement of ducts for a large line.

Various forms of **fibre conduit** have also been used to some extent. These are laid with concrete around and between them, so that if the fibre disintegrates in after years there will remain a concrete duct system. The principal advantage is in the ease of handling and lack of breakage.

201. Laying out a conduit line. In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the important considerations. The number of ducts must be sufficient to care for the local distribution, for feeders, for transmission lines and for future requirements. It is desirable to lay sufficient reserve ducts to care for probable requirements for about 5 years ahead.

The **maximum number of ducts** which it is advisable to put into a line is governed chiefly by the safety of the cable equipment. The space available for training the cables is limited, and if more than twenty to twenty-five cables are carried through a manhole, a large part of the load is endangered by a failure of any of the cables. Where conditions are such that a very large line must be used, protection may be had by separating one-half of the duct line from the other by a 6-in. concrete barrier and by building double manholes. A line having more than four ducts in each layer is to be avoided where possible on account of the difficulty of properly training the cables. The arrangement shown in Fig. 54 is a desirable one where [illegible] or more ducts are laid.

202. Manholes. Manholes must be provided in sufficient number to permit the drawing in of cable without overstraining the insulation. Thus the **manhole spacing** should be not over 500 ft., with large cables 400 ft. is a safer limit. Where distribution by overhead lines in alleys with underground lines on the street is used, manholes should be put opposite alley intersections as far as possible. The number of manholes required where numerous underground service connections are needed must usually be sufficient to enable services to be brought in at intervals of 25 ft. to 100 ft. In distribution by means of subway-type transformers and a secondary network, it is usually necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

Manholes should be so designed that the cables may be trained with a minimum of waste and with sufficient space to enable a jointer to work efficiently, as in the oval-shaped manhole shown in Fig. 55. At intersections a square design is preferable, as shown in Fig. 56. In practice it is usual to provide manholes 5 ft. by 5 ft. at **junctions** where there are eight ducts, that is, where two four-duct lines cross; 6 ft. by 6 ft. where there are twelve to eighteen ducts; 7 ft. by 7 ft. where there are twenty or more, and larger as the needs of the case may require.

The size and the shape of manholes are often governed by local obstructions such as gas or water pipes, or conduit lines of other companies. The depth must be sufficient to give head room, and yet should not be so great as to carry the floor of the manhole below the sewer level. Service manholes may be 5 ft. high inside' but junction manholes should be 6 or 7 ft. from roof to floor. In some cases a shallow form of manhole known as a **handhole** is used for distribution laterals. These are made about 3 ft. by 4 ft., and 4 ft. deep. They are placed above the conduit line so that only the top row of ducts enters the handhole. The distributing mains are thus accessible for service taps, and the through lines in the lower ducts are not in the way.

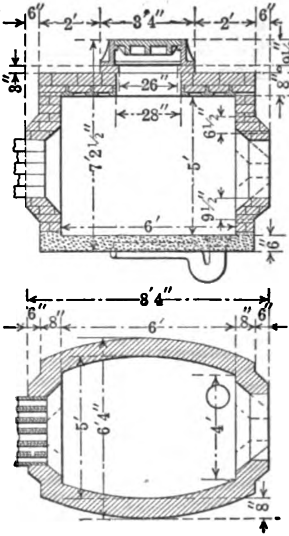

Fig. 55.—Oval manhole.

203. Forms of duct. Tile conduit is made in single- and multiple-duct pieces, single-duct pieces being about 18 in. in length, and multiple-duct 36 in. long. The dimensions of ducts in general use are shown in Fig. 57. Multiple-duct is somewhat cheaper than an equal number of single ducts and requires less labor. In a large system it is considered preferable to use single-duct to secure the advantage of having two thicknesses of tile between adjacent ducts. The single-duct also has the further advantage that the joints may be staggered, thus making it less likely that the heat of a burn-out may damage the cables in adjoining ducts.

204. Installation of conduit system. In laying a line of ducts the grades must be carefully established] so that no pockets are formed where standing water may freeze and injure the insulation of the cables and break the tile. It is important that manholes where work must be done frequently, or where transformers or junction boxes are installed, be provided with sewer connections. The conduit line is protected from future excavators, and made secure against the possibility of getting out of alignment, by surrounding it with 3 in. of concrete on all sides. The con-

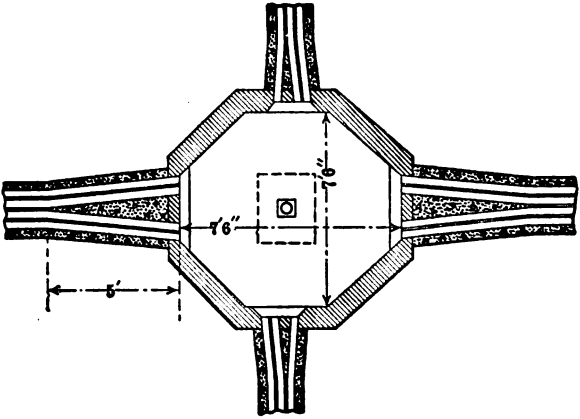

Fig. 56.—Square manhole.

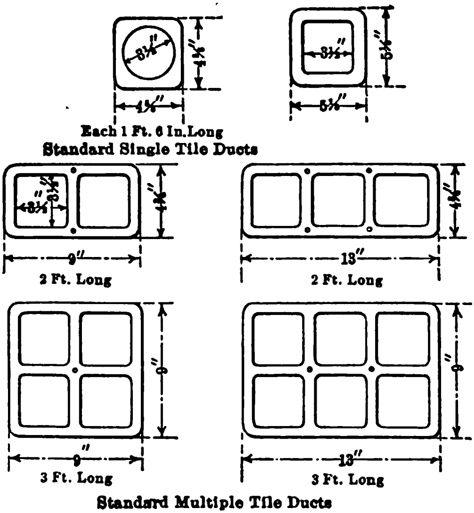

Fig. 57.—Forms of tile duct.

crete further acts as a water shed and minimizes the leakage of gas into the conduit system.

Manholes are constructed with brick walls and concrete floor and roof. Concrete walls may be used where there are no pipes to interfere with the use of the forms. The brick should be sewer brick, laid up with a good cement mortar, with an 8-in. wall. The roof must have sufficient strength to support the heaviest street traffic and its design, therefore, varies with the size and shape of the manhole. **Manhole covers** are made of cast iron, the upper surface of the cover being roughened or scored to prevent accidents to teams or pedestrians. It is desirable to provide openings in the covers for purposes of ventilation.

205. Cost of fifteen-duct line. The items of cost in constructing a fifteen-duct line as given by W. P. Hancock* are as follows:

	Per duct-foot	
Lumber at $15.00 per M ft.	$0.0105	
Concrete at $4.85 per yd.	0.0231	
Mortar at $3.98 per yd.	0.0026	
Tile at $0.05 per ft.	0.0502	
Total material		$0.0864
Excavation and filling at 15 cents per hr.	0.0266	
Placing lumber at 20 cents per hr.	0.0004	
Placing concrete at 15 cents per hr.	0.0029	
Placing mortar at 25 cents per hr.	0.0016	
Laying tile at 50 cents per hr.	0.0040	
Hauling away dirt at 50 cents per hr.	0.0047	
Total labor		0.0402
Inspection, 50 cents per hr.	....	0.0033
Engineering expenses	....	0.0214
Incidentals, 5 per cent.	....	0.0116
Grand total per duct-ft.	....	$0.1629

206. Cost per duct-foot for duct-lines of various sizes. The cost per duct-foot of various sizes of duct-lines without manholes, at various costs of paving per sq. yd., as given by Hancock,* are as follows (Par. **207**):

207. Table of Costs of Duct-lines per Duct-foot
Cents per Duct-foot

No. of ducts	Cost of repaving per square yard						
	None	$0.50	$1.00	$1.50	$2.00	$3.00	$3.50
2	24	29	34	38	43	52	56
4	22	25	27	30	33	38	41
6	20	22	24	26	28	32	34
9	19	21	22	24	25	28	30
12	19	20	21	23	24	26	28
16	18	19	20	21	22	24	25
20	17	18	19	20	21	22	23
24	17	18	18	19	20	21	22
30	16	17	17	18	19	20	21
40	16	17	17	18	18	19	20
50	16	16	17	17	18	19	19

208. Cost of manholes. The costs of certain sizes of manholes as built under conditions existing in the City of Chicago are given in the following table, in Par. **209**. The cost of paving is not included. The dimensions are those inside the manhole, the last being depth.

* Hancock, W. P. *Trans.* National Elec. Light Association, 1904.

209. Table of Costs of Manholes
(Based on Chicago Experience)

	3×3×4 ft.		4×5×5 ft.		5×5×6 ft.		6×6×6 ft.		8×8×6 ft.	
	Quan.	Cost	Quan.	Cost	Quan.	Cost	Quan.	Cost	Quan.	Cost
Excavation at $1.00 per cu. yd.	3.70	$3.70	7.77	$7.77	16.30	$16.30	19.00	$19.00	29.63	$29.63
Brickwork at $10.50 per cu. yd.	1.67	17.55	2.92	30.50	4.17	43.80	4.50	47.30	5.83	61.20
Concrete bottom at $7.00 per cu. yd.	......	......	0.37	2.49	0.56	3.92	0.67	4.69	1.18	8.26
Concrete top at $10.00 per cu. yd.	0.56	7.00	0.96	7.68	1.35	10.80	1.55	12.40	2.50	20.00
Roof-iron at 3 cents per lb.	105 lb.	3.15	129 lb.	3.87	153 lb.	4.59	178 lb.	5.34	227 lb.	6.81
Sewer connection at $20.00 each	......	......	1	20.00	1	20.00	1	20.00	1	20.00
Frame and cover at $15.00 each	1	15.00	1	15.00	1	15.00	1	15.00	1	15.00
Supervision and incidentals	......	2.25	......	2.25	......	2.25	......	3.25	......	3.25
Totals	......	48.65	......	89.56	......	116.66	......	126.98	......	164.15
Square yards repaving required	4.00	......	8.9	......	10.7	......	12.00	......	16.00	......

210. Types of cables. Cables for underground electric light and power circuits are made up in single, duplex, concentric, triplex, etc. Duplex and triplex cables are those in which two conductors are enclosed in one lead sheath side by side, while concentric cable is made up with the conductors concentrically disposed.

In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while multiple-conductor cables are used for through lines. Duplex cable has been used quite extensively in series-arc systems. It is difficult to train, and susceptible injury from bending at too small a radius. Duplex and triplex cables are somewhat less expensive than their equivalent in single-conductor cables with the same insulation.

The concentric arrangement is employed for large low-tension feeders in some cases. This arrangement is advantageous as it permits the use of a single duct for the feeder.

Low-tension distributing mains having three conductors of the same size are preferable of single-conductor cable, to facilitate making service taps. This work must be done while the lines are alive, and is much more easily accomplished when one polarity may be dealt with at a time. The same is true of service cables.

Transmission cables are almost universally of the three-conductor type. Insulation is placed on each conductor sufficient for the voltage between phases, and then a layer is placed over all three conductors in addition, as shown in Fig. 58, to provide insulation to ground.

211. Cable insulation. Cables are insulated with rubber, varnished cambric, or oiled paper. Rubber insulation is used where frequent taps are made, as on distributing mains, but not generally for feeders and transmission lines. Varnished cambric has been used to some extent in recent years as a substitute for rubber. Oiled paper is used almost exclusively for feeders and transmission lines, and can be used for primary distribution if the joints are well made and the ends are protected by suitable potheads.

212. Thickness of cable insulation. The smaller low-tension cables are provided with about $\frac{4}{32}$-in. insulation between conductors and lead; this is the least which it is advisable to use for mechanical reasons and is sufficient for 600 volts. In cables of 350,000 cir. mils to 1,500,000 cir. mils, it is customary to provide $\frac{5}{32}$ in. to $\frac{6}{32}$ in. of insulation, to insure sufficient mechanical strength to stand handling during installation. A thickness of $\frac{6}{32}$ in. is found sufficient for 2,000-volt to 6,000-volt single-conductor cables up to No. 4/0 A.W.G., while $\frac{10}{32}$-in. is required for potentials from 9,000 volts to 13,000 volts.

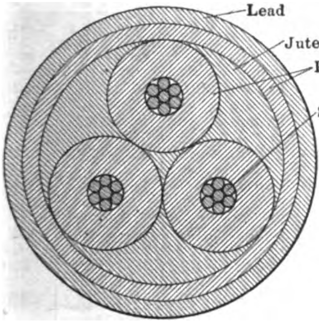

FIG. 58.—Cross-section of high-tension cable.

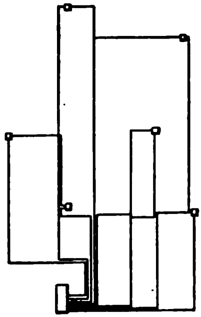

FIG. 59.—Lay-out of through cable lines to avoid the same routes.

213. The insulation provided in transmission cables in large transmission systems varies from 66 mils per 1,000 volts between conductors, at 6,600 volts, to 22 mils at 25,000 volts; and from 52 mils per 1,000 volts between conductor and ground, at 6,600 volts, to 16 mils at 25,000 volts.

214. Selection of duct position for cables. In placing cables in the duct-system a uniform method of selecting ducts should be followed as far as possible. Cables used in local distribution should be given a place, preferably in the top row, so that manholes can be built for service laterals without sinking them below the top row of ducts. Ducts should be selected for through lines so that they may be trained with the least interlacing with other cables. Lack of attention to this detail may result in a tangled condition of cables which greatly impedes any repair or reconstruction work.

215. Routing of cable lines. Through lines should be so routed as to utilize different duct lines to the best advantage. The service is better assured if transmission lines are separated as much as possible. This can be done by routing lines running to the same substation through different conduits, as indicated in Fig. 59.

216. Installation of cable. Cables are drawn into ducts by a line attached to a source of power. This line is put through the duct by the use of detachable rods of wood, which are pushed into the duct as they are joined together. They are then drawn through with the pulling-line attached, and disjointed as they come out. The cables are secured to the pulling-line by exposing the copper and making a secure mechanical connection, or by means of patent cable-grips, which are more quickly attached and removed.

The cable-pulling line is run over pulley-wheels leading out of the manhole to the source of power. Small-sized cable is wound on reels and cut to the be allowed to cool before it is moved, so that the compound will hold the parts rigidly in place.

In jointing three-conductor cables, the lead must be removed about 10 in. to facilitate the taping of the conductors (Fig. 60). In making joints for voltages of 6,600 volts and higher, it is important that as little air remain in the taping as possible. If paper tape is used, each layer should have compound poured over it before the next is applied.

The jointer requires the services of a helper in preparing the lead sleeves, heating solder and compound, and guarding the entrance to the manhole. A three-conductor high-tension joint in a paper cable usually requires about 4 hr. to complete, two joints a day being a fair rate of progress in such work.

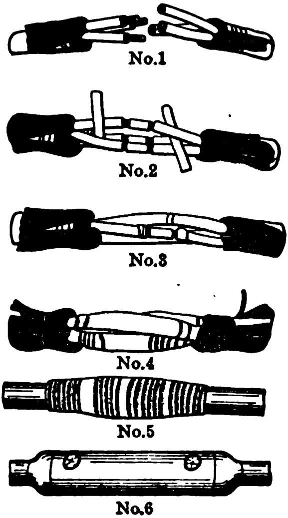

FIG. 60.—Cable splicing.

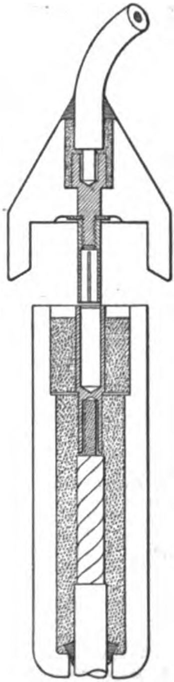

FIG. 61.—Porcelain pothead; single conductor type.

220. Pole terminals. In many primary distributing systems, it is usual to run feeders and important mains underground for some distance from the station, and connect with overhead lines in the more scattered areas. This class of distribution requires that the cable ends which are brought up the pole to the overhead lines be properly protected by **cable terminals or potheads.** Various types of terminal are in use, some of which include means for connecting and disconnecting the overhead line. Many such distributing systems have been equipped with porcelain potheads which have been very successful in protecting cables. The first such device was designed for a single-conductor cable, as illustrated in Fig. 61. The insulation is hermetically sealed by filling the porcelain sleeve with compound. The cap sheds all water and may be safely handled by a lineman when the line is alive. The connectors provide means for readily opening and closing the circuit when necessary for repair or alteration work. Other forms have been devised for multiple-conductor cables, in which there is a pot of cast iron with porcelain tubes set into the cover (Fig. 62).

221. Subway junction boxes. The arrangement of junction boxes and similar accessories in manholes should be worked out so as not to obstruct the space needed for the cables. Low-tension junction boxes are of two types, one of which is mounted on the wall in a vertical position, while the other is placed in the roof of the manhole so that it is accessible for replacing fuses or cleaning contacts from above ground. The surface type has its advantages in districts where the drainage of manholes is not perfect.

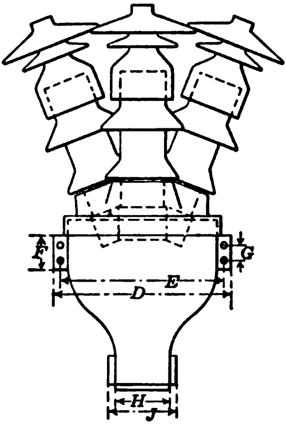

Fig. 62.—Cable pothead; triplex type.

222. Branch-line junction boxes. In a primary distributing system in which mains are underground, it is necessary to have means by which branches may be disconnected, without shutting down the circuit, when a transformer is to be connected or a cable repaired. Subway junction boxes with copper connections have commonly been applied to this work. The parts of the cable from which the lead has been removed are sealed in from moisture by wiped sleeves, or by filling the lower part of the box with hot compound. The **porcelain pothead** (Par. 220) has also been found convenient for this purpose, in manholes, as the cap may be submerged without permitting water to reach the live parts.

DISTRIBUTION ECONOMICS

223. General criterion for most economical size of conductor. The loss of energy in a conductor diminishes as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss follows the same law. The size of conductor with which the sum of the fixed charges on conductor and generating capacity, plus the value of energy loss, is a minimum, is the one which it is the most economical to employ.

224. Fixed charges consist of interest, depreciation, taxes and insurance. These are computed at different rates, depending upon the character of the equipment. **Interest** should be figured at not less than the rate paid on the bonded debt, which is about 5 per cent. (Sec. 25).

225. Depreciation is based upon the working life of the equipment, allowing for changes in the state of the art, and the scrap value of the equipment when taken out of service.

Weather-proof wire consists of about 80 per cent. copper and 20 per cent. insulation. It is conservative to figure 7 per cent. on the insulation, or 1½ per cent. of the whole wire, with 1 per cent. added for the labor of replacing, making a total of 2½ per cent. of the original cost of the wire. **Poles** have a life of about 15 years, with little salvage value. Other **overhead line material** must be replaced at intervals of 5 to 10 years. The average rate for **overhead lines** may thus be taken at about 5 per cent.

The life of lead-sheathed paper or rubber **cables** is indeterminate, but this may be conservatively taken at 15 years. The junk value is comparatively high, as the copper and the lead sheath constitute a considerable percentage of the cross-section of the cable. It is, therefore, safe to estimate depreciation at 3 per cent. for cables of No. 4/0 A.W.G. and larger, and at 5 per cent. for the smaller sizes.

226. Taxes and insurance must be considered as fixed charges of the same class as interest and depreciation. They vary somewhat with the locality, but are usually from 1.5 per cent. to 2 per cent., total.

227. The total fixed charges on underground cable and conduit may be taken at 5 per cent. interest, 4 per cent. depreciation, and 1 per cent. taxes, a total of 10 per cent. The total rate on the average overhead system may be taken at 5 per cent. interest, 5 per cent. depreciation, and 1 per cent. taxes, a total of 11 per cent.

228. General formula for annual conductor costs. The cost of a conductor varies inversely as its resistance per unit length, and the value of energy and generating capacity to supply it vary directly as the resistance per unit length. The total annual cost is

$$Y = \frac{a}{R} + bR + cR \qquad \text{(dollars)} \qquad (15)$$

in which a, b and c are constants depending on the cost of the conductor and the cost of energy. These are determined as follows: Par. 229 to 239.

229. Formula for annual fixed charges on wire. The cost of insulation varies approximately with the size of the conductor. For bare wire the product of weight per 1,000 ft., W, by resistance per 1,000 ft., for all sizes, is $WR = 32$; with weather-proof insulation $WR = 38$ for the sizes No. 4 to No. 0 A.W.G., or 36 for sizes from No. 2/0 to 350,000 cir. mils. The value of 1,000 ft. of conductor at 15 cents per pound is $0.15W$ dollars. Hence, when $W = 38/R$, the cost per conductor of a circuit L thousand feet long is

$$C_1 = 0.15WL = \frac{0.15 \times 38L}{R} \qquad \text{(dollars)} \qquad (16)$$

Taking the fixed charges at 9 per cent., the annual cost is

$$C_1 = \frac{0.09 \times 0.15 \times 38L}{R} = \frac{0.513L}{R} \qquad \text{(dollars)} \qquad (17)$$

Thus $a = 0.513L$, in this case (Eq. 14).

230. Formula for annual fixed charges on single-conductor cable. With underground conductors a change in the size of the conductor does not make a proportionate change in cost. The table in Par. 232 gives the cost per 1,000 cir. mils of various sizes of single-conductor and three-conductor lead-sheathed cables. The resistance per 1,000 cir. mils per 1,000 ft. of copper at ordinary temperatures is about 10.4 ohms. If M is the number of 1,000 cir. mils and P is the price per 1,000 cir. mils, the cost of a single-conductor cable is MP. $M = 10.4/R$ and the cost of the cable is $10.4PL/R$, where L is the number of thousands of feet.

For **single-conductor low-tension cable** the value of P averages $1.20 for cables from No. 2/0 A.W.G. to 500,000 cir. mils, and the value of each conductor is

$$C_2 = \frac{10.4 \times 1.2L}{R} = \frac{12.48L}{R} \qquad \text{(dollars)} \qquad (18)$$

Taking the fixed charges at 9 per cent., the annual conductor cost is

$$C'_2 = \frac{0.09 \times 12.48L}{R} = \frac{1.12L}{R} \qquad \text{(dollars)} \qquad (19)$$

and in this case $a = 1.12L$ (Eq. 14).

231. Formula for annual fixed charges on three-conductor cable. In the case of three-conductor cables the cost per 1,000 cir. mils in Par. 232 is based on the total cross-section of the three conductors. The cost of three-conductor cable is

$$C_3 = \frac{3 \times 10.4PL}{R} \qquad \text{(dollars)} \qquad (20)$$

and the annual charges are

$$C'_3 = \frac{0.09 \times 3 \times 10.4PL}{R} = \frac{2.8PL}{R} \qquad \text{(dollars)} \qquad (21)$$

and $a = 2.8PL$. Thus the value of a may be derived for different kinds of cable and at various values of copper, lead and insulation. Where a circuit is composed of more than one cable, this must be taken into account in figuring the total annual cost for the circuit; that is, for a two-wire circuit the value of "a" is doubled and for three cables it is trebled.

232. Cost of Lead-sheathed Cables

Size conductor A.W.G. or cir. mils	Cost per 1,000 cir. mils per 1,000 ft.			
	Single-cond. 3,000 volts	Three-cond. 10,000 volts	Single-cond. 300 volts	Three-cond. 300 volts
No. 2	2.20	2.80	1.90	1.85
No. 0	2.00	2.00	1.80	1.60
No. 00	1.70	1.85	1.60	1.50
No. 000	1.55	1.65	1.40	1.40
No. 0000	1.45	1.50	1.30	1.30
Cir. mils				
250,000	1.30	1.40	1.25	1.25
350,000	1.20	....	1.10	....
500,000	....	....	1.00	....
750,000	....	....	0.90	....
1,000,000	....	....	0.80	....
1,500,000	....	....	0.75	....

233. Fixed charges on generating equipment. Where conditions are such that generator capacity could be released for commercial load by the use of larger conductors, the fixed charges on generating equipment should be considered one of the elements of annual cost of a circuit. The station capacity required to supply the energy loss at the time of the maximum load I is $I^2RL/1{,}000$, in kw. The value of station capacity required to supply the loss on a feeder, when the cost is $100 per kw., is

$$C_4 = \frac{100 \times I^2RL}{1{,}000} \qquad (22)$$

and the fixed charges per conductor at 12 per cent., are

$$C'_4 = 0.12 \times 0.1 I^2RL = 0.012 I^2RL \qquad \text{(dollars)}$$

and $b = 0.012I^2L$ (Eq. 14).

234. Energy loss. The loss of energy on a circuit during a year is dependent upon the annual load factor of the load carried. In Fig. 63 typical load curves are shown for a lighting feeder which carries some day motor-load, for the months of March, June, September, and December. The energy losses will evidently be different on this feeder each month in the year, being less during the summer months than during the winter months.

The annual loss on a circuit may be computed with sufficient accuracy for practical purposes as follows: Take an average day in March, and compute the value of I^2R for each hour. Repeat this operation for the June, September and December curves. Multiply the sum of the losses on the four curves by 91, this being the number of days in each quarter of the year. This total is the annual loss in kilowatt-hours.

235. Loss factor. The ratio of the loss as thus calculated, to the value of the loss if the feeder had carried the maximum load of the year every hour of the year, may be called the loss factor, just as the ratio of the actual output for the year, to the possible output at the rate of the maximum load, is called the load factor of a circuit. If the loss factor of the feeder is 20 per cent., the annual loss is

$$\frac{I^2R \times 0.2 \times 365 \times 24}{1{,}000} = 1.752 I^2R \qquad \text{(kw-hr.)} \qquad (23)$$

The loss factor for a load having the characteristics illustrated in Fig. 63 is about 16 per cent.

236. Calculation of loss. Given the character of the load curve, the loss factor may be determined in the manner described (Par. **234** and **235**) and the annual loss of energy calculated from the maximum load I, in terms of R, the resistance per 1,000 ft. of conductor. The loss at the time of the annual maximum load being I^2RL, the annual loss is

$$\frac{I^2RL \times 8{,}760 \times F}{1{,}000} \qquad \text{(kw-hr.)} \qquad (24)$$

where F is the loss factor. The loss equals $1.40I^2RL$ kw-hr. when the loss factor is 16 per cent. The value of this energy may be taken at about 1 cent per kw-hr. in the smaller plants, 0.7 cent in the larger engine-driven plants and 0.5 to 0.3 cent in the turbine-driven plants. At 1 per cent. per kw-hr. the value of the annual energy loss per conductor, at 16 per cent. loss factor, is

$$C_3 = 0.0140I^2RL \qquad \text{(dollars)} \qquad (25)$$

and the constant c is equal to $0.0140I^2L$.

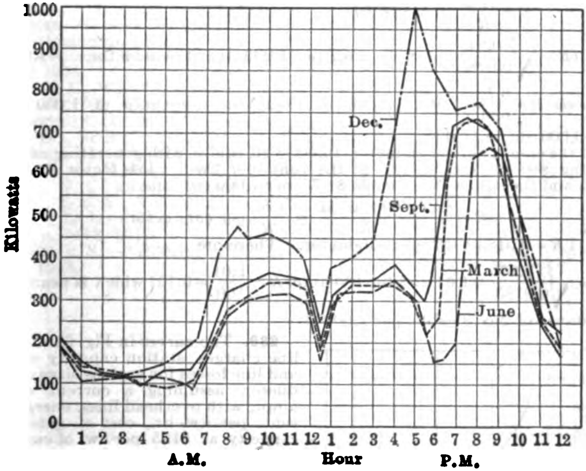

Fig. 63.—Typical load curves.

237. Summary of annual conductor costs; condition for minimum. The total annual cost is, therefore, the sum of the three quantities a/R, bR, and cR (Eq. 14). For weather-proof wire, with station capacity at $100 per kw., a loss factor of 16 per cent., and energy at 1 cent per kw-hr., the annual cost is

$$Y = \frac{a}{R} + bR + cR = \frac{0.513L}{R} + 0.012I^2RL$$

$$+ 0.014I^2RL = \frac{0.513L}{R} + 0.026I^2RL \quad \text{(dollars)} \qquad (26)$$

It is desired to ascertain at what value of R the sum of these three elements will be a minimum for a given current, at the time of the annual maximum load. The only variable in the equation being R, the value of Y will be a minimum, according to the rule of the calculus, when $\partial Y/\partial R = 0$.

If $Y = \frac{0.513L}{R} + 0.026I^2RL$, then $\frac{\partial Y}{\partial R} = \frac{0.026I^2R^2L - 0.513L}{R^2} = 0$. Therefore, $0.026I^2R^2L = 0.513L$, and $I^2R^2 = 0.513/0.026 = 19.7$; whence $IR = \sqrt{19.7} = 4.44$. For instance, if $I = 100$ amp., $R = 0.0444$ ohm, which is about the resistance per 1,000 ft. of a No. 4/0 conductor.

238. Examples of calculation of most economical size of conductor. Assume generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr. and the loss factor at 25 per cent. With single-conductor low-tension cable of 500,000 cir. mils to 1,000,000 cir. mils, the cost per 1,000 cir. mils averages 90 cents per 1,000 ft., **Par. 232.**

Hence $$\frac{a}{R}=\frac{0.09\times 10.4\times 0.9\,L}{R}=\frac{0.84L}{R},$$

$$bR=\frac{80\times 0.12I^2RL}{1{,}000}=0.0096I^2RL,$$

$$cR=\frac{0.004\times 8{,}760\times 0.25I^2RL}{1{,}000}=0.0087\ I^2RL.$$

$$Y=\frac{84\ L}{R}+0.0183I^2RL.$$

and $IR=\sqrt{\frac{0.84}{0.0183}}=\sqrt{46}=6.7$ per 1,000 ft. of conductor. With 600 amperes $R=\frac{6.7}{600}=0.011$, which is about the resistance of 1,000 ft. of 1,000,000-cir. mil cable.

In the case of three-conductor, 10,000-volt cables, with generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr., loss factor at 25 per cent. and the cost of No. 0 cable $1.75 per 1,000 cir. mils,

$$aR=\frac{\$2\times 0.09\times 10.4L}{R}=\frac{1.87}{R}\text{ per conductor.}$$

$(b+c)\ R=0.0183\ C^2RL$ per conductor. Therefore

$CR=\sqrt{\frac{1.87}{0.0183}}=1.01$ and for 100 amp. $R=\frac{1.01}{100}=0.101$ which is nearest the resistance of No. 0 cable, per 1,000 ft.

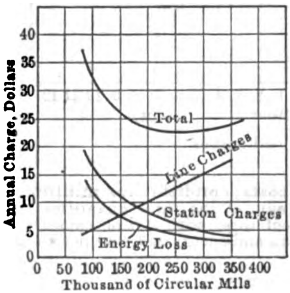

Fig. 64.—Elements of annual cost of a circuit.

239. The curves in Fig. 64 show the line charges, station capacity charges and line losses for various sizes of conductor, assuming a current of 100 amp., with overhead lines, energy at 1 cent. per kw-hr., cost of generating capacity at $125 per kw. of capacity, and loss factor 12 per cent.

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SECTION 13

INTERIOR WIRING

BY TERRELL CROFT

Consulting Engineer, Author American Electricians' Handbook

CONTENTS

(Numbers refer to Paragraphs)

SECTION 13

INTERIOR WIRING

RELATION OF WIRING TO FIRE RISK

1. The National Electrical Code was originally drawn in 1897, as the result of the efforts of the National Conference on Standard Electrical Rules, which comprised delegates from the various insurance, electrical, architectural and allied interests of the United States. The object of the conference was to formulate a set of rules for the installation and construction of electrical apparatus *in a manner free from fire hazard.* The *National Electrical Code* was the result of their work. This was immediately accepted as a standard and adopted by the National Board of Fire Underwriters. It at once placed electric lighting on a safe basis. At present practically all wiring is in accordance with Code rules; the fire insurance policies in some states and communities expressly provide that the Code shall be followed in detail. The National Conference on Standard Electrical Rules has disbanded and the work of the Underwriters' National Electrical Association and the National Conference has been taken over by the National Fire Protection Association, in which are represented the following organizations: American Electric Railway Association; American Institute of Electrical Engineers; Associated Factory Mutual Fire Insurance Cos.; National Board of Fire Underwriters; National Electric Light Association; National Electrical Contractors Association; National Electrical Inspectors Association.

Periodically the National Fire Protection Association convenes and makes such revisions or additions to the Code as are required by advances in the art. The *National Electrical Code* is revised every 2 years and a supplement and a "List of Approved Fittings," are issued semi-annually. Either of these can be obtained gratis on application to any of the Underwriters' Association offices or to any local inspection bureau.

2. Legal status of the Code. The Code has no statutory force, but merely comprises the rules and requirements of the National Board of Fire Underwriters. However certain cities have passed ordinances providing that all work installed in such cities shall be in accordance with the Code, which gives it a legal status in these cities. Moreover, other cities have legalized requirements of their own, which are, usually, essentially the same as the Code requirements. Where requirements are authorized by ordinance or statute they, of course, take precedence over the Code rules.

3. The National Code rules are of great economic importance in relation to fire hazard and fire insurance; without question fire loss amounting to many thousands of dollars has been averted by their use. When installing any electrical equipment, the first step should be to ascertain whether there are local installation rules (ordinances) in force in the community. If there are such rules, they should be followed; if there are none, the *National Electrical Code* rules should be followed.

4. Inspection. All electrical installations should be inspected, whenever an experienced inspector is available, to insure that they comply with either local or Code rules. In cities where rules have been adopted by ordinance, such inspection is usually mandatory. Where inspection is not mandatory, it is always advisable to retain an inspector from the most convenient Underwriters' Bureau to examine the work while it is being installed. Nominal fees are charged for such inspection.

All fittings and materials used in wiring installations should be approved by the Underwriters' Laboratories. Practically all standard equipment now being marketed is so approved and, usually, is so marked. When in doubt one should consult the "List of Electrical Fittings" referred to above.

METHODS OF WIRING

5. Wiring methods may be classified thus: (a) open or surface wiring; (b) concealed knob and tube wiring; (c) wooden-moulding wiring; (d) metal-moulding wiring; (e) flexible-tubing or circular-loom wiring; (f) rigid iron-conduit wiring; (g) flexible metallic conduit wiring; (h) flexible steel-armored cable wiring.

6. Open wiring on knobs and cleats (Fig. 1) is a cheap and satisfactory method if installed in compliance with Code requirements, and is largely used in industrial plants and in mercantile establishments where appearance is of small moment. Single-braid, rubber-covered or slow-burning weatherproof wire may be used. Wires having slow-burning insulation must not be used in damp places. The wires must be supported every 4.5 ft. (1.37 m.) except in buildings of "mill" construction where, if an inspector's authorization is secured, they may be supported at every beam, provided that the wires are No. 8 or larger and are carried at least 6 in. (15.2 cm.) apart. In dry places for voltages below 300, the wires must be separated at least 2½ in.

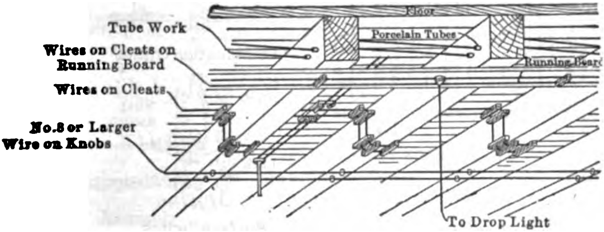


FIG. 1.—Methods of supporting open wiring.

(6.35 cm.), and they must be at least 0.5 in. (1.27 cm.) from the surface wired over. For voltages between 300 and 550, wires must be at least 1 in. (2.54 cm.) from the surface and must be separated 4 in. (10.2 cm.). In damp places, for voltages below 300, wires must be held 1 in. (2.54 cm.) from the surface. Where wires are exposed to mechanical injury protection must be afforded as specified by the Code. Wires must also be protected by porcelain tubes where they pass through walls, timbers or partitions. See the *National Electrical Code* for other minor requirements.

7. Knob and tube wiring (Fig. 2) is used in frame buildings, and is the cheapest method of concealed wiring. Although it has given fair satisfaction, it is being superseded by rigid conduit in progressive communities. In some cities only rigid iron or flexible conduit or flexible steel-armored cable is approved for concealed work.

The single-braid, rubber-insulated conductors are carried within the floors, walls and partitions of the building. Where passing through timbers they must be insulated with porcelain tubes. On a vertical run the wires must be protected from plaster droppings by tubes which extend at least 4 in. (10.2 cm.) above the horizontal timbers which have been pierced.

In structural-steel mill-type buildings, open wiring is carried on porcelain knobs or cleats which may be secured with stove bolts at points where there are spaces between the members or where holes are already punched. Sometimes it is desirable to screw the cleats to blocks which are clamped to the members with hook bolts.

Open work is especially suited to locations which are damp or hot such as dye works, breweries, dry kilns, metal refineries and the like. In such

9. Dimensions and capacities of wooden mouldings. Below are given the dimensions of standard two-wire wooden mouldings; the products of various manufacturers vary somewhat. All dimensions are given in inches (Fig. 3). (Kirkpatrick Mfg. Co.)

A Size of groove	Will accommodate wires		B	C	D	E	F
	Solid	Stranded					
0.250	14 to 12	.....	1[illegible]	[illegible]	1[illegible]	3/16	[illegible]
0.375	10 to 8	8	1[illegible]	3/4	1[illegible]	[illegible]	[illegible]
0.500	9 to 4	5 to 6	2[illegible]	1	1[illegible]	[illegible]	1
0.625	3 to 0	4 to 1	2[illegible]	1 3/16	1[illegible]	7/32	1[illegible]
0.750	....	0 to [illegible]	2[illegible]	1[illegible]	2 3/16	[illegible]	1[illegible]
0.875	....	[illegible] to 250,000	3[illegible]	1[illegible]	2 7/16	[illegible]	1[illegible]
1.000	....	250,000 to 500,000	3[illegible]	1[illegible]	2 11/16	[illegible]	1[illegible]

10. Metal moulding, which can be used only for exposed circuits, is now largely employed in the place of wooden moulding (Par. 8). It also finds application in new construction in commercial buildings and in industrial plants, being substituted for the open wiring method. This moulding occupies little space (see Fig. 4), is very neat in appearance and being sherardized, will take paint readily. The conductors in the moulding can be taken out for inspection at any time with little trouble. Alterations in or additions to the moulding system can be very easily and neatly made. Fittings are manufactured, whereby almost any possible wiring arrangement can be effected. See *National Electrical Code* and manufacturers' catalogues for further information. Metal-moulding wiring costs somewhat less than conduit and. for exposed work, provides a neater appearance. It can be used only where the potential difference does not exceed 300 volts and the power 660 watts. It must be continuous from outlet to outlet or to approved fittings. It should not be used in damp places.

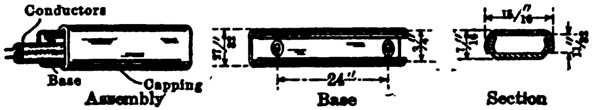


FIG. 4.—National metal moulding.

Single-braid, rubber-insulated wire can be used in metal moulding. Wires must be laid in—not fished. The moulding shown in Fig. 4 has a capacity for four No. 14 wires. All wires of an alternating-current circuit must be in the same moulding, and it will be found advantageous to treat direct-current circuits likewise.

11. Flexible tubing (circular loom, duraduct, etc.) is now seldom used except in combination with other methods of wiring. However, it is very useful and finds wide application for furnishing additional insulation and protection to conductors. It cannot be used in damp places. See *National Electrical Code* for further information. Where metal outlet boxes or switch boxes are used, flexible tubing must extend from the last porcelain support into the outlet box. It is used for encasing wires fished between walls and ceilings, each wire being separately encased. It is also used in open work where wires, are nearer each other than 2.5 in.; on wires crossing other wires, gas pipes, water pipes, iron beams, wood work, brick or stone; on wires at chandeliers and bracket outlets; on gas pipe back of insulating joints; on wires under the edges of canopies: Where space is limited and the 5-in. separation required between wires cannot be maintained, each wire must be separately encased in a continuous length of flexible tubing. Flexible tubing may also be employed as an added protection to wires; as for instance on portable wires around machinery and in show windows, etc., where added protection, although not required, is often desirable.

17. Standard Sizes of Conduits for the Installation of Wires and Cables (*As adopted, recommended and copyrighted by The Natl. Electrical Contractors Assn. of the U. S.*)

Conduit sizes based on the use of not more than three 90-deg. elbows in runs taking up to and including No. 10 wires, and two elbows for wires larger than No. 10. Wires No. 8 and larger are stranded. Special permission is required of the inspection department having jurisdiction for the installation of more than nine wires in the same conduit. The wires used by the telephone companies of various cities differ as to thickness of insulation. The table "A" gives values satisfactory for both light and heavy insulation. For explanation of column reference letters for table "A," see footnotes.

Size of wire		Single wires				Duplex wires		
A.W.G.	Circular mils	Single wire	Two-wire system	Three-wire system	Four-wire system	Size A.W.G.	Number of wires	Size of conduit
14	4,107	½	½	½	¾	14	1	½
12	6,530	½	¾	¾	¾	14	2	¾
10	10,380	½	¾	¾	1	14	3	1
8	16,510	½	1	1	1	14	4	1
6	26,250	½	1	1¼	1¼	12	1	½
4	41,740	½	1¼	1¼	1½	12	2	¾
3	52,630	½	1¼	1¼	1½	12	3	1
2	66,370	½	1¼	1¼	1½	12	4	1¼
1	83,690	¾	1½	1½	2	10	1	¾
0	105,500	1	1½	2	2	10	2	1
00	133,100	1	2	2	2½	10	3	1¼
000	167,800	1	2	2	2½	10	4	1½
0000	211,600	1¼	2	2½	2½			
	300,000	1¼	2½	2½	3			
	400,000	1¼	3	3	3½			
	500,000	1½	3	3	3½			
	700,000	2	3½	3½				
	1,000,000	2	4	4				
	1,500,000	2½	4½	5				
	2,000,000	3	5	6				

Single wires — Convertible system

Number and size of wires, A.W.G.	Size of conduit
1– 10 2– 14	½
1– 8 2– 12	¾
1– 6 2– 10	1
1– 4 2– 8	1
1– 2 2– 6	1¼
1– 1 2– 5	1¼
1– 0 2– 4	1¼
1– 00 2– 3	1½
1– 000 2– 2	1½
1– 0000 2– 1	2
1– 250,000 2– 0	2
1– 350,000 2– 00	2½

(A) Conduit capacities for various wires

Conduit	*a*	*b*	*c*	*d*	*e*
½	3	10	18	5	3
¾	5	20	30	10	6
1	10	30	40	15	10
1¼	16	70	100	25	16
1½	24	90	130	35	25
2	40	150	200	50	35

a. No. 14 R. C. double-braid solid wires. Based on straight run without elbows.

b. No. 16 light insulation fixture wires. Based on straight run without elbow.

c. No. 18 light insulation fixture wires. Based on straight run without elbow.

d. No. 20 braided and twisted pair. Switchboard or desk instrument wire. Based on not more than two 90-deg. elbows.

e. No. 19 braided and twisted pair. Standard $\frac{3}{64}$-in. insulation, telephone wire. Based on not more than two 90-deg. elbows.

18. Flexible steel-armored conductor (Fig. 6) has found considerable application during the last few years, due to its adaptability for electrical construction in finished buildings. It can be run with practically no regard for pipes or other grounded obstructions and can be fished long distances. It is more expensive than conductors in circular loom but it makes a thoroughly dependable job. Flexible steel-armored conductor consists of rubber-insulated wire or cable, protected from injury and to some extent from dampness by two layers of spirally wound flexible steel armor. It is manufactured "leaded" and "unleaded." The leaded conductor has

Rope-lay cable. A single-conductor cable composed of a central core surrounded by one or more layers of helically laid groups of wires. This kind of cable differs from the preceding in that the main strands are themselves stranded.

N-conductor cable. A combination of N conductors insulated from one another. (It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable," as in definition for "*Cable*" above.)

N-conductor concentric cable. A cable composed of an insulated central conducting core with tubular stranded conductors laid over it concentrically and separated by layers of insulation. Usually only 2-conductor or 3-conductor. Such conductors are used in carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

Duplex cable. Two insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

Twin cable. Two insulated single-conductor cables laid parallel, having a common covering.

Triplex cable. Three insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

Twisted pair. Two small insulated conductors twisted together, without a common covering. The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

Twin wire. Two small insulated conductors laid parallel, having a common covering.

21. Specifications for insulated conductors are given in detail in the *National Electrical Code*. Since these specifications are subject to revision, it is inadvisable to repeat them here. Practically all rubber-insulated wire on the market is manufactured in accordance with Code requirements, and to each coil is fastened a tag indicating the approval of the Underwriters' Laboratories. Unapproved rubber-insulated wire should not be installed.

22. Allowable or Safe Current-carrying Capacities of Insulated Copper Wires

(1913 *National Electrical Code*)

Circular mils	A.W.G.	Table A Rubber insulation. (Amp.)	Table B Other insulations. (Amp.)	Circular mils	A.W.G.	Table A Rubber insulation. (Amp.)	Table B Other insulations. (Amp.)
1,624	18	3	5	200,000	......	200	300
2,583	16	6	10	300,000	......	275	400
4,107	14	15	20	400,000	......	325	500
6,530	12	20	25	500,000	......	400	600
10,380	10	25	30	600,000	......	450	680
16,510	8	35	50	700,000	......	500	760
26,250	6	50	70	800,000	......	550	840
33,100	5	55	80	900,000	......	600	920
41,740	4	70	90	1,000,000	......	650	1,000
52,630	3	80	100	1,100,000	......	690	1,080
66,370	2	90	125	1,200,000	......	730	1,150
83,690	1	100	150	1,300,000	......	770	1,220
105,500	0	125	200	1,400,000	......	810	1,290
133,100	00	150	225	1,500,000	......	850	1,360
167,800	000	175	275	1,600,000	......	890	1,430
211,600	0000	225	325	1,700,000	......	930	1,490
				1,800,000	......	970	1,550
				1,900,000	......	1,010	1,610
				2,000,000	......	1,050	1,670

24. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 600 to 1,500

Size A.W.G.	Size Cir. mils	No. of wires in cond.	Diam. of wires comprising cable, mils.	Thickness of rubber in inches	Diameter over all, Single braid, Mils	Diameter over all, Single braid, 64ths	Diameter over all, Double braid, Mils	Diameter over all, Double braid, 64ths	Approx. weight per 1,000 ft., tape and braid
				Solid					
14	4,107	....	....	1/16	239	15.3	289	18.5	46
12	6,530	....	....	1/16	256	16.4	306	19.6	58
10	10,380	....	....	1/16	277	17.75	327	20.9	75
8	16,510	....	....	1/16	304	19.45	354	22.6	100
6	26,250	....	....	5/64	382	24.2	446	28.5	153
4	41,740	....	....	5/64	425	27.2	489	31.3	212
2	66,370	....	....	3/32	498	31.9	582	37.2	310
1	83,690	....	....	3/32	561	35.9	645	41.25	394
				Stranded					
1	83,690	19	66.4	3/32	604	38.65	688	44.0	405
0	105,500	19	74.5	3/32	645	41.25	729	46.6	490
00	133,100	19	83.7	3/32	691	44.25	775	49.6	595
000	167,800	19	94.0	3/32	742	47.5	826	52.8	715
0000	121,600	19	105.5	3/32	800	51.2	884	56.5	875
......	400,000	37	104.0	7/64	1,032	66.0	1,116	71.4	1,570
......	600,000	61	99.2	1/8	1,227	78.5	1,311	83.9	2,300

25. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 1,500 to 2,500

				Solid					
12	6,530	....	....	3/32	318	20.4	368	23.55	85
10	10,380	....	....	3/32	339	21.7	389	24.9	100
8	16,510	....	....	3/32	380	24.3	444	28.4	130
6	26,250	....	....	3/32	414	26.5	478	30.6	175
4	41,740	....	....	3/32	456	29.2	520	33.3	240
2	66,370	....	....	3/32	509	32.6	573	36.65	330
1	83,690	....	....	7/64	592	37.0	676	43.25	420
				Stranded					
8	16,510	7	48.6	3/32	398	25.5	462	29.6	140
6	26,250	7	61.2	3/32	436	27.9	500	32.0	185
4	41,740	7	77.2	3/32	504	32.25	588	37.6	250
2	66,370	7	97.4	3/32	564	36.1	648	41.5	340
1	83,690	19	66.4	7/64	635	40.6	719	46.0	435
0	105,500	19	74.5	7/64	676	43.25	760	48.6	520

26. Current-carrying capacity of copper wires. If the current carried by a given conductor is too great, the conductor will become so hot that it will be unsafe, or may, if insulated, damage its insulation. Certain safe current values have been determined for different sizes of conductor, and are listed in Par. 22. Less current is permissible in rubber-insulated

34. Dimensions and Weights of Weather-proof and Slow-burning Solid Copper Wire and Cable
(*General Electric Co.*)

Size A.W.G. and cir. mils	Weather-proof: Approx. wts. per 1,000 ft. (lb.)		Weather-proof: Approx. overall diameters, in.		Slow-burning: Approx. weights per 1,000 ft. (lb.)			Slow-burning: Approx. overall diameters, in.			A.W.G. and cir. mils.
	Triple braid	Double braid	Triple braid	Double braid	Weather-proof white finish	Weather-proof black finish	Under-writers	Weather-proof or white	Weather-proof or black	Under-writers	
Solid wire											
1	310	290	0.445	0.405	350	340	330	0.445	0.445	0.445	1
2	255	232	0.400	0.374	290	280	280	0.400	0.400	0.400	2
4	164	146	0.346	0.320	200	190	180	0.346	0.346	0.346	4
6	112	97	0.303	0.278	140	127	125	0.303	0.303	0.303	6
8	75	64	0.264	0.245	95	85	90	0.264	0.264	0.264	8
10	53	46	0.221	0.197	70	60	65	0.221	0.221	0.221	10
12	35	27	0.200	0.172	52	42	40	0.200	0.200	0.200	12
14	25	20	0.182	0.155	40	30	30	0.182	0.182	0.182	14
16	19	15	0.169	0.142	30	24	22	0.169	0.169	0.169	16
Stranded											
1,000,000	3,478	3,360	1.451	1.365	3,880	3,980	3,578	1.451	1.451	1.451	1,000,000
750,000	2,615	2,551	1.300	1.210	3,020	3,100	2,720	1.300	1.300	1.300	750,000
600,000	2,113	2,060	1.190	1.105	2,370	2,460	2,204	1.190	1.190	1.190	600,000
500,000	1,781	1,740	1.108	1.027	2,010	2,080	1,858	1.108	1.108	1.108	500,000
400,000	1,445	1,405	1.020	0.940	1,670	1,700	1,509	1.020	1.020	1.020	400,000
300,000	1,126	1,090	0.930	0.846	1,290	1,310	1,170	0.930	0.930	0.930	300,000
250,000	937	905	0.862	0.780	1,080	1,120	981	0.862	0.862	0.862	250,000
0,000	806	753	0.785	0.708	910	960	844	0.785	0.785	0.785	0,000
000	655	610	0.728	0.648	745	785	686	0.728	0.728	0.728	000
00	515	470	0.662	0.599	590	625	550	0.662	0.662	0.662	00
0	420	382	0.605	0.555	485	510	449	0.605	0.605	0.605	0
1	328	300	0.518	0.470	360	380	360	0.518	0.518	0.518	1
2	267	251	0.440	0.415	300	335	294	0.440	0.440	0.440	2
4	173	153	0.379	0.353	205	230	196	0.379	0.379	0.379	4
6	117	103	0.327	0.305	145	165	135	0.327	0.327	0.327	6
8	75	69	0.290	0.270	97	105	94	0.290	0.290	0.290	8

voltages as high as 600. These include single-pole, double-pole and triple-pole switches; three-way or four-way switches, for the control of hall lamps from any one of several locations; and the electrolier switches. They can be obtained (for 250 volts) for currents as large as 30 amp. Snap

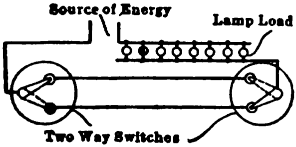


FIG. 7.—Control of circuit from two locations with two-way switches.

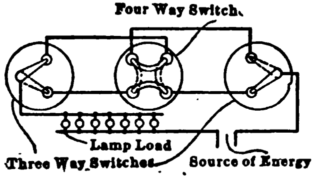


FIG. 8.—Control of circuit from any one of more than two locations.

switches are usually preferable to knife switches from an operating standpoint as any one can operate them, under normal conditions, without drawing a destructive arc. Indicating switches, which show by their appearance whether they are open or closed, should always be used. Flush snap switches are installed in pressed-steel switch boxes which are set in walls or partitions, so that only the plate and operating buttons are visable. Types can be obtained which will furnish practically the same service as surface snap switches. They are more expensive but present a neater appearance than surface switches.

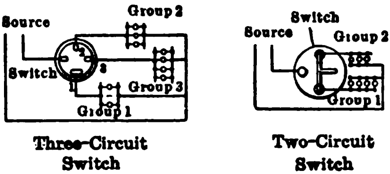


FIG. 9.—Wiring for electrolier switches.

40. Three-way and four-way switches. Switches for controlling a group of lamps from either of two locations are wired as indicated in Fig. 7. Two "three-way" snap switches are required. This scheme is largely used for the control of hall lamps. Switches for controlling a group of lamps from any one of more than two locations are connected as in Fig. 8. A "three-way" switch is used at each end of the circuit and as many additional "four-way" switches

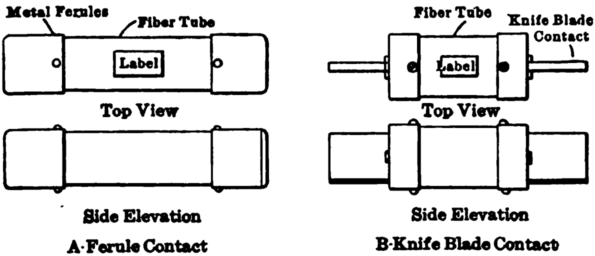


FIG. 10.—National Electrical Code standard enclosed fuses.

are necessary as there are additional control locations. This arrangement is used for hall lamps so that they can be controlled from any floor.

41. Electrolier switches (Fig. 9) control lamps in independent groups such as would be used in an illuminated dome or of an electrolier. Switches

46. Cut-outs or fuse blocks are devices whereby fuses can be inserted in an electrical circuit. Detailed specifications covering cut-outs for all approved currents and voltages are given by the Code. A combination of the Edison plug cut-out, and the ferule fuse and fuse-plug casing that can be used in connection with it, constitutes a most satisfactory fuse arrangement. However, this arrangement is limited to a capacity of 30 amp. at 125 volts. The Edison plug cut-out, which has a right-hand thread, is approved only for 125 volts; the Bryant Electric Co. makes a similar cut-out having a left-hand thread, which is approved, under certain conditions, for 250 volts. The right-hand thread cut-out is approved for only 125 volts because the Edison fuse-plug, which is not safe at a greater voltage, can be used in it. Cut-outs for open-link fuses consist merely of slate blocks, having mounted on them the necessary terminals.

47. Diameters of Wires of Various Materials that will be Fused by a Current of a Given Strength

(Knox's "Electric Light Wiring." Derived from tables of W. H. Preece)

Current in amp.	Copper		Aluminium		German silver		Iron	
	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.
1	0.0021	43	0.0026	41	0.0033	39	0.0047	37
2	0.0034	39	0.0041	38	0.0053	35	0.0074	33
3	0.0044	37	0.0054	35	0.0069	33	0.0097	30
4	0.0053	35	0.0065	34	0.0084	31	0.0117	29
5	0.0062	34	0.0076	32	0.0097	30	0.0136	27
10	0.0098	30	0.0120	28	0.0154	26	0.0216	24
15	0.0129	28	0.0158	26	0.0202	24	0.0283	21
20	0.0156	26	0.0191	24	0.0245	22	0.0343	19
25	0.0181	25	0.0222	23	0.0284	21	0.0398	18
30	0.0205	24	0.2500	22	0.0320	20	0.0450	17
35	0.0227	23	0.0277	21	0.0356	19	0.0498	16
40	0.0248	22	0.0303	20	0.0388	18	0.0545	15
45	0.0268	21	0.0328	20	0.0420	18	0.0589	15
50	0.0288	21	0.0352	19	0.0450	17	0.0632	14
60	0.0325	20	0.0397	18	0.0509	16	0.0714	13
70	0.0360	19	0.0440	17	0.0564	15	0.0791	12
80	0.0394	18	0.0481	16	0.0616	14	0.0864	12
90	0.0426	18	0.0520	16	0.0667	14	0.0935	11
100	0.0457	17	0.0558	15	0.0715	13	0.1003	10
120	0.0516	16	0.0630	14	0.0808	12	0.1133	9
140	0.0572	15	0.0698	14	0.0895	11	0.1255	8
160	0.0625	14	0.0763	13	0.0978	10	0.1372	7
180	0.0676	14	0.0826	12	0.1058	10	0.1484	7
200	0.0725	13	0.0886	11	0.1135	9	0.1592	6
225	0.0784	12	0.0958	10	0.1228	8	0.1722	5
250	0.0841	12	0.1028	10	0.1317	8	0.1848	5
275	0.0897	11	0.1095	9	0.1404	7	0.1969	4
300	0.0950	11	0.1161	9	0.1487	7	0.2086	4

WIRING CALCULATIONS AND LAYOUTS

48. The resistance of a circular-mil-foot of commercial copper wire (a wire 1 ft. long and having cross-sectional area of 1 cir. mil) is usually quoted as from 10.6 to 10.8 ohms, at 75 deg. fahr. (24 deg. cent.). For wiring calculations 11 ohms per mil foot is a sufficiently accurate assumption. (See Sec. 4 for the Annealed Copper Standard.) On this basis the resistance of any commercial copper conductor is:

$$R = \frac{11 \times l}{\text{cir. mils}} \quad \text{(ohms)} \qquad (1)$$

centages of the receiver voltage, a drop of from 1 to 3 per cent. is satisfactory and a 4.5 per cent. drop is the maximum. (See Par. **53**.) The above values represent the voltage drops from the source of assumed constant voltage to the lamp. Because of the extreme sensitiveness of the incandescent lamp to variations in voltage, the lamps may be subjected to overvoltages if the drops suggested above are exceeded—which will materially decrease their life; they may also be subjected to undervoltages when the circuit is loaded—which will decrease their brilliancy (Sec. 14). Some central-station companies specify that the total drop in 110-volt, interior-wiring circuits shall not exceed 1 volt.

52. Allowable voltage drop in motor circuits. A 5 per cent. drop is in accordance with excellent practice and a 10 per cent. drop or even a slightly greater one is often considered satisfactory. The drop should be calculated on the basis of full-load motor current. Where incandescent lamps are on the same circuits with motors the drops suggested in Par. **51** should not be exceeded. In designing motor circuits the question of conductor economy (Par. **73**) should be considered.

53. Apportionment of voltage drop. In circuit design it is necessary to apportion the total drop among the various component circuits—feeders, mains, sub-mains and branches. In incandescent lighting most of the drop is confined to the feeders because if there were excessive drop in the mains and branches, lamps located close together but served by different mains and branches might operate at decidedly different brilliancies.

With an isolated plant, that is where energy is generated on the premises, the drop may be apportioned exactly as indicated (Par. **54**). Where the premises is served by a central station (Par. **55**), the practice of the utility concern may allow 2 volts drop in its secondary mains and the service to the premises. In such a case, the total drop within the premises should not exceed 1 to 2 volts. Where a utility company is to give service, it should be consulted regarding its practice in this respect. Some central stations require that the voltage drop in interior wiring installations which they are to serve, shall not exceed a certain maximum. In any case, it is frequently the practice to allow one volt drop for the branches and to apportion the rest of the available drop to the main circuits and feeders.

54. Typical Apportionment of Drop in 110-Volt Lighting Circuits

Part of circuit	Proportion	4 volts total drop		3 volts total drop	
		Actual drop, volts	Per cent. drop	Actual drop, volts	Per cent. drop
Branches	1 volt	1	0.91	1	0.91
Mains	1/3 remainder	1	0.91	2/3	0.60
Feeders	2/3 remainder	2	1.82	1 1/3	1.21
Total		4	3.64	3	2.72

55. Apportionment of drop on 2,400-volt distribution systems is often made under the assumption that the secondary voltage at the transformers remains practically constant. This will be found true in a well laid-out system, particularly if automatic feeder regulators are used.

56. Apportionment of drop in motor circuits is frequently made on the basis that 1 volt will be allowed in the branches, two-thirds of the remaining drop in the mains and one-third in the feeders. Most of the drop should be confined to the mains in order that a variation in the load on one motor of a group will affect the others as little as possible. Where motor circuits are fed by transformers, it is usually assumed that the voltage at the secondary side of the transformers remains practically constant, and therefore all of the allowable drop is apportioned to the secondary circuit. Where a group of motors is fed by a main circuit and branches, the drop in the branches, if they are not too long, is frequently 1 volt or less, under normal working conditions, because the insurance rules require that a branch conductor serving a motor be capable of safely carrying a current 25 per cent. greater than the normal full-load current of the motor.

Where circuits are long and the conductors lie far apart, the results given by the approximate formulas should be checked by the Mershon-Diagram (Sec. 12) which considers the effects of power-factor and reactance Although the Mershon method is a trifle tedious, it will be found the quickest and the best when all things are considered. The use of the tables, that are frequently given for the determination of alternating-current conductors, will probably lead to inaccurate results, unless the user is familiar with their derivation. The effects of electrostatic capacity are inconsequental and need not be considered in ordinary interior wiring calculations.

62. Line-reactance voltage drop may be decreased either by diminishing the distance between the wires, or by dividing the copper into a greater number of circuits. Reactance is little affected by changing the size of the conductor. In interior wiring installations the conductors can be no nearer together than certain minimum distances specified by the *National Electrical Code*. Where installed in conduit the conductors are so close together that their reactance is practically negligible. All the wires of any alternating-current circuit (two wires for a single-phase circuit, three wires for a three-phase circuit or four wires for a two-phase circuit) should be carried as close together as feasible or, in a conduit installation, should all be in the same conduit, in accordance with the Code.

63. Skin effect in interior wiring calculations is ordinarily of little consequence, and need not be considered unless conductors are larger than 600,000 cir. mils in area. (Sec. 2 and Sec. 12.) As a general proposition conductors larger than 600,000 cir. mils are very difficult to handle, and, hence, are uneconomical to install; therefore, when greater area is required it is usual to arrange several conductors in parallel. Some engineers will use no conductor larger than 300,000 cir. mils in interior wiring. Fiber-cored cables (Par. 36 and 37) should be used where conductors larger than 600,000 cir. mils are required.

64. Calculation of alternating-current circuits of high power-factor, such as are used for supplying incandescent lamps: in this case treat the circuits as if they were direct-current circuits, using Eq. 3, Par. 59. This method is not strictly accurate but is sufficiently so for ordinary conditions. If the circuits are long and the wires are widely separated, the conductor sizes obtained as above should be checked by the Mershon-diagram (Sec. 12).

65. To calculate single-phase, alternating-current circuits where line reactance may be neglected. The following formulas can be safely used for the calculation of branch circuits and also of feeders and mains where the conductors are carried in conduit or are not very long. Where the circuits are of considerable length the result given by the formula should be checked with the Mershon diagram (Sec. 12). The current may be found from the expression:

$$I_1 = \frac{Kw. \times 1{,}000}{E \times p.f.} \text{ (amps.)} \tag{4}$$

wherein, I_1 = current in amperes, $Kw.$ = kilowatts input of the load, E = voltage of circuit and $p.f.$ = power-factor of load.

$$\text{cir. mils} = \frac{22 \times I_1 \times L}{V}. \tag{5}$$

Wherein, *cir. mils* = area of conductor; I_1 = current in amperes; L = length (one way) of the circuit in feet and V = volts drop allowable.

66. Calculations of single-phase branches from three-phase circuits are made in the same way as those for any other single-phase circuit (Par. 65). However it must be remembered that if the branch is connected between one of the three phase wires and the neutral, the voltage impressed on the branch circuit will be 0.58 × the voltage across any two mains of the three-phase circuit

67. To calculate two-phase, four-wire, circuits where line reactance can be neglected the following formulas can be used. The limitations for this method are the same as those for single-phase circuits as outlined, Par. 65. As with the single-phase equations (Eq. 4 and 5, Par. 65), the Mershon diagram (Sec. 12) should be used for checking the conductors

For a four-wire, two-phase circuit (assuming balanced currents)

$$P = \frac{4 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{44 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (12)$$

For a three-wire, three-phase circuit (assuming balanced currents)

$$P = \frac{3 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{33 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (13)$$

Wherein, P = the power, in watts, lost in the circuit; I = the current in amperes which flows in each of the wires of the circuit; L = the length (one way) of the circuit; and *cir. mils* = cross-sectional area in circular mils of each of the wires. The above formulas can be used only when all of the wires of the line are of the same size.

73. Conductor economy in interior wiring installations always should be considered as a matter which is subordinate to the Code requirements. Obviously any conductor selected for a specific installation must fulfil the requirements of mechanical strength, ample carrying capacity (Par. 22 and 26), and permissible voltage drop (Par. 51 and 52). Frequently one of these three considerations will definitely determine the size of the conductor; however, a calculation of the resistance or I^2R (power) loss (Par. 72) may indicate that it will be desirable to use a larger size than is otherwise necessary.

74. Annual charges may be considered, in connection with the economical selection of a conductor size, to be made up of two items: (*a*)

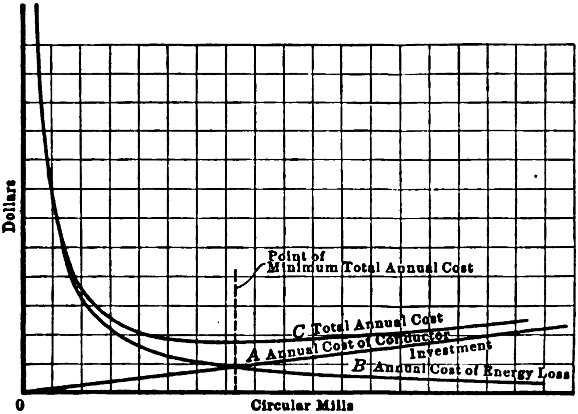


Fig. 14.—Graph illustrating Kelvin's law.

resistance-loss charges; (*b*) investment charges. Resistance-loss charges depend upon the resistance, the current and the unit cost of energy, and may be decreased by an increase of conductor size. This, however, calls for a greater investment with consequently larger investment charges. A conductor should be selected of such a size that the total annual charge (Sec. 25) will be a minimum.

In Fig. 14 the effect of a variation of conductor size on resistance-loss charge, investment charge, and total annual charge is shown graphically. The interest charges on the conductor increase directly with its cross-sectional area (curve *A*, Fig. 14). The resistance-loss charges decrease inversely as the cross-sectional area of the conductor (curve *B*, Fig. 14). The total annual charge (curve *C*, Fig. 14), the sum of curves *A* and *B*, is at its minimum value directly over the point where curves *A* and *B* intersect; that is, the conductor size that will have the least total annual cost is that

79. Factors for determining the mean annual current. To ascertain the mean annual current for substitution in Eq. 14, Par. 75, multiply the maximum current by the ratio applying to the conditions under consideration, given in the column headed "*Factor*" in the following table. The table is calculated on a basis of 24 hr. × 365 days = 8,760 hr. per year.

Example. If a maximum current of 1,000 amp. (I) flows ¾ of the time or 6,570 hr. per year and a current of 750 amp. (¾I) flows ¼ of the time or 2,190 hr. per year the factor "0.944" would be used; that is, the value 0.944 × 1,000 amp. = 944 amp. would be the mean annual current for substitution in the equation of Par. 75 (Eq. 14).

	Proportion of maximum current "I" carried				Factor
	¼I	½I	¾I	I	
Proportion of time current is carried	0	0	0	1	1.000
	0	0	¼	¾	.944
	0	¼	0	¾	.901
	0	0	½	½	.844
	0	0	0	¾	.866
	¼	0	0	¾	.875
	0	¼	¼	½	.838
	0	0	¼	½	.820
	¼	0	¼	½	.810
	0	½	0	½	.790
	0	¼	½	¼	.771
	¼	¼	0	½	.760
	¼	0	½	¼	.744
	½	0	0	½	.729
	0	½	¼	¼	.718
	0	0	0	½	.707
	¼	¼	¼	¼	.685
	0	¾	0	¼	.661
	½	0	¼	¼	.650
	¼	½	0	¼	.611
	½	¼	0	¼	.586
	¾	0	0	¼	.545
	0	0	0	¼	.500

80. Two-phase distribution may be effected with four or with three wires. In the former case there is a pair of wires for each phase, while in the latter there is one wire for each phase and a common wire for both phases. The circuits must be balanced on either side, just as in the case of a three-wire, direct-current system, the only difference being that where three wires are used, the common wire is 1.4 times as large as either of the other two, since it must carry 1.4 times as much current. Motors are connected to both phases and employ all three or all four wires as the case may be. With four wires, the lamps are connected to each phase as though the supply were single-phase and care should be exercised to balance each phase as nearly as possible.

81. The three-phase system is usually employed where motors form a greater part of the load. Three conductors are necessary. Where lamps are required they are either balanced on the three-phases or connected between each main conductor and a common conductor of smaller size usually connected to the middle point of the star-connected secondary. The e.m.f. between any one of the three wires and the neutral is 0.577 (or 0.58) times the e.m.f. between the mains.

82. Two-wire and three-wire systems. Most interior wiring follows the two-wire system, the three-wire system being used principally for feeders and mains. With the direct-current three-wire system, (lamps and motors) on the plans and then so locate the panel boxes that no lighting branch circuit shall be much over 100 ft. (30.5 *m*) in length, or have a load much greater than 440 watts. Panel boxes should be so located that they are accessible and that the circuits can be readily run to them. Compute the load on each panel box and indicate it, at the box, on the drawing. Lay out the mains and feeders (see Fig. 16). First decide whether the hall or public lights will be controlled separately or with the private lights from the main switchboard, because this feature affects the arrangement of the feeders and possibly that of the mains. Next decide whether there should be a separate feeder to each floor or whether several floors or portions thereof will be served by one feeder. Where it is not necessary to control the loads on the different floors separately, and where the resulting conductor size will not be prohibitively large, the cheapest and probably the best arrangement is to serve several or possibly all floors with one feeder. Usually, the only limit to the number of floors that may be served with one feeder is the re-

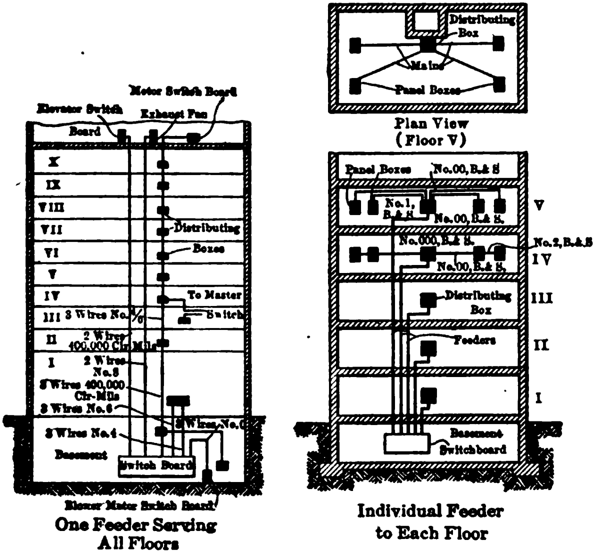


FIG. 16.—Wiring lay-outs in large buildings.

finement of control that is desired from the main switchboard. It is frequently necessary to make several tentative lay-outs and computations before the most desirable arrangement is found. Segregated motors and groups of motors, unless very small, should be served by independent feeders.

87. Arrangement of feeders. Solely on a basis of initial cost, it is usually cheaper to run a few large conductors than a number of small ones. It does not pay, however, to endeavor to install conductors larger than 1,000,000 cir. mils. When large capacity is necessary, use several conductors having the aggregate capacity required. For alternating currents, conductors larger than 700,000 cir. mils are not desirable because of skin effect. Often the space available for conductor runs necessitates small conductors (Par. 86 and 63).

88. Motor circuits are subject to many special Code requirements. One unfamiliar with its rulings should refer to the Code before he attempts

90. Compilation of estimates. Experience and a reliable note-book of labor costs applying to the community under consideration are the most valuable aids. Read the specifications or inspect the premises and make a wiring lay-out if there is none available. Make a list (Fig. 17) of all material required, following some definite system. A good method is to consider each distribution center—one at a time—and tabulate all the material required for the circuits feeding from it. Number or letter the distribution centers in accordance with a certain scheme and designate the branches with sub-notations. Indicate this notation on an estimating sheet similar to that of Fig. 17, in connection with your tabulation. Then proceed, tabulating panel-box, main, feeder and entrance material. After all is tabulated, the items can be totaled and these total values used for ordering material. Allow for some extra material for losses and breakages. Figure labor cost on a unit basis, that is, the cost of stringing wire being a certain value per 100 ft., the cost of erecting conduit being so much per unit length and so on through the entire list of materials. See cost data elsewhere for unit costs. A small job can be estimated with fair accuracy on a basis of so much per outlet, without the necessity of compiling a bill of materials.

INSTALLATIONS

91. Service entrances, (Fig. 19). A cut-out and a fuse block should protect the switch. The wall should be bushed where the conductors pass through unless they are in conduit, and the tubes or conduit should be cemented in the wall. Tubes should slant outwardly and downwardly to

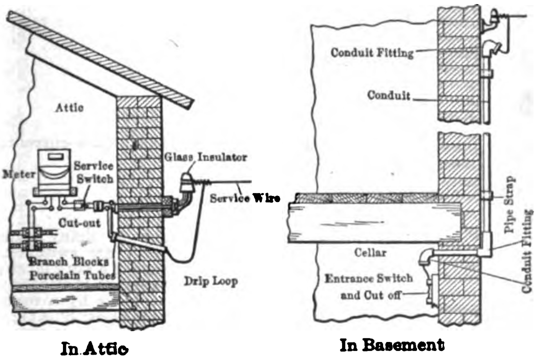
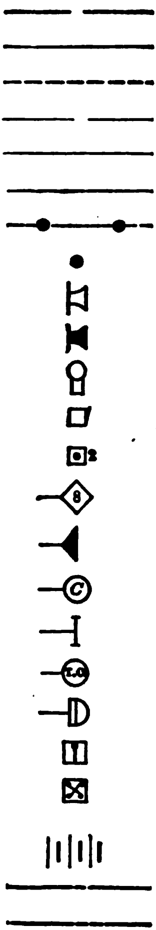


FIG. 18.—Service entrances.

prevent the entrance of moisture, and a drip loop should be formed of the service wires. The entrance switch should be so arranged that it will disconnect all of the equipment in the building except the main cut-out. Where conduit is used, the two or the three rubber-insulated wires should be carried in one conduit.

92. Panel-box panels may consist merely of porcelain cut-outs held to the back of the box with wood screws, or they may be more elaborate. The panel merely provides a convenient means of connecting the branch circuits to a main through fuses. Switches may be used in both main and branch circuits or they may be omitted entirely. Many satisfactory installations are in operation without switches, but switches are a great convenience for opening circuits when replacing fuses or for testing. In general, knife switches should not be used in branch circuits for the control of the lights, as they are frequently not of sufficiently strong construction to withstand permanently such service. Branch-lighting circuits should be controlled by either flush or surface snap switches mounted outside the panel box.



Main or feeder run concealed under floor.

Main or feeder run concealed under floor above.

Main or feeder run exposed.

Branch circuit run concealed under floor.

Branch circuit run concealed under floor above.

Branch circuit run exposed.

Pole line.

Riser.

Telephone outlet; private service.

Telephone outlet; public service.

Bell outlet.

Buzzer outlet.

Push button outlet. Numeral indicates number of pushes.

Annunciator. Numeral indicates number of points.

Speaking tube.

Watchman clock outlet.

Watchman station outlet.

Master time clock outlet.

Secondary time clock outlet.

Door opener.

Special outlet for signal systems, as described in specifications.

Battery outlet.

Circuit for clock, telephone, bell or other service, run under floor, concealed. Kind of service wanted ascertained by symbol to which line connects.

Circuit for clock, telephone, bell or other service, run under floor above, concealed. Kind of service wanted ascertained by symbol to which line connects.

Heights of center of wall outlets (unless otherwise specified):	
Living Rooms	5 ft. 6 in.
Chambers	5 ft. 0 in.
Offices	6 ft. 0 in.
Corridors	6 ft. 3 in.
Height of switches (unless otherwise specified)	4 ft. 0 in.

Fig. 19B.

fore, difficult to state even approximately what the cost of distributing systems for lighting should be. In large cities, these variations are not extreme and it is possible to state the limits within which the cost, expressed in terms of the usual contractor's price per outlet, should lie. The figures given below apply to interior wiring of all classes, from the small residence to the large hotel or office building. They cover the portion of the work from the main source of supply, assumed to be at the building line. In case the building is lighted from its own plant these figures will apply to the portion of the installation lying between the lamp and the plant switchboard. No lamps, fixtures or reflectors are included in these prices:

Exposed wiring, $1.50 to $1.60 per outlet.

Wire in wooden moulding, $2 to $2.50 per outlet.

Concealed knob and tube wiring, $2.50 to $3 per outlet, with $1 added per switch outlet.

Wiring in iron conduit and in new buildings, $4.50 to $5 per outlet.

Wiring in iron conduits in concrete buildings, $5 to $6 per outlet.

In the above, switches and base-board plugs are considered as outlets when the iron box is included. If the switch and plate are also to be furnished, approximately $1 per outlet of this nature should be added. For the larger installations in modern buildings the price of $7 per outlet, including all wiring and feeders up to the lighting fixture, has been found to be a fairly close figure.

98. Cost of Residence Wiring

Cost for Different Numbers of Outlets, Single Floor Construction, Concealed Knob and Tube Work in Finished Buildings

(*Central Station Development Company, of Cleveland, Ohio*)

No.	Cost	No.	Cost	No.	Cost	No.	Cost	No.	Cost
5	$15.85	17	$37.40	29	$57.20	41	$77.82	53	$100.82
6	17.85	18	39.65	30	58.85	42	79.75	54	102.85
7	19.85	19	40.70	31	60.50	43	81.75	55	104.77
8	21.85	20	42.35	32	62.15	44	83.60	56	106.70
9	23.85	21	44.00	33	63.80	45	85.50	57	108.62
10	25.85	22	45.65	34	65.45	46	87.45	58	110.55
11	27.50	23	47.30	35	67.10	47	89.37	59	112.47
12	29.15	24	48.95	36	68.75	48	91.30	60	114.40
13	30.80	25	50.60	37	70.40	49	93.22	....	....
14	32.45	26	52.25	38	72.08	50	95.15	....	....
15	34.10	27	53.90	39	73.97	51	97.07	....	....
16	35.75	28	55.55	40	75.90	52	99.00	....	....

Add as per following for outlets under other than single floors and for hardware and drop cords.

Under double flooring otherwise than hardwood. Second or third story.

Ceiling outlet.. $1.00 extra.
Switch outlet for any center outlet......................... 1.00 extra.

Under hardwood flooring, single, double or triple. Second and third story.

Ceiling outlet.. $3.00 extra.
One switch outlet for any center outlet..................... 3.00 extra.
Additional on same gang for same center outlet.............. 1.50 extra.

Switches, hardware and drop cords as per following:

Push-switches, each .... $1.00 extra.
Push-3-way switches, per set of two switches .... 2.75 extra.
Porcelain base switches, each............................... .35 extra.
Porcelain base Edison receptacles, each..................... .35 extra.
Baseboard flush plate receptacles, each..................... 1.15 extra.
Drop cord, key sockets each................................. .60 extra.
Drop cord, chain sockets, each.............................. .75 extra.

will be $20. The number of outlets upon which these figures are based does not include switch outlets, but only the actual lamp outlets. In old buildings the cost of the conduit and wiring work is $20 to $25 per outlet and $30 in the extreme West.

PROTECTION

103. General principles regarding the use of fuses. Fuses or some other form of overload protection should be used where the protection of conductors or appliances against overload is desirable. The *National Electrical Code* specifies in detail as to their application. Constant-potential generators should be protected against overload by fuses or their equivalent. Single-pole protection is acceptable under certain conditions for direct-current generators. Fuses should be placed at every point where a change is made in the size of wire, unless the fuse on the larger wire is of such capacity that it will protect the smaller one.

Fuses should be inserted in all service wires, and should be located in an accessible place as near the entrance to the building as possible. For three-wire systems, the neutral wire need not be fused, provided the neutral wire has a carrying capacity equivalent to that of the larger of the outside wires, and if the neutral is grounded. No group of small receivers, whether motors, incandescent lamps or heating appliances, requiring more than 660 watts should depend on one cut-out. The rated capacity of a fuse protecting any wire should not exceed the safe carrying capacity of that wire as specified in Par. 22. Each wire for a motor circuit, except at a switchboard, should be protected by a fuse whether or not circuit-breakers are used, except where the motor is of such large capacity that fuse protection cannot be obtained, in which case it is only possible to use circuit-breakers.

104. Fuses vs. circuit-breaker. Fuses possess a time element of operation (see Fig. 20) which circuit-breakers do not have unless specially designed therefor. Due to this property, fuses delay the opening of an over-loaded circuit, where the operation would be practically instantaneous with circuit-breakers; fuses, then, may be preferable for motor circuits and for circuits that are subject to very brief overloads, especially where expert supervision of electrical apparatus is maintained, as in large mills and factories. Where there are many fuse replacements, the cost of fuse renewals is considerable.

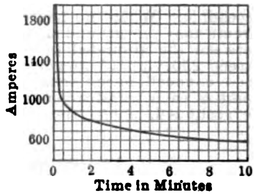


FIG. 20.—Typical performance curve of a 400-ampere, 500-volt, National Electrical Code standard fuse.

Circuit-breakers can be reset in less time and with less trouble than is required to replace blown fuses, and no spare parts are required. Circuit-breakers may, therefore, be preferable where the time saved by their use is an important consideration. The first cost of the circuit-breaker equipment is more than the cost of fuse equipment, but under severe service the circuit-breakers will prove less expensive in the end.

105. Grounding the neutral of three-wire circuits. It is important that the path through the neutral remain intact. Grounding promotes this condition, and the Code authorizes it, provided that: (a) the neutral is thoroughly grounded at the central station; (b) in underground systems the neutral is grounded at each distributing-box; and (c) in overhead systems, every 500 ft. Normally in a well-designed system, the neutral carries a minimum of current. Frequently, in underground systems, a bare copper wire drawn in the ducts constitutes the neutral. If the neutral becomes open, the pressure normally existing between the outer wires may be imposed on the equipment connected between the neutral and an outer wire; under these conditions the equipment may be ruined and a fire may result, since the voltage thus imposed will be twice that for which the equipment was designed.

106. Alternating-current, low-voltage, secondary circuits should be grounded. This is the recommendation of the *National Electrical Code* and is the practice of progressive central-station companies. Grounding prevents accidents to persons and damage, by fire, to property. If some point of a low-voltage secondary circuit is grounded, no point of the circuit can rise above its normal potential (except under unusual conditions) in case of a breakdown between primary and secondary windings of the transformer, or of other accidental connection between the primary and secondary circuits. See The *National Electrical Code* for further information regarding grounding.

The ground connection should be made at a neutral point or wire if one is

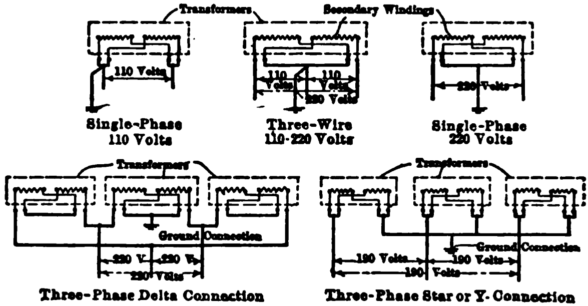


Fig. 21.—Ground connections to secondaries of commercial transformers.

accessible. Where no neutral point is accessible, one side of the secondary circuit may be grounded, provided the maximum difference of potential between the grounded point and any other point in the circuit does not exceed 250 volts (*National Electrical Code*). Fig. 21 illustrates how some of these connections are arranged with commercial transformers. The neutral point of each transformer feeding a two-phase, four-wire secondary, should be grounded, unless the motors taking energy from the secondary have

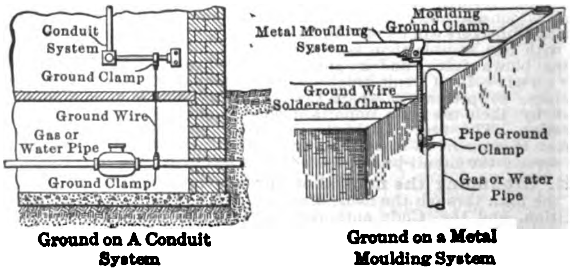


Fig. 22.—Methods of grounding.

interconnected windings. Where they are interconnected, the center or neutral point of only one transformer is grounded. No primary windings are shown in the illustration and the secondary winding of each transformer is shown divided into two sections, as in commercial transformers.

107. All metal conduit and metal-moulding systems must be grounded (see Fig. 22), by attaching an approved clamp (there are many on the market) to a conduit or moulding of the system and connecting it with a ground wire to another clamp attached to a water or gas pipe on the street side of the meter. The wire must be soldered in the clamps. All parts of the conduit or moulding system must be in good electrical contact. In an ungrounded system of conduit, "sneak" currents are possible. These leak from one wire to the conduit through an abrasion of insulation and reach the other side of the line through another ground. The resistance of the path may be sufficient to hold the "sneak" currents below the line fuse capacity, and yet these currents may be sufficient to start a fire. Grounding the conduit also eliminates the possibility of electrical shock to persons coming in contact with the conduit. In combination fixtures the gas pipe should be in thorough electrical contact with the conduit or moulding system at each outlet box.

Wire for grounding conduit or moulding must be of copper, at least No. 10 B. & S. gage, where the largest wire contained in system is not greater than No. 0 B. & S. gage. It need not be greater than No. 4 B. & S. gage where the largest wire contained in conduit is greater than No. 0 B. & S. gage. The wire must be protected from mechanical injury.

MISCELLANEOUS

108. Wire for bell signal work in dry places is usually No. 18 copper, double-cotton-covered and paraffined. Where more than two or three bells or similar devices are connected to the circuit, or where the circuits are long, No. 16 wire should be used. No. 14 is frequently used for battery wires. Rubber-covered, twisted-pair wires, like those used for interior telephone wiring, can often be used to advantage in damp places or where the circuits are exposed. No. 20 wire, although sometimes used, is too small for reliable work. Annunciator and twisted-pair wire is made with insulating coverings of different colors, so one can be selected that will match the surroundings, and be inconspicuous. Cables of annunciator wire, which can be obtained with practically any number of conductors from 2 up to 200, are very convenient and economical for large installations. In perfectly dry locations, a cable having a paraffined, braided-cotton covering can be used, but if it is to be exposed to dampness a lead-covered cable should be installed. By having the cable conductors covered with braids of different colors, the conductors can be readily identified. A kind of weather-proof wire called "damp-proof," is quite satisfactory for exposed wiring in damp places. It is more expensive than annunciator wire, but it has a better appearance when installed. See the *National Electrical Code*, the "Telephone" section in this book and the Western Electric Co. catalogue for further information.

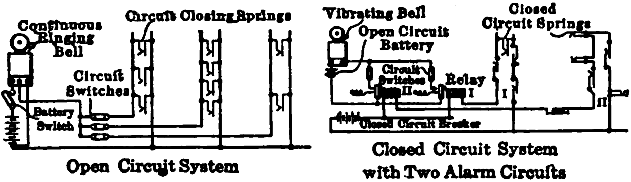


FIG. 23.—Burglar-alarm system.

109. Telephone wiring may follow the practice of the central-exchange or the intercommunicating system. In the former, single pairs of wires radiate from a switchboard to all stations. In an intercommunicating system, a cable of twisted pairs of insulated wires extends continuously through all the stations. This cable must contain at least one more wire than there are stations (Sec. 21). Conductors of No. 25 A.W.G. have been used; also No. 22 and No. 19, according to transmission requirements (Sec. 21).

110. Fire alarm wiring should be very carefully and substantially installed. As a general proposition, the wires should be heavier than would be used in ordinary signal practice; nothing smaller than No. 14 should be used indoors and nothing smaller than No. 8 out of doors. For interior lines, rubber-insulated copper should be used, while for outside construction, weather-

111. Electric gas-lighting wiring may follow the multiple system or the series system (Fig. 24). In the multiple system a spark is made by the breaking of an electrical circuit containing a reactance coil. One side of the circuit is usually grounded on the gas pipe. Electrically equipped burners of many types are obtainable. Certain spark coils are equipped with relays which sound an alarm if the system becomes short-circuited. Open circuit cells are used, a battery of 6 Leclanché cells in combination with a spark coil being usually sufficient.

In the series system, a spark gap is installed at each burner. The spark may be fed from induction coils or from frictional or static machines. The series system may be best adapted to large auditoriums, where many lamps are used in groups. It is now seldom used because such places are almost invariably lighted with electricity. See the "American Electricians' Handbook."

112. Electric bell and annunciator wiring. The possibilities for different circuit combinations are almost numberless. Those shown in Fig. 25 are typical. Two ordinary vibrating bells will not work well together in series; so when it is necessary to connect two bells in series, one should be a single-stroke bell. A multiple arrangement is preferable. The best arrangement of battery cells may be determined by trial. An ordinary bell requires about 0.1 amp. for its operation. Return call-bell circuits (*B*, Fig. 25) are so arranged that, when a station is signalled, the party called can respond by pressing his button. Ground return circuits may be used but are undesirable. Continuous-ringing bells are so arranged that, when the button is pressed, the bell continues to ring until reset. For elevator annunciators a cable is used, having as many conductors as there are buttons and one additional battery wire. If two annunciators are to operate simultaneously, their drops should be connected in series. See the "American Electricians' Handbook" for further information.

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SECTION 14

ILLUMINATION

BY PRESTON S. MILLAR

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CONTENTS

(*Numbers refer to Paragraphs*)

PRODUCTION OF LIGHT

CHARACTERISTICS OF ELECTRIC LAMPS

ACCESSORIES FOR ILLUMINANTS

ILLUMINATION CALCULATIONS

APPLIED ILLUMINATION

PHOTOMETRY

where

J = radiation intensity; C = constants;
θ = temperature in deg. abs. and e = logarithmic base

Curves of radiation from a black body, computed according to this law, appear in Fig. 2.

5. Perfect black-body or temperature radiation is not found in artificial illuminants. Among incandescent electric lamps it is approached—most closely by "untreated" carbon-filament lamps (10-watt, 110-volt and 50-watt, 220-volt types)—in lesser degrees by "treated"-carbon, "metallized"-carbon and tungsten-filament lamps. The carbon filaments depart from a black body less than does platinum, for which a displacement-law constant (Par. 4) of 2630 has been found.

6. Gray-body radiation is distributed throughout the spectrum in the same proportions as black-body radiation, but is everywhere less intense. It differs from black-body radiation in quantity, not in quality.

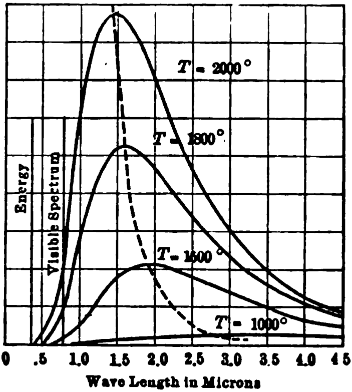


FIG. 2.—Black-body radiation at several temperatures.

7. Selective radiation is distributed differently throughout the spectrum and does not obey the laws of black-body radiation. If it is relatively strong between the limiting wave lengths of visibility, particularly if near the middle of the visibility range, the body produces more light, and the selectivity is favorable. Curves of black-body, gray-body and of one kind of selective radiation are given in Fig. 3.

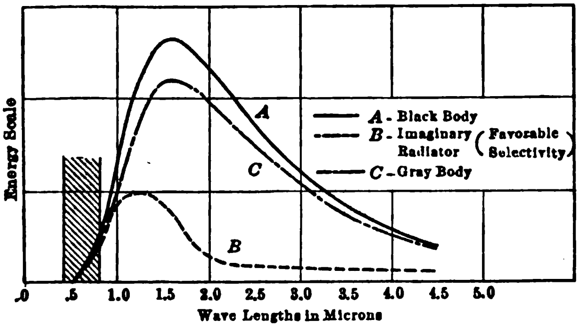


FIG. 3.—Three kinds of radiation.

8. Luminescence is that form of light production in which the radiating body (usually a gas or vapor) changes its nature in the process. Such radiation usually is characterised by a line spectrum. Luminescence embraces all forms of light production other than incandescence. In electric lighting it is the process by which light is obtained from gases or vapors. The mercury-vapor and the metallic-electrode (magnetite and

There can be no one value for the mechanical equivalent of light applicable to all illuminants, if all energy in the visible range is included, because of the variation of eye sensibility with wave length. If, however, a narrow band of spectral radiation be separated and studied, a definite and reproducible ratio between energy and light value may be obtained. And if this band be selected from the part of the spectrum where the light value is highest (say 0.55μ), the minimum possible mechanical equivalent of light will result. Ives,* having compared with his own the experimental data and calculations of other investigators, has assigned the value of 0.02 watt per mean spherical candle, or 0.0016 watt per lumen, as the most probable mechanical equivalent of yellow-green light, to which the eye is most sensitive.

With this criterion of light producing efficiency available for the highest point of the ocular-luminosity curve (Fig. 5), a scale of ordinates for that curve is established, and the curve yields the sensibility coefficient for each wave length. This applied to the radiation curve (Fig. 2), gives a curve of visibility, from which the total illuminating power may be integrated. The value so obtained should equal the candle-power or the lumens as measured by a photometer. The value of mean spherical candle-power per watt or of total lumens per watt, when stated in terms of the most efficient light per watt, yields the "reduced luminous efficiency." (Drysdale's terminology.) The table of Par. 13 shows data of this kind based upon Ives' compilation.

13. Efficiency of light production

(Electrical World—Vol. LVII, p. 1566)

	Watts per mean sph. c-p.	Per watt		Reduced luminous efficiencies (based on radiated energy)
		Mean sph. c-p.	Lumens	
				Per cent.
Yellow-green 0.55μ......	0.02	65	800	100
Firefly..................	....	....	....	96
Black-body, about 5,000 deg. abs.	....	10	125	15
Ditto, excluding energy outside limits 0.76μ to 0.38μ.	....	22	274	34
Ditto, excluding energy outside limits 0.70μ to 0.40μ.	....	26	330	41

14. In "reduced luminous efficiency" (see Par. 13) we have a very practical measure of efficiency of light production, because for any illuminant the ordinary commercial rating is directly comparable with the standards of highest possible efficiency. With this system of rating, everything depends upon the correctness of the standard of light production. But it may be noted that all artificial illuminants are so low in efficiency that a considerable error in fixing the standard would not alter materially the conclusions as to the inefficiency of illuminants. Standards for this purpose appear in Par. 16.

15. White-light efficiency. "Reduced luminous efficiency" (Par. 14) is the light flux per watt in per cent. of the yellow-green flux obtained from 1 watt radiated at 0.55μ. Such yellow-green light would be undesirable for most illuminating purposes. The generally accepted ideal is white light. Ives† has proposed the radiation between 0.70μ and 0.40μ from a black body at 5,000 deg. abs. as a standard of white light, and has assigned 330 lumens per watt as the most probable value of the most efficient white light obtainable. This is a satisfactory criterion for illuminating purposes. Ives‡ also has studied the spectrophotometric curves of some of the common incandescent sources to ascertain what proportion of their light is available to

* Luminous Efficiency, *Trans.* I. E. S., Vol. V, p. 113.
† *Electrical World*, Vol. LVII, 1909, p. 1566.
‡ Bulletin, Bureau of Standards, Vol. VI, p. 238.

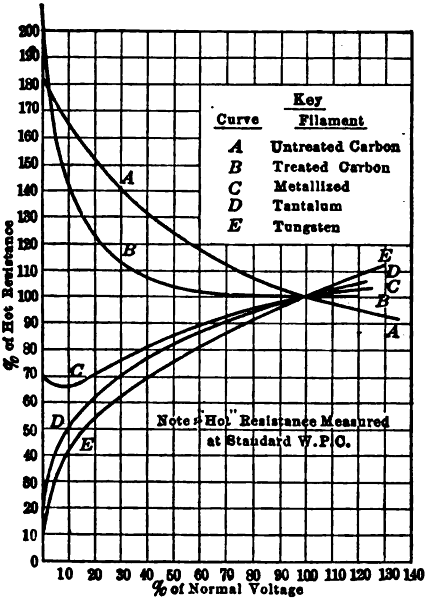


FIG. 6.—Resistance characteristics of incandescent lamps.

21. Resistance of filament lamps

Lamp	Cold resistance	Resistance at standard efficiency
20-watt untreated-filament	1062 ohms	582 ohms
60-watt treated-carbon	459 ohms	225 ohms
60-watt metallized-carbon	156 ohms	222 ohms
50-watt tantalum..................	44 ohms	262 ohms
60-watt tungsten..................	16.5 ohms	206 ohms

22. The physical characteristics of these lamps (Par. 20) are shown in Fig. 7, 100 per cent. volts corresponding with rated efficiency. Throughout a range of a few volts above and below normal, these relations may be expressed as parabolic equations.

$$\frac{V_1}{V_2} = \left(\frac{e_1}{e_2}\right)^b \qquad (4)$$

The exponents* are not determined beyond question, particularly for tungsten filament (Mazda) lamps, where improvements in manufacture are being made so rapidly that statistics for the final establishment of these values are not available for lamps of latest manufacture. Best known values for the exponents are given in Par. 23, and are reasonably accurate throughout a working range of voltage variation. Par. 24 shows corresponding exponents for the variation in life with change in watts per candle.

* Edwards, E. J. *General Electric Review*, March, 1914.

25. Ives compilations of spectrophotometric and colorimetric values of illuminants

Source	Energy value by wave-lengths										Sensation values		
	0.41μ	0.43μ	0.47μ	0.49μ	0.53μ	0.55μ	0.57μ	0.59μ	0.65μ	0.69μ	Red	Green	Blue
1 Black body at 5,000 deg. abs.	72.0	79.0	91.0	92.5	98.0	99.0	100.0	100.0	97.1	93.5	33.3	33.3	33.3
S											26.8	27.2	46.0
2 Blue sky	177.0	185.0	180.0	162.0	132.0	120.0	108.0	100.0	82.0	72.5			
C											32.0	32.2	35.8
3 Overcast sky	......	......	......	......	......	......	......	......	......	......	34.6	33.9	31.5
4 Afternoon sun	......	......	......	......	......	......	......	......	......	......	37.7	37.3	25.0
5 Hefner	1.9	3.5	10.5	16.3	37.5	53.2	74.5	100.0	210.0	320.0	50.5	40.3	6.2
											55.0	38.8	6.2
6 3.1-w.p.c. carbon lamp	4.0	7.0	18.0	25.5	47.0	62.0	79.0	100.0	176.0	234.0	50.9	40.6	8.5
											51.3	40.4	8.3
7 Acetylene	5.5	9.6	21.9	30.3	52.0	66.5	82.0	100.0	160.0	205.0	48.1	41.0	10.9
											49.1	40.5	10.5
8 Tungsten 1.25 w.p.c	6.5	10.2	22.8	31.5	52.5	66.5	82.0	100.0	158.0	201.0	47.9	41.1	11.0
											48.7	40.5	10.9
9 Nernst	......	......	......	......	......	......	......	......	......	......	49.2	40.7	11.1
10 Welsbach, ¼ per cent. cerium	......	......	......	......	......	......	......	......	......	......	42.5	40.8	16.7
11 Welsbach, ¾ per cent. cerium	......	......	26.4	38.3	64.0	78.0	90.0	100.0	114.0	120.0	45.2	42.0	12.8
											45.5	42.0	12.5
12 Welsbach, 1¼ per cent. cerium	......	......	......	......	......	......	......	......	......	......	47.2	41.8	11.0
13 D. C. arc	......	21.8	37.0	45.5	65.5	76.0	88.0	100.0	142.0	170.0	41.0	36.3	22.7
14 Mercury arc	......	......	......	......	......	......	......	......	......	......	29.0	30.3	40.7
15 Yellow flame arc	......	......	......	......	......	......	......	......	......	......	52.0	37.5	10.5
16 Moore carbon dioxide tube	......	......	......	......	......	......	......	......	......	......	31.3	31.0	37.7

range of flicker as the frequency is increased; and the more marked flicker when the finer-filament lamps are operated at a given frequency. They indicate that the tungsten lamp is less adaptable for use upon low-frequency currents than the carbon lamp.

Experience indicates that while lighting from 25-cycle circuits is satisfactory for many purposes, yet is not entirely satisfactory for all classes of service with all sizes of lamps. This frequency appears to be just a little too low to be generally acceptable.

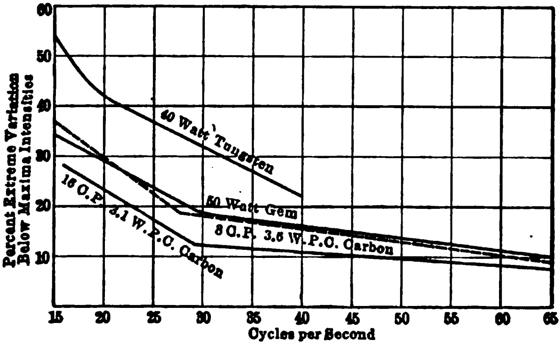


FIG. 8.—Flicker as indicated by cyclic candle-power variations.

29. Limits of acceptability for multiple incandescent lamps. The measure of rating uniformity of incandescent lamps in respect to light intensity, energy consumption and efficiency is indicated by the limits of acceptability prescribed in the standard specifications.

Type	Watts	Permissible variation from standard rated values		
		c-p.	watts	watts per candle
105 to 125 volts...	......	....	....	....
Tungsten (Mazda).	40	....	± 15 per cent.	± 8 per cent.
Gem..............	50	±7.5 per cent.	± 7 per cent.	....
Carbon...........	50	± 15 per cent.	± 11 per cent.	....

30. Spherical reduction factor. It has been customary, when dealing with incandescent lamps, to measure and rate them in terms of mean horizontal candle-power. As for most purposes, the total light produced is the quantity to be considered, it is often desirable to reduce these values to mean spherical candle-power. The ratio of the mean spherical to the mean horizontal candle-power is the spherical reduction factor. For certain lamps this is shown as follows:

	Approximate spherical reduction factor
Treated carbon-oval filament....................	0.82
Metallized carbon (Gem) oval filament..........	0.82
Tantalum..	0.77
Mazda, 60 watts.................................	0.78

36. Untreated carbon filaments are now employed principally in sign lamps of the 10- and 20-watt sizes of the 110-volt range, and in lamps of the 220-volt range. As the filament has a higher resistance, it is shorter and may be disposed in a small bulb, where the longer treated filament cannot be utilized. As they are capable of only 30 to 40 per cent. of the useful life of treated-filament lamps, they are operated at a lower efficiency and are used only where necessary. Abroad, notably in England, they have been employed much more generally than in America, due to the prevalence of 220-volt circuits. See Fig. 9.*

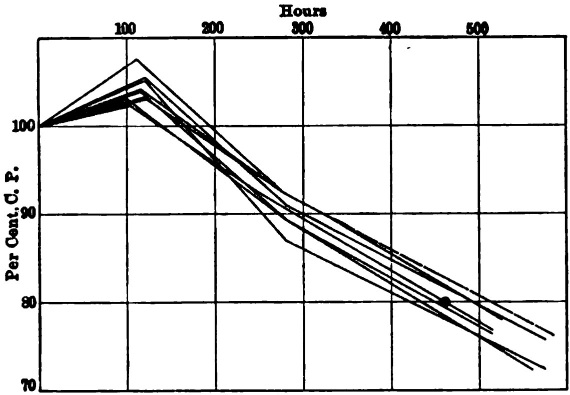


FIG. 9.—Typical candle-power performance of 16 c-p., 220-volt, "untreated" carbon-filament lamps at 3.8 watts per mean horizontal candle-power.

37. Untreated carbon-filament lamps

Rated and average watts	Mean horizontal c-p.	Total lumens	Commercial rating watts per mean horizontal c-p.	Specific consumption watts per mean spherical c-p.	Specific output lumens per watt	Average total life
105 to 125 volts						
10	2.0	21.2	5.0	5.88	2.12	2,000 hr.
20	4.8	51.2	4.15	4.88	2.56	1,000 hr.
200 to 260 volts						
35	7.95	84.0	4.40	5.24	2.40	1,000 hr.
60	16.26	170.4	3.69	4.40	2.84	750 hr.
120	32.52	340.8	3.69	4.40	2.84	750 hr.

38. Candle-power-performance curves of typical high-grade treated carbon filament lamps are given in Fig. 10, being a combination of curves published by several lamp manufacturers from independent tests of their products.

39. The candle-power deterioration throughout life is due in approximately equal parts to decrease in watts occasioned by increase in filament resistance, and to increase in absorption of light due to bulb blackening.

* Howell. *Transactions* American Institute of Electrical Engineers, June 19, 1905.

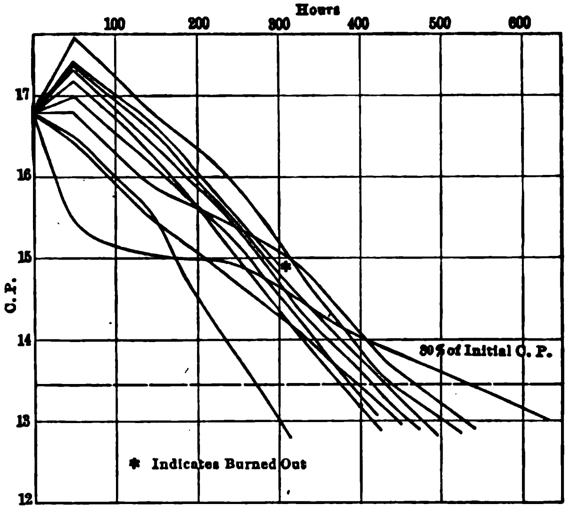


Fig. 10.—Typical candle-power performance of 50-watts, 110-volt "treated" carbon-filament lamps at 2.97 watts per candle.

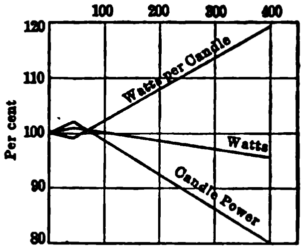


Fig. 11.—Change during "useful" life—"treated" carbon-filament lamp.

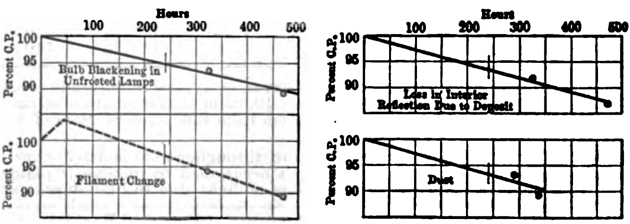


Fig. 12.—Analysis of candle-power decline in frosted carbon-filament lamps.

Fig. 11 shows change in candle-power, watts and watts per candle of an average high-grade treated carbon filament lamp throughout useful life.

40. Frosted carbon-filament lamps decline in candle-power at about twice the rate of clear lamps. An analysis of the cause of such decline appears in Fig. 12.*

41. Performance on direct current compared with alternating current. So far as is known there is no material difference between the performance of carbon lamps on direct-current and on 60-cycle sine-wave current.

42. The rating uniformity of treated carbon-filament lamps is suggested in Figs. 13 and 14, which exhibit extremes of good and bad practice.

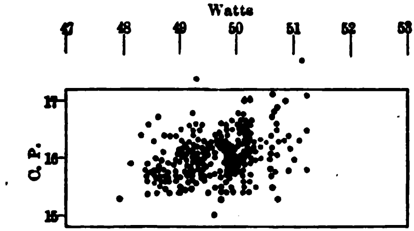


Fig. 13.—Rating of well-selected group of carbon-filament lamps.

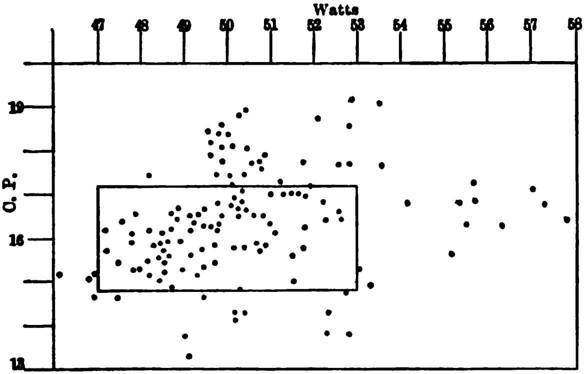


Fig. 14.—Rating of poorly selected group of carbon-filament lamps.

43. Passing of the treated carbon-filament lamp. At the present time (summer, 1914) the treated carbon-filament lamp is almost obsolete. The higher efficiency of tungsten (Masda) lamps and of metallized (Gem) carbon lamps, has rendered the use of carbon-filament lamps very uneconomical, and the demand for them has almost ceased.

METALLIZED CARBON-FILAMENT LAMPS

44. In manufacture this filament is baked in an electric furnace before being treated or flashed. After treatment a second baking at high tempera-

* Millar. *Electrical World*, 1907, Vol. XLIX, p. 798.

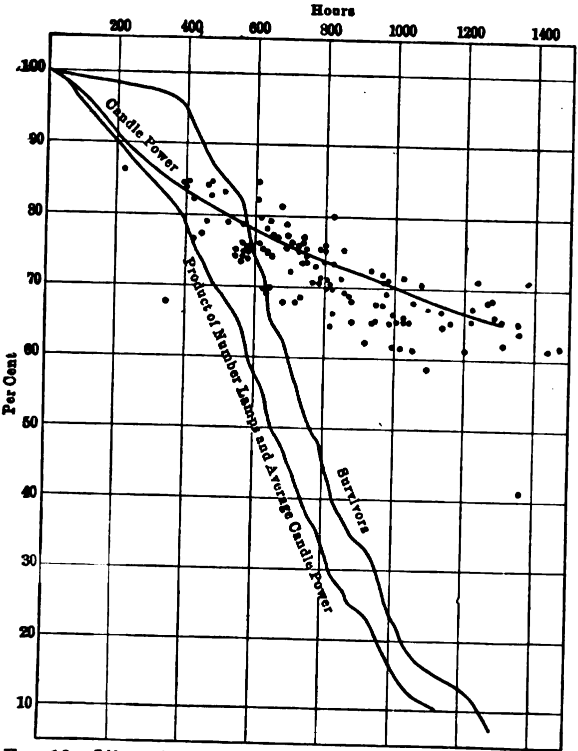


FIG. 16.—Life performance of 80-watt Gem lamps at 2.46 w.p.c.

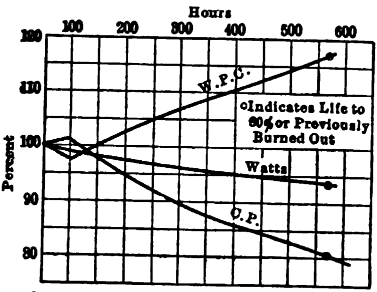


FIG. 17.—Life performance of a typical 50-watt Gem lamp at 2.5 w.p.c.

sales in 1912. Already this place has been surrendered to the tungsten-filament lamp. Probably the metallized carbon-filament lamp will become obsolete within the next few years.

TANTALUM FILAMENT LAMPS

52. Standard tantalum lamps

(Employed in very small quantities)						
Rated and average watts	Mean hori-zontal c-p.	Total lu-mens	Commercial rating watts per mean hori-zontal c-p.	Specific con-sumption watts per mean spher-ical c-p.	Specific output lumens per watt	(On d.c.) average total life
25	12.7	126.0	1.97	2.56	5.04	800 hr.
40	22.35	221.6	1.79	2.32	5.54	600 hr.
50	27.93	277.0	1.79	2.32	5.54	600 hr.
80	44.69	443.2	1.79	2.32	5.54	500 hr.

53. Performance upon alternating current.* The tantalum lamp performs less acceptably upon alternating current than upon direct current. Fig. 19 shows the breaking up of the filament after burning upon an alternating current circuit. From this, the character of the effect which is responsible for the inferiority on alternating current is apparent.

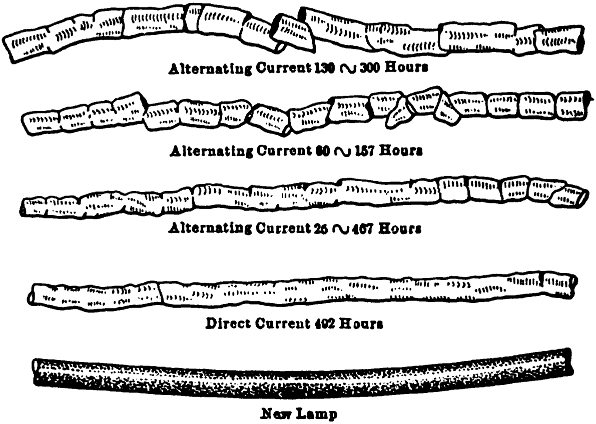


FIG. 19.—Appearance of tantalum filament after operation as stated.

54. Comparative performances on various frequencies*

Nature of supply	Hours "Useful Life"
Direct current	606
25 cycles	324
60 cycles	151
130 cycles	122

* *Transactions* American Institute Electrical Engineers, November 23, 1906.

were attached to the lead wires in a special manner which contributed to the ruggedness of the lamp.*

61. Drawn wire. This was followed shortly by the announcement that tungsten wire had been drawn, and that drawn-wire tungsten lamps had been made successfully. Wire thus drawn was perfectly ductile, but, in the process of exhausting the bulbs and burning for a short time in the factory, much of the ductility was destroyed. Nevertheless, by employing a long filament of this wire, wound continuously as in the tantalum lamp, a much stronger tungsten lamp was achieved than previously had been available. Some idea of the increase in strength of the filament itself is given by the diagram in Fig. 20.†

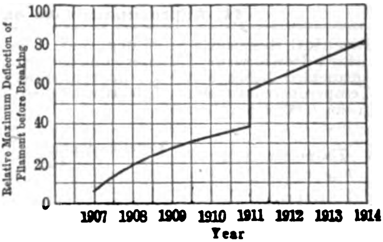


FIG. 20.—Increasing strength of tungsten filaments.

62. Modern manufacture of tungsten lamps. "The raw material used in the filament factory is a concentrated ore of tungsten, from which pure tungstic oxide, a fine-grained yellow powder, is obtained. This is 'doped' and reduced to tungsten metal by hydrogen in an electric furnace; the metal produced being in powder form, rather coarse grained, gray in color, and very heavy. This tungsten powder is formed into ingots about ¼ in. square and 6 in. long, by pressure alone, no binder being used. The pressure, which is very great, is applied transversely and compacts the tungsten so that the ingot can be handled. It is then placed in an electric furnace in an atmosphere of hydrogen and heated to a white heat, the effect of this heat being to compact and strengthen the ingot and make it a good conductor of electricity. The ingot is then placed in an atmosphere of hydrogen and heated to near the melting point, long enough to thoroughly sinter the ingot. The ingot now has a high luster, and the powder particles of which it is composed are welded together quite firmly. The square ingot now goes to a swaging machine. It is heated to white heat, taken out into the open air and swaged. During this operation a cloud of tungstic oxide rises from the ingot. The ingot is reheated and swaged several times before the square ingot becomes round. The heating and swaging are continued until the ingot is changed to a rod, 3/100 in. in diameter and 30 ft. long. Before this, when the rod is about 9/100 in. in diameter, it begins to have a fibrous structure. At 3/100 it has a well-developed fibrous structure, but can easily be broken by bending back and forth once or twice.

From thirty mils the rod or wire is reduced in size by hot drawing through diamond dies. The wire is heated to a bright red heat and is still red hot after passing through the die. This degree of heating is continued until the wire is only three mils in diameter, which is about the size of the filament in a 100-volt, 100-watt lamp. Below this, the temperature of drawing is reduced and the last drafts of any wire are made below red heat. The wire is now quite ductile and the last drafts may be made cold if desired. During this drawing the wire is lubricated with graphite, which forms a coating and prevents oxidation of the wire. It also lubricates the wire when it passes through the die. The last draft is made through a very perfect die which reduces the diameter of the wire very slightly, and in this way very long pieces are made which are the same size throughout."‡

Wire so produced is cut accurately to length and is wound upon the filament supports. A bulb-blackening preventive is introduced. After

* Scott. "A New form of Tungsten Lamp," *Proceedings* National Electric Light Association, May, 1910."

† "Recent Progress in the Art of Lamp Making" by Randall and Edwards, National Electric Light Association, 1913.

‡ J. W. Howell. *General Electric Review*, March, 1914.

68. Classification of principal tungsten vacuum lamps, according to type and size

	Watts	Volts		Watts	Volts
Sign lamps......	2½	10–13	General lighting	150	100–130
	5	10–13		250	100–130
	5	50–65		400	100–130
	10	100–130		500	100–130
General lighting.	15	100–130		25	200–260
	20	100–130		40	200–260
	25	100–130		60	200–260
	40	100–130		100	200–260
	60	100–130		150	200–260
	100	100–130		250	200–260

69. Rating. Mazda lamps for multiple circuits are rated in watts. It is the present rating practice in this country to maintain the wattages of

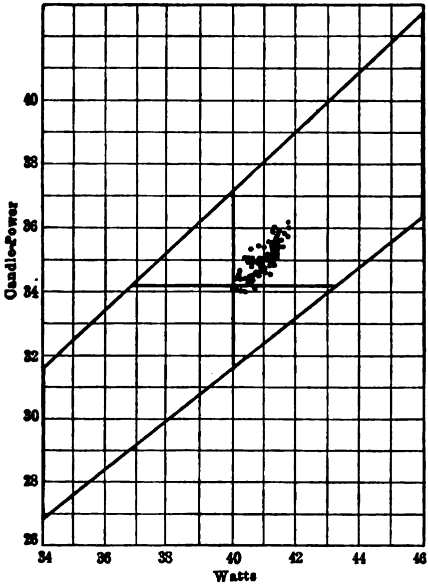


Fig. 22.—Rating of group of drawn-wire Mazda lamps.

lamps and to increase the candle-power whenever improvements in lamp manufacture warrant efficiency increase. Typical rating of carefully manufactured and assorted Mazda lamps is indicated in Fig. 22. The outline shown in the diagram represents the standard limits of acceptability for such lamps. See Par. 29.

75. Loss of light due to frosting of bulbs*

	Per cent. loss of light*	
	Bowl frosted	All frosted
Straight side bulbs, 25 to 250 watts.......	3	8
Round bulbs, 25 to 40 watts..............	5	8

76. Influence of external temperature upon the performance of lamps. But little information is available on this subject. Among carbon-filament lamps it has been found that relatively high external temperatures (200 deg. fahr.) result in a few poor-vacuum lamps, which "slump" in candle-power. This presumably is due to the water vapor expelled from the glass at the higher temperature. Among Mazda lamps more care is taken to eliminate water vapor, and this effect, not very serious among carbon lamps, should be less noticeable in the performance of Mazda lamps.

77. Influence of the character of the current supply upon the performance of Mazda lamps is not available as conclusive data. It has been asserted that differences in wave form of alternating current affect the performance materially. This is not accepted, however, and the weight of evidence appears to indicate the contrary. It is known, furthermore, that the performance on respectively sine-wave 60-cycle current and direct current does not differ enough to influence practice.

78. Concentrated filaments. An improvement effected in 1913 is the winding of the filament in a very fine helix which greatly reduces its length and makes possible modified forms of lamps. This concentrated filament† is employed in lamps designed for projection work in which it is important to reduce the over-all dimensions of the light source. It also has been used in tubular lamps for show-cases. The life of such lamps is shorter than that of lamps of the standard type.

79. Linolite lamps are a special form of tubular lamps particularly adapted for use in lighting show-cases, and other spaces for which their dimensions are favorably adapted. No data are available as to the relative life of such tubular lamps and ordinary bulb lamps at a given efficiency.

TUNGSTEN FILAMENT LAMPS FILLED WITH INERT GAS

80. General effects of the gas.‡ As a result of work of the Research Laboratory of the General Electric Company it has been found that inert gas within the bulb of a tungsten lamp operates to: (a) cool the filament; (b) reduce the rate of evaporation; (c) convey the evaporated material to the top of the bulb. The problem of increasing the efficiency of tungsten lamps—at least those having stouter filaments—is that of avoiding bulb blackening, which is the life-limiting feature.

The cooling effect of an inert gas decreases the candle-power of the filament, and in this respect the gas is detrimental. To obtain the same efficiency as in a vacuum it is necessary to increase the watts and operate the filament at a higher temperature. On the other hand the gas pressure reduces the

* Courtesy Edison Lamp Works.
Hyde. *Electrical Review*, April 6, 1907.
Millar. *Electrical World*, Vol. XLIX, p. 798.

† Randall and Edwards. "Recent Progress in Lamp Making." *Transactions* National Electric Light Association, 1913.
Harrison and Edwards. *Transactions* Illuminating Engineering Society, Vol. VIII, p. 533.

‡ Langmuir. *Transactions* American Institute Electrical Engineers, October, 1913.
Langmuir and Orange. *Transactions* American Institute Electrical Engineers, October, 1913.

Series lamps				
Amp.	Candle-power	Volts	Watts	Watts per horizontal c-p.
5.5	60	8.5	46.8	0.78
	80	10.8	59.2	0.74
	100	13.1	72.0	0.72
	250	30.9	170.0	0.68
	400	49.5	272.0	0.68
6.6	60	7.1	46.8	0.78
	80	9.0	59.2	0.74
	100	10.8	71.0	0.71
	250	24.6	162.5	0.65
	400	38.8	256.5	0.64
	600	56.7	384.0	0.64
7.5	60	6.2	46.8	0.78
	80	7.9	59.2	0.74
	100	9.5	71.0	0.71
	250	21.0	157.5	0.62
	400	33.1	248.0	0.62
	600	49.6	372.0	0.62
15.0	400	14.4	216.0	0.54
20.0	600	15.0	300.0	0.50
	1000	25.0	500.0	0.50

GENERAL CHARACTERISTICS OF ARC LAMPS

84. The electric arc is unstable on constant-voltage supply because of its volt-ampere characteristics whereby the voltage decreases as the current is increased. It is essentially a constant-current device. When used upon multiple circuits, ballast resistance, if direct-current, or reactance, if alternating-current, must be placed in series with the arc to limit the current. All arc lamps must be provided with automatic operating mechanisms to start the arc and to feed the electrodes as they are consumed. In addition, lamps for series service must be provided with shunt devices which protect the lamp and maintain the circuit in case the lamp fails to operate.

85. Operating mechanisms usually are actuated by electromagnets or solenoids, often in conjunction with weights and dashpots or other restraining device. "Series lamps," having series magnets only, regulate for constant current in the lamp. "Shunt lamps," employing shunt magnets only, regulate for constant voltage. The more usual "differential lamp" is equipped with both series and shunt magnets, and regulates for constant relation between current and voltage. Much ingenuity has been displayed in developing feeding mechanisms for arc lamps. Numerous methods have been employed, among which may be mentioned the gravity, clutch, rocker-arm, brakewheel, clockwork, motor and hot-wire feeding devices. These applications are described in publications of manufacturers and the principal methods are described in text-books.

86. Classification of arc lamps. Arc lamps may be classified in a number of ways according to the viewpoint. The classifications adopted in Par. 87 are comprehensive. In the following pages the several types of arc lamps are discussed in the order indicated. Vacuum tube lamps, which might be included in this class, are discussed later (Par. 116).

CARBON-ELECTRODE ARC LAMPS

88. The open arc is now regarded as obsolete. In its most common form it was of the direct-current 9.6-amp. type—the old "full arc" to which the rating of "2,000 c-p.," was applied in earlier years. The arc is about 3/16 in. (0.48 cm.) long and of low luminosity. The end of the negative (lower) electrode, after a few hours of burning, assumes a conical shape and yields some little light by incandescence. The end of the positive (upper) electrode becomes concave, and the "crater" thus formed is the chief source of light produced by the lamp, the process being that of incandescence. Only the feeble light from the arc itself is produced by luminescence. The end of the positive electrode becomes intensely hot, attaining at the hottest part of the crater to from 3,900 to 4,000 deg. cent.*

89. Light distribution from the open arc. Fig. 24 shows the open carbon arc.† It will be apparent at once that the lower electrode obstructs a large portion of the light emanating from the crater. The curve in Fig. 25 shows actual distribution of light compared with probable distribution if the lower electrode were transparent,‡ the difference illustrating the loss of light due to obstruction by the lower electrode.

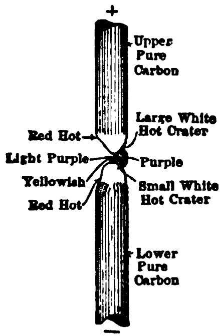


FIG. 24.—Open carbon arc.

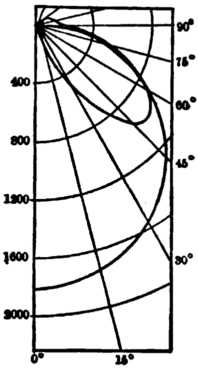


FIG. 25.—Distribution of light in vertical plane about 9.6-amp. direct-current open arc lamp. Also estimate of distribution if obstruction of lower electrode could be avoided.

90. Photometric and electrical data on direct-current open carbon arc lamps

	"Full arc"	"Half arc"
Amperes	9.6	6.6
Watts	450	325
Mean spherical candle-power	410	240
Maximum candle-power	900 to 1,200	....
Specific consumption—watts per candle	1.09	1.35
Nominal candle-power rating	2,000	1,200

91. Electrode life—open arc lamp. The open arc lamp suffered from short life of electrodes, unsteadiness of light, and poor light distribution. The electrode life was 7 or 8 hr. and it became common practice to

* Weidner & Burgess. Bulletin Bureau of Standards, Vol. I, No. 1, 19.

† Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.

‡ Trotter. "Illumination—Its Distribution and Measurement," p. 147.

trodes are raised to a high temperature, but neither attains the high temperature of the anode in the direct-current arc. The characteristics of light distribution from the two types of lamps appear in Fig. 27. It is general practice to equip the alternating-current lamps with a reflector which directs, below the horizontal, some of the light which would otherwise be distributed above the horizontal. The multiple lamps are less efficient than the series lamps. A certain amount of ballast is necessary, and this accounts for the difference between the line voltage (100 to 120 volts), and the arc voltage (70 to 75 volts). If the circuit is for alternating current, a reactance is employed, which does not occasion a large wattage loss but reduces the power-factor. If a direct-current circuit, a resistance is used, which occasions a direct loss in watts.

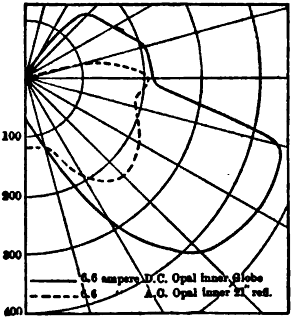


FIG. 27.—Light distribution in vertical plane about enclosed carbon arc lamps.

96. Intensified carbon arc lamps. The efficiency of a carbon arc lamp may be increased by diminishing the diameter of the electrodes with a given current or by increasing the current with given electrodes. In intensified carbon arc lamps the diameter of the carbons is reduced, producing a gain in efficiency and a light which is more nearly white and steadier than that of the ordinary enclosed arc lamp of which it is a refinement. Such lamps are used chiefly for lighting interiors where white light is desired, as in clothing stores. The intensified carbon arc was developed in Europe and exploited in small sizes operating at 2 and 3 amp., with an electrode life of 20 hr. or less. In this country the developments were along the lines of somewhat larger lamps operating at higher currents and longer electrode life. Typical lamps of this type are somewhat smaller than ordinary enclosed arc lamps, and are designed for either direct-current or alternating-current service. Small-diameter electrodes (about 7 mm.) are used, and life of about 70 hr. is realized. With opal globes an efficiency corresponding with approximately 2 watts per mean spherical candle-power is obtained in the direct-current lamp. The General Electric Company has developed a lamp of this type for direct-current service, in which two converging 6-mm. upper-positive carbons are used with a vertical lower carbon of 9.5 mm. diameter. This lamp is somewhat larger and more substantially built than other lamps of the class. The specific consumption when employed with an opal globe is slightly more than 2 watts per mean spherical candle-power.

THE FLAME ARC LAMP

97. Nature of flame arc. Impurities in the carbon are detrimental in the arc lamp of types in which the chief light production is accomplished through the incandescence of the electrode ends. As carbon is the most refractory material known, impurities are always more volatile, and their presence tends to reduce the temperature of the electrode ends. Hence, in the manufacture of carbons for such lamps, purity is considered of first importance. In the flame arc, the purpose is to secure light from the arc rather than from the electrode ends. The carbon is impregnated with chemicals which, when volatilized and driven into the arc, become highly luminous. The lower temperature of the carbon ends, due to these impurities, is immaterial, since little dependence is placed upon the ends for light production. The flame arc is simply a carbon arc into which mineralized salts are introduced. These may be of calcium, for yellow light; of barium and titanium, for white light; and of strontium, for reddish light. The carbon electrode serves as an electrical conductor and assures a hot and steady arc. The chemicals with which it is impregnated include those which are efficient light producers, and others whose functions are to promote high arc temperature and to steady the arc.

LONG-BURNING FLAME ARC LAMPS

102. General features. With the development of flame arc lamps which have an electrode life of 100 hr. or more, the flame arc has been placed in a position to compete with other illuminants for street-lighting service. In this type, electrodes of about $\frac{7}{8}$ in. (2.22 cm.) diameter are employed within a globe which restricts the air supply. It is known as the "long-burning" or "enclosed" flame arc. Long electrode life is secured at the expense of some efficiency. For this type of lamp, solid impregnated carbons have been developed in place of the familiar cored carbons employed in the original flame arc lamps. These are available in both yellow and white light forms, the latter being slightly less efficient. See Fig. 30.*

103. Electrical characteristics of flame arc lamps of one manufacture appear in Par. 104. To adapt the alternating-current lamps for use upon various circuits, compensators are supplied, sometimes built in and sometimes external to the lamp proper.

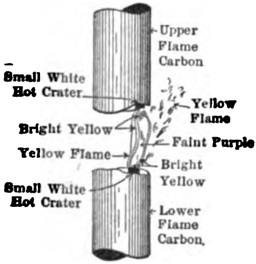


Fig. 30.—Long-burning flame arc.

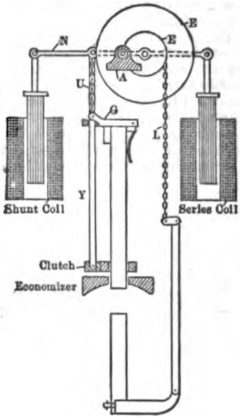


Fig. 31.—Mechanism of long-burning alternating-current flame arc lamp.

104. Approximate electrical data of long-burning flame arc lamps of one manufacture

	Amperes		Volts		Terminal watts	Power-factor, per cent
	Terminal	Arc	Terminal	Arc		
Alternating-current multiple 110-volt (compensator)	7.5	10.5	110	47	540	66
Alternating-current series.....	10.0	10.0	60	47	465	78
Alternating-current series (compensator)	7.5	10.0	86	47	500	78
Alternating-current series (compensator)	6.6	10.0	98	47	500	78
Direct-current multiple 110-volt.	6.5	6.5	110	67	715	....

105. Life of electrodes. Carbons for enclosed flame arc lamps are usually of $\frac{7}{8}$ in. diameter and are 14 in. long. The unused portion of the upper is used for trimming the lower. A life somewhat in excess of 100 hr. is had. The mechanism of an alternating-current enclosed flame arc lamp of one make is illustrated in Fig. 31.

* Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.

111. Photometric data on magnetite arc lamps, standard electrode

	Volts	Watts	Mean spherical candle-power	Watts per mean spherical candle-power
4-amp.—clear globe................	78	312	240	1.30
6.6-amp—opal globe, internal reflector	78	515	695	0.74
6.6-amp.—ornamental-alabaster globe	78	515	725	0.71

NOTE.—The new (Autumn, 1914) electrodes result in a gain of about 45 per cent. in efficiency, over that shown above for standard electrodes. A 5-amp. lamp has been added to the schedule, giving, with the new electrode, about the same light as the present 6.6-amp. lamp.

112. Light distribution characteristics. The distribution of light about three types of magnetite arc lamps is shown in Fig. 33, manufacturers' data being employed.

113. Regulating mechanism. In Fig. 34 are shown the essential regulating features of the magnetite lamp.* The electrodes are separated when no voltage is applied at the lamp terminals. When the circuit is energized, the electromagnet *O* raises its core *D*, bringing the lower or negative electrode *A* into contact with *B*, starting the arc. This closes the circuit through series coil *S* and short-circuits *OR*, releasing *D* and allowing the lower electrode *A* to drop into its position as fixed by the clutch *Q*. As *A* is consumed, the shunt magnet *P* is strengthened, withdrawing core *F* until finally the shunt circuit *OR* is closed at *MN* and the arc is restruck. This mechanism regulates for constant arc length.

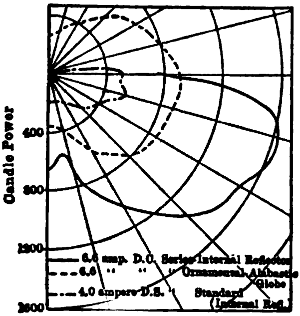


FIG. 33.—Distribution of light in vertical plane about magnetite arc lamps.

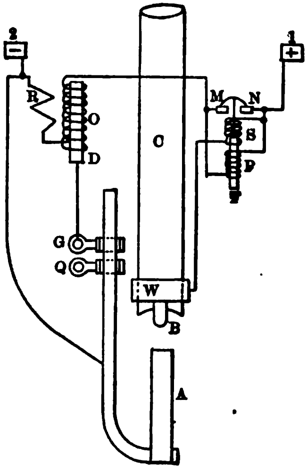


FIG. 34.—Regulating mechanism of magnetite arc lamp.

114. The ornamental magnetite lamp is a modification of the standard form, the regulating mechanism being placed below the arc. In efficiency and operating characteristics it is quite similar to the standard pendant lamp.

* Steinmetz. "Radiation, Light and Illumination," p. 158.

121. Data on low-pressure mercury arc lamps. Data upon commercial forms of Cooper Hewitt low-pressure lamps are given in Par. 120. The tubes employed are about 1 in. in diameter and are in length about 1 in. for one and one-third volts of the vapor column. A life of about 4,000 hr. is claimed for the tubes, with a candle-power decline of about 25 per cent. in the first 1,000 hr.

122. Color. The light given by the low-pressure mercury vapor lamp is greenish-blue, and is without red rays (Fig. 4, Par. 8). This bars the lamp from use for many purposes. It has been found to be well adapted for use, however, in installations where color values are of little importance, as in print shops, warehouses, some factories, drafting rooms, etc. It has been found to have peculiar value in work where fine detail discrimination is required.

123. Correcting the color. Attempts have been made to correct the color value of the mercury vapor lamp. Other materials, tungsten for example, have been employed with mercury. The mercury lamps have been used in combination with incandescent lamps.* Ives† reports that one candle-power mercury vapor light, mixed with 0.54-candle-power tungsten-lamp light, yields a good white light for general purposes. Hewitt has employed a fluorescent paint to transform some of the radiation in the green portion of the spectrum into radiation of longer wave length.

124. High-pressure mercury arc lamp. In order to benefit by the higher efficiency obtainable at high vapor pressure an evacuated tube of

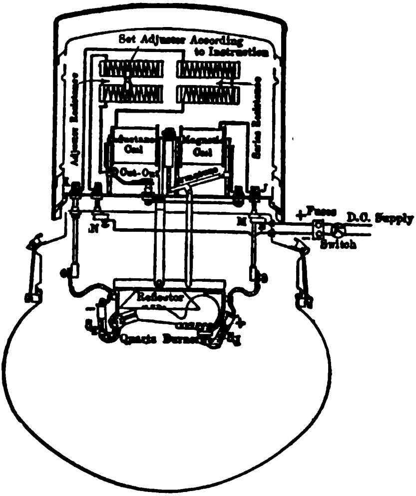


Fig. 36.—High-pressure, quartz-burner mercury arc lamp.

fused quartz is used, as glass softens at a lower temperature than that required. The lamp is operated upon the same basic principles as underlie the operation of the low-pressure lamp. The cathode is of mercury and the anode is of mercury or tungsten. The quartz tubes (burners) are 5 to 10 in. long. The operating mechanism, illustrated in Fig. 36, is equivalent to that of the low-pressure lamp.

* Marshall. *Trans.* Illg. Eng. Society, 1909, p. 240.
† Bulletin, Bureau of Standards, Vol. VI, p. 265.

In starting, the tube is tilted by an electromagnet, which is short-circuited as soon as the arc is struck by the breaking of the conducting stream of mercury. At first the current is high, about three times normal, and the arc voltage is very low, the excess voltage being taken up by the ballast resistance. The lamp gives relatively little light and that of an abnormally green color. The heavy current quickly vaporizes the mercury, increasing the vapor pressure and resistance of the arc. Gradually a condition of normal operation is approached, and, after about 15 min. current and voltage at the arc are of substantially correct values. It is understood that lamps are being developed, or have been developed, for alternating-current service and for series service.

125. Data on high-pressure mercury vapor lamps

Direct-current supply	Burner volts	Current	Terminal watts
110	85	3.8	418
220	165	3.3	725
550	345	2.0	1,100

125. Efficiency and life of quartz lamps. But little is published regarding the efficiency of the quartz lamp. Difficulty in photometry of its greenish light may account for this, at least in part. Experience in this country shows, however, that early reports of very high efficiency, which emanated from Europe, are not being realized in the forms of this lamp which have been developed. Six-tenths of a watt per mean spherical candle-power seems indicated as the initial specific consumption of a 220-volt direct-current multiple lamp. About three quarters of a watt per candle is required for the 110-volt multiple direct-current lamp. In a series type a somewhat higher efficiency should be realized. A burner life of 2,000 hr. is claimed by the manufacturers.

127. Moore tubes—nitrogen. The Moore tube for general lighting purposes is manufactured in lengths up to 200 ft. from glass tubes about 1.75 in. in diameter. This is filled with nitrogen which is replaced as required by an ingenious automatic valve which feeds the tubes at intervals of about 1 min. The tube ends are enclosed in a sheet-metal box containing the tube electrodes, the gas tank, the gas valve, step-up transformer, etc. The efficiency of the nitrogen tube is of the order of 100 lumens per ft. and the consumption is about 2.5 watts per c-p. The power-factor is about 75 per cent. The life of the tubes is very long.

128. Moore tubes—carbon dioxide. Tubes, which are usually shorter when employing carbon-dioxide gas, yield light which very closely approximates average daylight. As the efficiency is quite low, the use of these tubes is practically confined to color-matching purposes. Carbon-dioxide tubes have been manufactured in lengths of the order of 10 ft., devised to form a daylight window, and also in the smaller sizes.

129. Neon tubes. A six-meter tube operates at about 800 volts. The tubes are of about 1.75 in diameter. The electrodes are relatively large in order to reduce vaporization and avoid exhaustion of the gas. The tubes have a limited life, which, however, is said to be sufficient for commercial purposes. The life is longer for long tubes. The specific consumption is about 0.6 watt per candle. The light of the neon tube is distinctly lacking in blue radiations. In order to correct for this, a little mercury is employed in some of the tubes, with the neon. Such tubes are said to operate at about 1.0 watt per candle. When used in certain combination with tubes containing pure neon, a light which closely simulates daylight in appearance is obtained. A modified form of neon tube in which tubes of much smaller diameter are employed, is arranged to form script letters which serve for electric signs.

ACCESSORIES FOR ILLUMINANTS

GENERAL PRINCIPLES

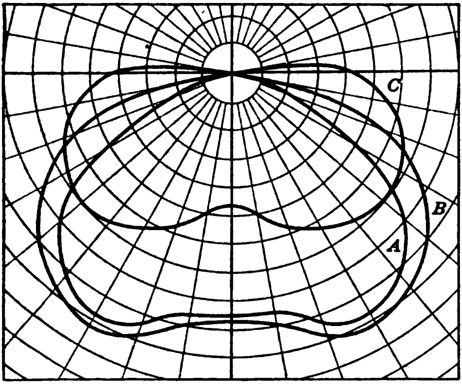
130. The purposes commonly served by lighting accessories are as follows: (a) redirection of light; (b) concealment (partial or complete) of light source; (c) decoration. Local conditions peculiar to the installation determine choice and the weight to be given of these factors.

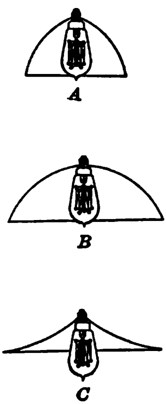
Class of service for which designed primarily	Reflector: Material	Reflector: Nature of reflecting surface	Reflector: Most usual shape	Influence upon light flux: Distribution characteristic	Light above horizontal: Transmitted light	Light above horizontal: From source	Per cent. reduction in total flux
Industrial..	Enameled iron	Glossy	Flat inverted bowl or dome	Broad		Much	7–45
				Medium	None		20–50
	Aluminum finished	Matt	Inverted bowl or dome	Medium and Narrow	None		20–60
				Broad			15–30
	Mirrored glass	Glossy	Inverted bowl or dome	Broad	None		12–18
				Medium	None		15–20
				Concentrated	None		25–35
Commercial.	Mirrored glass	Glossy	Bowl or dome	Broad	None		12–18
				Medium	None		20–35
				Concentrated	None		25–45
				Asymmetrical	None		25–45
	Prismatic glass	Glossy or matt	Bowl or dome	Broad	Much		7–12
				Medium	Much		9–15
				Concentrated	Much		12–29
	*White glass, light density	Glossy or matt	Bowl or dome	Broad	Much		6–12
				Medium	Much		7–18
	White glass, medium density	Glossy or matt	Bowl or dome	Broad	Some		8–15
				Medium	Some		10–18
	White glass, dense	Glossy or matt	Bowl or dome	Broad	Little		12–25
				Medium	Little		15–30
Decorative utility.	Prismatic glass, etched	Matt	Various	Various	Various		10–30
	White glass, etched	Matt	Various	Various	Various		10–30
	Tinted glass	Matt or glossy	Various	Various	Little		20–79
	Colored glass	Matt or glossy	Various	Various	Little		20–70
							30–80
		Shades					
Chiefly decorative.	Etched clear glass	Matt or glossy	Various				
	Fabrics	Matt	Various				
	"Art" glass	Matt or glossy	Various				
	Metal or pottery	Matt or glossy	Various				

† Influence upon light flux is usually not considered where shades are used primarily for ornamentation. Unless combined with a utility reflector the redirection of light is usually negligible and the reduction in light flux large. Etched glass or sandblasted shades should rarely be used. Most other shades as the term implies are more or less effective in shading the light source, and the opportunity which they offer for artistic treatment is often seized with pleasing results.

* Opal, phosphate, cased opal, milk, etc.

"The distribution shown in curve *A* may be classed as intensive. By placing the lamp somewhat lower in the reflector, a more extensive distribution of light may be secured which will be preferable for most locations requiring a general illumination. This form of curve, so far as distribution in the lower hemisphere is concerned, is practically ideal for industrial lighting purposes where the lamps are suspended at usual heights. The form of this curve is desirable both because it tends toward a uniform illumination on the work, and because the lamp filaments are well screened. On the other hand, it must be remembered that the wider reflector, *B*, will in practically all cases supply 10 or 15 per cent. more useful light than can be obtained from a bowl-shaped unit in either the intensive or extensive position. Furthermore, the shadows resulting from the use of a light source of large diameter, such as *B*, are less sharp than those from *A*."





Percentage Light Flux			
Unit	*A*	*B*	*C*
Total Light from Lamp	100.0	100.0	100.0
Light Absorbed by Reflector	37.0	18.6	14.8
Light in Upper Hemisphere	0.0	0.0	6.4
Light in Lower Hemisphere	63.0	81.4	78.8
Light in 60 Deg. Zone	53.4	59.2	41.3

FIG. 37.—Light redirection by reflectors of various shapes.

139. Data on reflectors. In Par. **140** are given statistics of reflectors used with 100-watt Mazda lamps, showing the light absorbed by the reflectors, some characteristics of the distribution obtained, and some physical data on the reflectors.

REFLECTORS FOR INDUSTRIAL LIGHTING

141. Porcelain-enameled reflectors.* "Any practical reflecting surface absorbs a considerable percentage of the light incident upon it. When incandescent lamps were first used in industrial lighting, the efficiency of porcelain as a reflecting surface was recognized, and various translucent reflectors of this material came into extensive use. However, they were not found entirely successful because they were lacking in mechanical strength; in many locations breakage resulted, causing the loss of the reflector and, which was more serious, often damaging material or injuring employees. It was largely for this reason that they were replaced by the

* Bulletin 20, National Electric Lamp Association.

familiar tin cone reflectors which, though less efficient, had the advantage of greater mechanical strength. The difficulties that were met in the first attempts to enamel a metal surface with porcelain which has a high reflecting power and adheres without cracking, have been overcome, and to-day the porcelain-enameled steel units are most frequently employed in industrial plants. They combine with the strength of a metal shell the high reflecting power of porcelain. Such a surface absorbs approximately 35 per cent. of the incident light."

142. Light absorption. The most effective porcelain-enameled reflectors intercept the light which is more than 60 deg. above the nadir and redirect it with a loss of about 30 per cent. of the total flux. The absorption, however, varies considerably with the quality of the enameling.

143. Enamel-paint reflectors. "Metal reflectors with a surface of white enamel paint are available at prices materially lower than those asked for the porcelain-enameled products. However, owing to the relatively rapid depreciation of this surface and to the fact that these reflectors are seldom designed with proper regard for the efficient distribution of light, their use is likely to result in the waste of a considerable portion of the money annually expended for lighting. A loss of even 10 to 20 per cent. of the light in this manner will each year amount to several times the added cost for the most efficient equipment.

144. Aluminumized reflectors. "Aluminumized reflectors have approximately the same initial efficiency as the porcelain enameled, and allow a better control of the direction of light rays. Moreover, their cost is lower than that of porcelain-enameled equipment. On the other hand, reflectors of this class have heretofore failed to maintain their high initial efficiency in service. Their use is, therefore, to be recommended only where a better control of the light flux—for example, a concentrated distribution—is desired. An aluminumized surface has recently been developed which is superior to the older forms in maintaining efficiency.

145. "Mirrored-glass reflectors form another class of opaque units which find some application in industrial lighting. These reflectors make possible a control of light rays even better than that secured with the aluminumized units. They excell in efficiency the other classes of equipment discussed, and the best mirrored reflectors appear to retain their efficiency with practically no loss throughout life. Their cost, however, is higher than for the other units, and, in common with all glass reflectors, they are limited to those locations where breakage is not a serious matter. They are especially valuable where a concentrated light is required."*

146. Prismatic-glass reflectors. Like other relatively fragile reflectors these may be used only where danger of breakage is small. They are not subject to the action of fumes or gases as some metal reflectors. They are extremely efficient, and where high concentration of light is desired, they are superior to white-glass reflectors.

147. Opaque reflectors. Certain further comments of an impartial nature are excerpted from a paper by Powell,† and an article by Stickney and Powell.‡ "The great majority of industrial reflectors are of the opaque diffusely reflecting types. The reflecting surfaces may be of enameled porcelain, white-enamel paint, or aluminum either painted or mat. The enameled porcelain reflectors are especially advantageous, if of a high quality, because of ease of cleaning, resistance to acid fume, resistance to heat, and ability to withstand weather in outdoor service. These reflectors are perhaps not quite so efficient when new as those finished in white paint and as usually designed do not yield so wide a range of distribution characteristics as do some other types of reflectors.

"Aluminum-finished reflectors offer a wide range of distribution characteristics, and are efficient and satisfactory when new. In most forms they are liable to serious depreciation due to the collection of dust, and as a result of cleaning. One manufacturer now markets an aluminum-finished reflector

* Bulletin 20, National Electric Lamp Association.

† An Investigation of Reflectors for Tungsten Lamps, General Electric Review, 1913, p. 717.

‡ Data Concerning Incandescent Lamp Reflectors, *Electrical World*, September 6, 1913, p. 477.

which has a coat of lacquer, which is said to facilitate cleaning and render the surface permanently efficient.

"Mirror reflectors are of high efficiency and offer opportunities for a wide range of design, as to light distribution. Compared with other industrial reflectors, they are however somewhat costly and fragile."

REFLECTORS FOR COMMERCIAL LIGHTING

148. Translucent reflectors. In commercial lighting opaque reflectors are rarely used except in show windows. It is a usual requirement that considerable light shall be thrown upon the ceiling and walls which dictates the employment of translucent reflectors. As commercial lighting offers, perhaps, the readiest field for the sale of new types of lighting auxiliaries, a wide variety of translucent-glass reflectors has been designed. This type includes prismatic glass and a great variety of white glass, as opal, phosphate glass, etc. In each type these reflectors are to be found in various sizes and shapes, differing in light-distribution characteristic. The several types and makes of reflectors differ among themselves in efficiency, light transmission, etc. Where high concentration of light is required, the prismatic-glass reflectors offer some advantage. Among many of the white-glass reflectors there is little choice, except in appearance. The differences are those largely of appearance of the glass itself, and of ornamentation. Neglecting these two features, the white-glass reflectors of various makes are to be grouped naturally in regard to the amount of light transmitted, it being the general order that those which transmit the most light reflect less light downward. ... reflectors, commercial reflectors may be procured with ...ting surfaces, the latter being preferable for almost ...inating standpoint, though they require some- ...y-surface reflectors.

... of the translucent reflectors are of ... that they are very pleasing in appear... of decorative glassware. Still, ... are designed predominantly ... value where the illumination is ... oration. Among the latter ... and of various fabrics. It ... shades. On all reflectors ... including many which are ... ring data are available. ...50.

... Mazda lamps

otherw... "art" glass and ... le to attempt to show ... industrial and commercial ligh... tive in appearance, definite engin... rmation of this kind appears in Par. 1...

...ribution of light in various zones about ... and inverted bowl reflectors*

Type of reflector	Typical zonal distribu... 0 to 60 deg., per cent.	0 to 90 deg., per cent.	0 to 180 deg., per cent.	...sor... per ce...
...ic—focusing	50	68	87	13
...tic—intensive	44	65	87	13
...tic—focusing (satin finish)	40	60	87	13
...ized steel—intensive	51	58	58	42
...ized steel—extensive	52	61	61	39
...atic—intensive (satin finish)	37	57	87	13
...m density—opal	40	54	82	18
...atic—extensive	40	62	86	14
...y density—opal (depolished)	41	59	72	28
...density—opal	34	57	91	9
...atic—extensive (satin finish)	33	55	88	12
...lamp (for comparison)	16	47	100	....

* ...veet. "The Choice of Reflector," Illg. Eng. Society, New York Section, ..., 1912.

Porcelain-e...
Porcelain-e...
Porcelain-e...
Porcelain-e...
Porcelain-e...
Aluminum f...
Aluminum f...
White-glass ...
White-glass ...
White-glass ...
White-glass ...
Opal or opal...
Opal or opal...
Opal or opal...
Opal or opal...
Cased—opal...
Cased—opal...
Cased—opalescent flare...
Cased—opalescent flare...
Prismatic-glass inverted bowl...
Prismatic-glass inverted bowl...

* Stickney and Powell. ... Electrical W...

151. Depreciation due to dust. Certain information has been published showing the depreciation in reflecting efficiency due to collection of dust on lamps and reflectors in industrial service. Perhaps the most comprehensive data applicable to modern equipments of reflectors and Masda lamps is that shown in Bulletin 20 of the National Lamp Works of the General

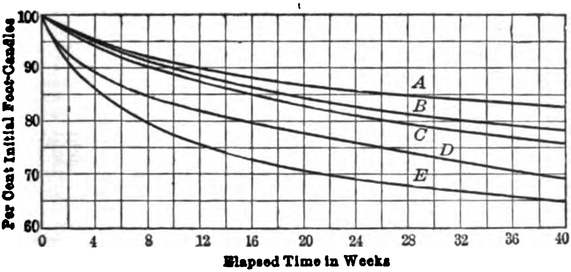


FIG. 38.—Reduction in light due to dust.
A. Dome enameled steel. *C*. Dense opal glass.
B. Bowl enameled steel. *D*. Prismatic glass.
E. Light density opal glass.

Electric Company published October, 1913. This is summarised in Fig. 38. The curves show decrease in illumination on the working plane.

152. Enclosing glassware. The sphere commends itself for many purposes of ornamentation and is therefore a popular form in design of lighting auxiliaries. It, with various modifications as to shape, forms an important class. Obviously, light absorptions run higher and light control is less definite than is the case with open-mouth reflectors. In the matter of redirection of light, much may be accomplished in an ordinary glass sphere by varying the location of the light source within the sphere, but the tendency with such glassware is always to yield distribution characteristics which approach a circle. There are some forms of enclosing glassware, however, in which special attention has been given to this phase of the subject with very notable success in the redirection of light. Par. 153 gives some data upon enclosing glassware of various types.

153. Photometric data upon enclosing glassware employed with 1,000 lumen Masda lamp*

Description	Lumens with glassware				Per cent. light absorbed by glassware
	0 to 60 deg.	0 to 90 deg.	90 to 180 deg.	Total	
10-in., 2-piece pressed-Alba ball ...	182	379	385	754	24
14-in., 2-piece pressed-Alba ball ...	190	384	335	719	28
12-in., 1-piece blown-Alba ball	223	469	395	864	14
12-in., blown-Alba acorn	243	476	347	822	18
12-in., cased Melilite ball	181	396	321	717	28
12-in., ground-glass ball	206	484	419	903	10
14-in., prismatic reflector bowl	412	589	180	769	23
12-in., prismatic reflector ball	455	618	103	721	28

* "Characteristics of Enclosing Glassware." Lansingh, *Transactions* Illuminating Engineering Society, 1913, p. 447.

BOWLS FOR INDIRECT LIGHTING

154. Cove lighting. Recognition some years ago of the need for concealing brilliant light sources from view led to systems of indirect lighting in which the light was thrown upon some reflecting surface which became a secondary source of illumination. One method consisted in locating the lamps within a cornice or cove concealed from view and illuminating the room via the ceiling. By this system, control of the light was largely lost, and efficiency of utilisation was very low. In one case reported, only 15 per cent. of the total light produced by the lamps was delivered upon a working plane.* While this low efficiency was perhaps an extreme and better values have been realized, yet the cove lighting system was so inherently low in efficiency as to be unsuccessful.

155. Indirect lighting fixtures. A more recent development of indirect lighting is one in which the lamp is located within bowls, usually hung centrally in a room or bay. By backing the lamps with efficient reflectors, and controlling the direction of light, a higher order of efficiency may be obtained and a more desirable direction of the light secured. Indirect lighting systems possess the advantage of high diffusion, and are therefore valued where freedom from shadow and glare is a consideration of primary importance. Some statistics showing the proportion of the total light produced which may be delivered upon a working plane by this system of lighting are given in Par. 156.

157. Luminous-bowl. A recent development is the luminous-bowl indirect-lighting unit. In this fixture the bowl is rendered luminous for purposes of decoration only, it usually being of the same order of brightness as the ceiling immediately above it, which is the principle secondary light source. In some fixtures in which as much as possible of the light is directed upon the ceiling, small auxiliary lamps are employed for the purpose of rendering the bowl luminous. These may be wired separately, providing, themselves, a feeble illumination which, as an alternative to the use of principal lamps, may be useful for special purposes in certain installations.

SEMI-INDIRECT LIGHTING UNITS

158. Translucent bowls. A development of the past few years consists in the use of glass bowls enclosing the light source and reflecting most of the light to the ceiling, as in the indirect lighting system, while transmitting in various proportions enough light to give an appreciable direct component. Some data upon bowls of this type, of one manufacture, are presented in Par. 160. Referring to the data in this table it will be seen that the authors have made a study of the influence of contour of bowl upon the distribution of light, and likewise of the influence of optical density of glassware. Their conclusions from these figures and others given in the paper, follow in Par. 159. Data on semi-indirect installations appear in Par. 163.

159. Effect of change of light source and bowl contour. "The distribution of light is materially affected by changes in the position of the lamps within the bowl; changing from a single lamp to a closely clustered group of two or three lamps does not introduce large variations in the distribution characteristics, although the single lamp results in a somewhat wider distribution above the horizontal. The ratio of light above the horizontal to that below the horizontal in the four types of glass of the contour 3, chosen for this purpose, vary from 1.26 for the least dense (etched glass) to 6.4 for the most dense (Calla); and the effect of change in the contour of the bowls is that with the shallower bowls the distribution both above and below the horizontal is not so wide, more light being centred near the bowls while with the deeper bowls there is, of course, a larger ratio horizontal."

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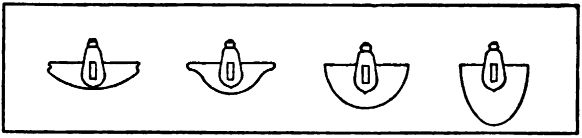
* "The Elements of Inefficiency in Diffused Lighting Systems." Millar. *Transactions* Illuminating Engineering Society, 1907, p. 583.

160. Photometric data of semi-indirect glass bowls employed with one Mazda lamp*

Description of glassware	Contour, see Fig. 39	Per cent. of total light from lamp which is distributed within stated zones†			
		180 deg. to 120 deg.	180 deg. to 90 deg.	90 deg. to 0 deg.	Total
Etched crystal glass with new cut design....	3	22	47	37	84
Druid................	3	27	54	30	84
Veluria...............	1	36	60	25	85
	2	36	58	24	82
	3	30	57	24	82
	4	28	60	24	84
Calla.................	1	44	68	11	79
	2	46	71	11	82
	3	41	68	11	79



1 2 3 4

Fig. 39.—Contours referred to in Par. 160.

161. Reflectors in railway coaches. Some information upon the distribution of light in a typical railway day coach has been made available by the Committee on Illumination of the Association of Railway Electrical Engineers.‡ While railway-car illumination is to some extent a special problem, yet the behavior of most reflectors in such service is an important indication of what may be expected in other lines. In the tests which are here recorded, the car was equipped with Mazda lamps located in the centre deck or monitor, and spaced at intervals of two and three seats respectively. Conditions in all respects were favorable to lighting efficiency because the equipment was new and clean and operated under correct conditions. As indirect and semi-indirect equipments were used, it is important to note that the coefficient of diffuse reflection of the car ceiling was 65 per cent.

162. Data on railway-coach lighting. Results are summarized in Par. 164 which shows a description of the auxiliaries, the total light produced by the lamps, the average intensity of illumination throughout a horizontal plane 33 in. above the floor, the per cent. of the total light produced which is delivered to such horizontal plane and the angle above the nadir at which the lamp filament is screened from view by the reflector. The total horizontal area lighted was 566 sq. ft.

In these railway-car tests open-mouth reflectors are shown to deliver upon the horizontal plane of reference, proportions of the total light which range from a maximum of 59 down to a minimum of 25 per cent. Indirect-lighting equipments with ceiling of the quality stated, deliver upon the plane of reference about 25 per cent. of the total light produced in the car. Slightly better values are shown for the enclosing and the semi-indirect equipments.

* "A Photometric Analysis of Diffusing Bowls with Varying Indirect Component." Rowe and Magdsick, *Trans.* Illg. Eng. Soc., 1914.

† 180 deg. is the Zenith; 0 deg. is the Nadir.

‡ *Railway Electrical Engineer*, October, 1913, and Report of 1914 Committee of Association of Railway Electrical Engineers.

163. Data on semi-indirect lighting installations

Source of data	Type of unit	Area illuminated	Ceiling	Walls	Per cent. total flux falling on working plane	In terms of comparable direct lighting system. Per cent.
Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715.	Alba Hem. 3 60-watt lamps	Display room 60 by 37 ft.	White	White	30.8	....
Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715	Alba Hem. 3 60-watt lamps	Office 60 by 48 ft.	White	White	31.2	....
Henninger, I. E. S. Trans., 1912, p. 248	Inverted prismatic	Room 18 ft. 10 in. by 23 ft.	Factory white	Natural pine	......	50.6
Cravath, I. E. S. Trans., 1912, p. 402	Bowl-shaped opal glass (inverted)	Small room 12 by 16 ft. 6 in.	Light cream	Light green	37.6	71.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	....	....	Light	....	25.0	55.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	....	....	Medium	....	18.0	42.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	....	....	Dark	....	11.0	28.0
N. E. L. A. Handbook for Railway Elec. Engineers	....	....	Light	....	35.0	65.0
Aldrich and Malia, I. E. S. Trans., 1914, p. 111	Inverted opal reflector 100-watt lamps	Large room	Light cream	Light buff and green	50.7	92.2
Edwards and Harrison, I. E. S. Trans., 1914, p. 171	Inverted opal reflector and hemisphere	Small room 14 ft. 6 in. by 17 ft. 9 in.	Light	Green-gray	21.0	62.0

ACCESSORIES FOR SPECIAL PURPOSES

165. Show-window lighting. For show-window lighting and certain other purposes an asymmetrical distribution of light is usually required. Example of reflector designed for such a purpose is shown in Fig. 40.

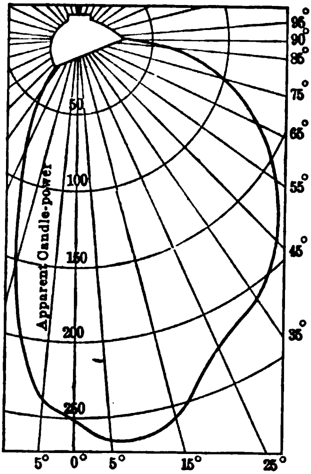


Fig. 40.—Asymmetrical distribution, adapted to show-window lighting.

166. Street lighting. Various auxiliaries for redirecting part of the light produced by street illuminants have been developed. Some of the most effective in this respect are to be found among the newer designs of auxiliaries for Mazda type *C* (gas-filled) series lamps. Illustration of this is given in Fig. 41. In some street illuminants, as the magnetite and metallic-flame arc lamps, a reflector is built in the lamp casing. In others, the diffusing globes with which the lamps are equipped are so shaped as to modify the distribution characteristic materially. These are inconspicuous methods of accomplishing a measure of light redirection which usually is less marked than that accomplished by the use of external reflectors.

167. Glass plates. Translucent glass plates consisting either of frosted glass, opal glass, so-called art glass, ribbed glass or prismatic glass are largely employed as skylights and as diffusing screens for artificial lighting. Some data upon the transmission coefficient of such glasses are given in Par. 169.

168. Glass for redirecting daylight. Ribbed and prismatic glass is used to a large extent in industrial lighting for directing into large rooms a

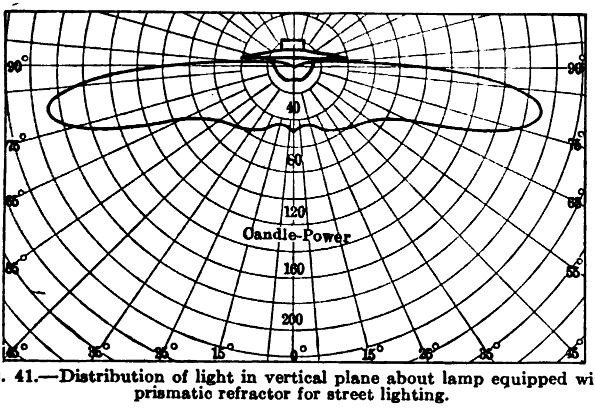


Fig. 41.—Distribution of light in vertical plane about lamp equipped with prismatic refractor for street lighting.

greater amount of skylight than would otherwise be available. Some tests by Professor Norton are commented upon in the Johns Hopkins University

170. Headlights may be considered in this connection but only in a general way because the design of headlights is a specialty in itself and has but little application in general illuminating practice. An excellent symposium on the subject is to be found in recent articles by Messrs. Sugg, Dennington and Porter.* Much attention has been given to the subject of locomotive headlights and an excellent résumé of state laws on this subject together with comments is to be found in the report of the Committee of Locomotive Headlights of the Association of Railway Electrical Engineers.†

ILLUMINATION CALCULATIONS

GENERAL CONSIDERATIONS

171. Light flux. According to approved concept, light is regarded as luminous flux.‡ The output of a lamp is its **total luminous flux.** The brightness of a diffusely reflecting or transmitting surface is proportional to its **specific luminous flux.** The intensity of illumination received on any surface is the **flux density.** Thus luminous flux is analogous to magnetic and electrostatic flux. Comprehension of light flux is facilitated by considering a point source to be located at the centre of an imaginary non-reflecting sphere. The total luminous flux produced by a source of 1 c-p. radiated uniformly, is divided by the number of unit solid angles or steradians in the sphere in order to arrive at the unit of luminous flux which is the lumen "equal to the flux emitted in a unit solid angle (steradian) by a point source of 1 c-p."

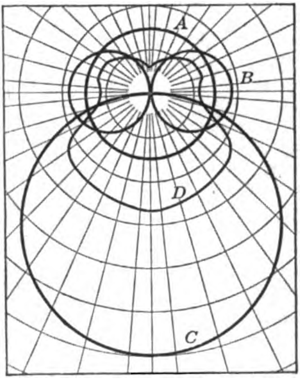


FIG. 42.—Four distributions of a given flux.

172. Distribution of light. In practice, light is rarely radiated uniformly, and it is therefore necessary to consider the flux to be distributed in a great variety of ways. The determination of light distribution characteristics of sources, is a regular part of illuminating engineering practice, and most calculations performed involve this distribution characteristic. In Fig. 42 are illustrated four different distributions of a given luminous flux. The curves show a section of revolution. The circle (curve *A*) indicates uniform distribution from a punctiform source; curve *B* shows distribution from a theoretical line source, distributing no light at the poles. Curve *C* shows the distribution from a uniformly radiating circular disc, and curve *D* shows a light-distribution characteristic typical of a certain class of reflectors.

COMPUTATION OF TOTAL FLUX, OR MEAN SPHERICAL CANDLE-POWER

173. Zonal areas. In Fig. 43, curve *D* from Fig. 42 is reproduced. The polar diagram at the left shows the flux density or intensity in any direction, in the vertical plane, considered. Referring to the representation of a sphere on the right, it will be noted that the total area of a zone of a given altitude at the equator is much greater than the total area of a similar zone near the pole. The flux density, or intensity, of the light distributed throughout each zone, is indicated in the distribution curve to the left. The area of each zone must be multiplied by the mean flux density, in order to obtain the total flux distributed throughout the zone.

* *Electrical World*, October 11, 1913, pp. 741-745.
† *Railway Electrical Engineer*, October, 1913.
‡ Sharp. "The Concepts and Terminology of Illuminating Engineering," *Trans.* Illg. Eng. Society, 1907, p. 414.

177. Constants for computation of mean spherical candle-power or total flux from light-distribution data

10 deg. zones		15 deg. zones		30 deg. zones	
Angles from vertical axis	K	Angles from vertical axis	K	Angles from vertical axis	K
175 deg. 5 deg.	0.016	180 deg. 0 deg.	0.009	180 deg. 0 deg.	0.034
165 deg. 15 deg.	0.046	165 deg. 15 deg.	0.067	150 deg. 30 deg.	0.259
155 deg. 25 deg.	0.074	150 deg. 30 deg.	0.131	120 deg. 60 deg.	0.448
145 deg. 35 deg.	0.100	135 deg. 45 deg.	0.184	90 deg.	0.518
135 deg. 45 deg.	0.124	120 deg. 60 deg.	0.226	....	.....
125 deg. 55 deg.	0.142	105 deg. 75 deg.	0.253	....	.....
115 deg. 65 deg.	0.158	90 deg.	0.261	....	.....
105 deg. 75 deg.	0.168	....	.....	....	.....
95 deg. 85 deg.	0.174	....	.....	....	.....

178. Kennelly's method. Kennelly has devised a graphical method of rectilinear construction for determinations similar to those carried on by means of a Rousseau diagram.*

179. White-Wohlauer method. The "Fluxolite" diagram facilitates the same kind of computations, but yields total lumens instead of mean candle-power.†

COMPUTATION OF ZONAL FLUX

180. Zonal flux. This does not differ from calculation of total flux. In fact most determinations of total flux or of flux in one hemisphere are merely additions of zonal-flux values. The Rousseau, Kennelly and White Wohlauer methods yield zonal flux readily. Constants for use in determining mean zonal candle-power directly from angular candle-power values are given in Par. 181 for certain zones. Multiply the sum by 2π (6.28) times the difference between cosines of limiting angles to obtain corresponding lumens.

181. Constants for use with candle-power values to yield approximate mean zonal candle-power

Angle from vertical axis at which c-p. is known	Constants 75-deg. zone	Constants 60-deg. zone	Constants 45-deg. zone	Constants 30-deg. zone
10-deg. intervals				
70 deg.	0.221	....	....	....
60 deg.	0.204	0.147	....	....
50 deg.	0.180	0.267	....	....
40 deg.	0.151	0.224	0.383	....
30 deg.	0.117	0.174	0.297	0.301
20 deg.	0.080	0.119	0.203	0.445
10 deg.	0.041	0.060	0.104	0.226
0 deg.	0.005	0.008	0.013	0.029
15-deg. intervals.				
75 deg.	0.170	....	....	....
60 deg.	0.304	0.219	....	....
45 deg.	0.249	0.369	0.295	....
30 deg.	0.176	0.261	0.446	0.432
15 deg.	0.090	0.135	0.230	0.504
0 deg.	0.012	0.017	0.029	0.064

* Kennelly. *Electrical World,* March 28, 1908.

† Wohlauer. *Illuminating Engineer,* Vol. III, p. 655.

CALCULATIONS OF ILLUMINATION INTENSITY

185. Classification of methods. Assuming that light distribution data, such as those presented in Fig. 44 are available, it becomes possible to compute the illumination produced upon any given plane by the light source in any given location. For the sake of simplicity it will be considered that the light source, whose distribution is indicated in the diagram, is mounted over the centre of a horizontal plane which is to be illuminated. For such computations there are three customary methods. The flux of light delivered upon the horizontal plane will be the sum of that directed toward the plane from the source and that reflected to the plane from ceiling walls, etc.

186. Flux method (direct light). For many purposes an approximate calculation of the flux delivered upon the plane of reference is adequate. In such cases it may serve to determine the approximate square feet of the plane to be illuminated and to estimate the total flux which will reach such plane. For example, assume that a certain room has a floor area 12 ft. 7 in. by 12 ft. 2 in., and that it is desired to estimate the light flux delivered upon a horizontal plane 36 in. above the floor from a light source located over the centre of the area, and 6 ft. 4 in. above the plane of reference.* Roughly, the flux delivered within an angle of 45 deg. above the horizontal will fall upon this plane. Applying zonal constants (Par. 181) to the candle-power values in Fig. 44, we have either or both of the following:

Angle	Constant c-p.	Angle	Constant c-p.
40	0.383×100 = 38.3	45	0.295× 99 = 29.2
30	0.297×102 = 30.3	30	0.446×102 = 45.4
20	0.203×105 = 21.3	15	0.230×107 = 24.6
10	0.104×110 = 11.4	0	0.029×113 = 3.3
0	0.013×113 = 1.51	....	....
Mean zonal c-p.......102.81		Mean zonal c-p.......102.5	

With a mean candle-power of 103 distributed throughout a zone extending from the nadir to 45 deg., the flux in lumens is found by multiplying 103 by the number of unit solid angles in the 45. deg. zone or $103 \times 2\pi (\cos\theta_0 - \cos\theta_{45}) = 190$ lumens.

187. Flux method (indirect light). Referring to report of test* of the installation described it will be seen that the lumens directed to the plane of reference by the lighting unit are 191 in number, with which value the above determination is in accord. The light source produces 779 lumens. As 191 lumens reach the plane of reference (779 − 191 =) 588 are incident upon ceiling and walls, where they are partly absorbed and partly reflected either toward the plane of reference or elsewhere. The greatest uncertainty in estimating total flux on a plane is arriving at the amount of such indirect light. The test* shows that 189 lumens or (189/588 =) 32 per cent. of this flux, which the lighting unit directed elsewhere, ultimately reached the plane of reference, thus equalling the light directed toward the plane by the lighting unit. In this case the room was small and the reflection from ceiling and walls was more effective than usual. If instead of a room the area is a bay in a larger room, the light, which here falls upon the walls, will add to the illumination of adjoining bays, and the bay under consideration will profit likewise from adjoining bays. In any installation this indirect light must be estimated taking into consideration the flux directed elsewhere than upon the plane of reference and the reflecting qualities and location of the reflecting surfaces. Some data on this subject are given in Par. 196.

EFFICIENCY OF UTILIZATION

188. Definition. Where the illumination of such a plane is the principal purpose of the lighting installation, the ratio of flux delivered upon the plane to total flux produced by the illuminant is sometimes called the "efficiency of

* Actual conditions described by Sharp and Millar, "Illumination Tests," *Trans.* Illg. Eng. Soc., 1910, p. 391.

reflector, 42 per cent. of the total light produced is delivered upon the plane of reference if the walls have reflection coefficients of 30 per cent., while 45 per cent. is delivered upon the plane if the reflection coefficients of the walls amount to 60 per cent. These very complete data should be helpful in forming a correct estimate of the net ratios of light utilisation in small and medium sized rooms with central-ceiling equipments.

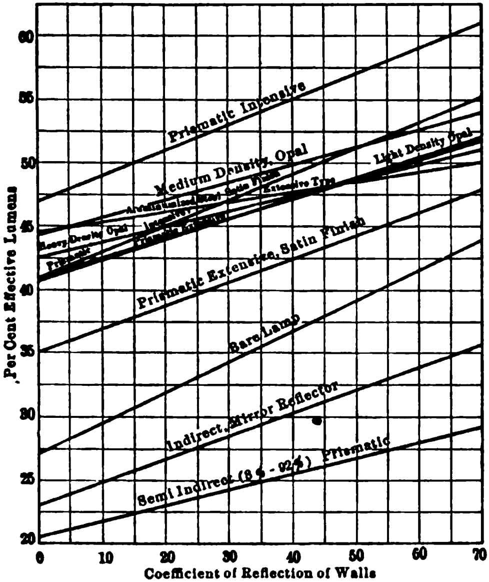


FIG. 45.—Per cent. flux delivered upon working plane when reflection coefficient of ceiling is 0.60.

192. Influence of wall reflection on efficiency of utilization. A study of these data of Sweet (Par. 191), indicates that with 60 per cent. ceilings the loss in flux on the plane of reference involved in changing from 40 per cent. to 10 per cent. reflection walls, ranges, for the several equipments, from 5 per cent., in the case of opaque reflectors where very little light is incident upon the walls, to a maximum of 20 per cent. in the case of a bare lamp. The details of these losses are given in Par. 194.

193. Comment on flux method. From the foregoing (Par. 189 to 192) a reasonably accurate estimate of the influence of ceiling and walls may be formed. As the flux directed toward the plane of reference by the lighting unit may be computed quite accurately where a light distribution curve is available, and as this direct lighting is usually the greatest proportion of the total which reaches such plane, it will be seen that estimates of the illumination produced may be made very quickly by this method, and will be usually as precise as conditions require. The computation of the angle below which all of the flux is directed toward the plane, is a simple matter of triangulation. Most recent light-distribution data are accompanied by zonal-flux data (Fig. 44) which makes the approximation of the total flux within the directly applied zone a mere matter of addition. Where zonal values are not available computation of the flux from the light distribution curve is reasonably simple (Par. 186).

accomplished by using a reflector which, while directing most of the light toward the plane, will still transmit sufficient to light the ceiling and walls acceptably. With such equipments it is reasonable to expect that 50 per cent. of the light may be delivered upon the plane of reference. At once it is established that 764 lumens should be generated within the room. This will be produced by a 100-watt Mazda lamp, which produces about 1,000 lumens, leaving a margin of 25 per cent. for absorption by reflector, depreciation due to dust, etc.

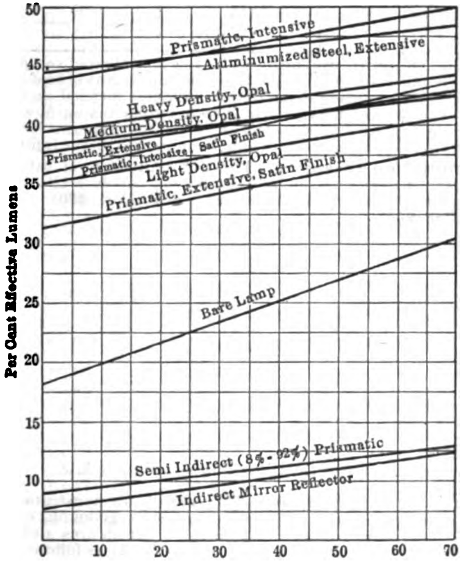


FIG. 47.—Per cent. flux delivered upon working plane when reflection coefficient of ceiling is 0.20.

196. Absorption-of-light method. An alternative method of computing light flux for an illumination installation is the "Absorption-of-light" method.* This is based upon the fundamental consideration that all of the light within a room being absorbed, the illuminants must produce the sum of the light flux absorbed by the various surfaces. That is to say, the average incident flux upon each surface multiplied by the coefficient of light absorption characteristic of that surface and by the area of the surface will yield the total flux absorbed by that surface, and the sum of the flux absorbed by all exposed surfaces within a room must aggregate the total flux to be produced by the lighting unit. (In such case, of course, the absorption of light involved in the use of an auxiliary must be added to this aggregate to ascertain the total amount of light to be produced by the illuminant proper.) Referring to the room already mentioned,† we find the data necessary to verify this method. These are summarized in Par. 197.

* McAllister. "The Absorption-of-light Method of Calculating Illumination," *Electrical World*, November 21, 1908.

† Actual condition described by Sharp and Millar "Illumination Tests," Trans. Illg. Eng. Soc., 1910.

202. Table of squared and cubed cosines (Par. 203)

Angle (deg.)	Cosine Squared	Cosine Cubed	Angle (deg.)	Cosine Squared	Cosine Cubed
1	1.000	1.000	21	0.871	0.813
2	0.999	0.998	22	0.859	0.797
3	0.997	0.996	23	0.847	0.780
4	0.995	0.993	24	0.834	0.762
5	0.992	0.988	25	0.821	0.744
6	0.989	0.983	26	0.808	0.726
7	0.985	0.978	27	0.794	0.707
8	0.980	0.971	28	0.780	0.688
9	0.975	0.963	29	0.764	0.668
10	0.970	0.955	30	0.750	0.649
11	0.963	0.945	31	0.735	0.630
12	0.956	0.935	32	0.719	0.610
13	0.949	0.925	33	0.703	0.590
14	0.941	0.913	34	0.687	0.570
15	0.933	0.901	35	0.671	0.550
16	0.924	0.888	36	0.654	0.529
17	0.914	0.874	37	0.638	0.509
18	0.904	0.860	38	0.621	0.489
19	0.894	0.845	39	0.604	0.469
20	0.883	0.829	40	0.587	0.449
41	0.569	0.429	66	0.165	0.0673
42	0.552	0.410	67	0.153	0.0596
43	0.535	0.391	68	0.140	0.0526
44	0.516	0.372	69	0.128	0.0460
45	0.500	0.353	70	0.117	0.0400
46	0.483	0.335	71	0.106	0.0345
47	0.465	0.317	72	0.0955	0.0295
48	0.448	0.300	73	0.0855	0.0250
49	0.430	0.282	74	0.0759	0.0209
50	0.413	0.265	75	0.0669	0.0173
51	0.396	0.249	76	0.0585	0.0142
52	0.379	0.233	77	0.0506	0.0114
53	0.362	0.218	78	0.0432	0.00900
54	0.345	0.203	79	0.0363	0.00695
55	0.329	0.189	80	0.0300	0.00523
56	0.312	0.175	81	0.0244	0.00383
57	0.297	0.161	82	0.0194	0.00270
58	0.281	0.149	83	0.0149	0.00181
59	0.265	0.137	84	0.0109	0.00114
60	0.250	0.125			
61	0.235	0.114			
62	0.221	0.103			
63	0.206	0.0936			
64	0.192	0.0842			
65	0.179	0.0754			

of a surface which is not a perfect diffuser may vary with angle of view, but if it is large enough to cover the field of view, its apparent brightness will not vary with distance.

206. Relation of brightness to incident light. This may be stated only for a projected area of a perfectly diffusing plane surface for which $b = mE$ where b is the brightness; m is the coefficient of diffuse reflection; and E is the incident flux. Brightness is expressed in candle-power per sq. cm. or in candle-power per sq. in. Interiors as illuminated at night have brightness values of the order of 0.0005 candle-power per sq. cm.

APPLIED ILLUMINATION

THE FUNDAMENTALS OF VISION

207. Contrast vision. We see things by reason of contour, relief and color, *i.e.*, shade perception and color perception. According to Fechner's law of sensations we perceive a fixed fractional difference of the total, irrespective, within limits, of the amount of the total sensation, and the sensation is proportional to the logarithm of the stimulus. This minimum perceptible contrast is usually of the order of 1 per cent., and, with increasing brightness within wide working limits, the visual power increases but slowly.

208. Color sensations. Ocular discernment as presented in the Young-Helmholtz theory is based upon three primary sensations: red, green and blue-

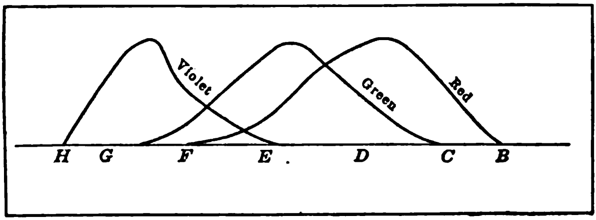


FIG. 51.—Primary color sensations.

violet, respectively. These overlap much as shown in Fig. 51, the curves of which show what color sensations will be stimulated by radiation of any given wave lengths within the visible spectrum. The seat of color sensation is said to lie in the cones of the retina which are found almost exclusively in the fovea, the rods being limited largely to employment in twilight vision.

209. Protective equipment of eye. The protective apparatus of the eye against excessive radiation, consists, first, of the **pupil**, whose automatic response to changes in intensity of light under certain conditions are shown* in Fig. 52. It will be seen that the area of the pupil aperture does not alter sufficiently to protect the eye against effects of the large changes in illumination which it must encounter; the second protective element is to be found in retinal adaptation.

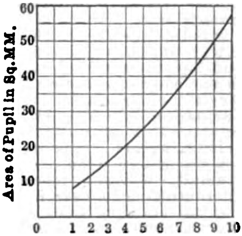


FIG. 52.—Reaction of pupil to variations in light.

210. Other ocular characteristics. Some of the physiological characteristics of the eye which are of importance in illumination work are as follows: (a) **adaptation,** the slow retinal change which supplements the rapid pupillary change both tending to adjust the eye

* Lambert's Experiments as reproduced in the "Art of Illumination" by Bell.

accomplish this it may be necessary to provide an illumination of uniform intensity, or the flux may have to be distributed dissymmetrically. Shadows are important, contrasts must be correct and a careful study of the intensities necessary to produce brightness of the right order is essential to success in lighting installations.

215. Intensities for various classes of service. For the more usual classes of work, intensities of illumination range from 1 to 7 foot-candles. In some classes, as in draughting rooms, 10 to 20 foot-candles are required. In other classes of lighting, very much higher values must be provided, notably in show-window lighting where the demand for great brilliancy fixes a standard of 25 or 30 foot-candles for general purposes and in industrial work, as in sewing upon dark garments where the work is done over limited areas, values as high as 100 foot-candles may be desirable. The standard to be set in any given installation must be reached after careful study of the local conditions and of the requirements peculiar to that installation. Pronouncements of various writers on this subject are of value in serving as a general guide, but they should not be regarded as final for any particular installation. A compilation of published data on intensities is presented in Par. **219**.

216. Direction. The best direction for the strongest component in any illumination system is peculiarly a matter for determination after study of local conditions. In natural lighting there is usually a strongly directed component, the only exception being a condition of diffused light such as that produced by mists, rain, etc. A great variety of directions for this principal component is experienced, ranging from one almost directly downward at mid-day in the summer to one which is almost horizontal just after sunrise or just before sunset. It is probable that the most pleasing direction for daylight conditions lies well between these two extremes.* The direction of light in interiors illuminated from side windows is unnatural and in many instances is neither pleasing nor comfortable. This is especially true of offices in high buildings where nothing but the sky is visible through the window from a point well in the interior of the room.

217. Direction of light affects appearance. A suitable direction for light is very important in industrial work where the avoidance of shadows and the avoidance of glare are of paramount importance. The appearance of a room is very largely dependent upon the direction of the light.† In ornamentation, relief designs are absolutely dependent upon the relation of light and shade.‡ Usually they require not only a noticeable directed component but also they require that the direction of that component shall be correct. So also, in the general appearance of a room and of the objects contained in it, shadows are important and their proper direction is a prominent factor in determining the final appearance of the room. The direction of incident light is, to some extent, a determining factor in the extent and characteristic of the reflection from surfaces.‖

218. Diffusion. See Par. **220**. If light from a point source passes through crystal glass or is reflected by a mirror, the rays are uniformly divergent, that is characteristically radiating. If the crystal glass or the mirror be replaced by an etched glass and a mat reflecting surface respectively, the uniform radiating characteristic is lost, the rays are scattered, and further propagation takes place in a multiplicity of directions. Such light is called diffused light. If the surface which occasions the diffusion is of large area and the illuminated object is relatively close to the diffusing surface, it is illuminated by diffused light. If, however, the object is relatively far removed from the diffusing surface, it is illuminated by light from essentially one direction, the rays are nearly parallel, and the light is but little diffused. Hence, diffusion is a relative term, and the subject is difficult to treat in a definite way.

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* "Distribution of Luminosity in Nature." Ives and Luckiesh, *Trans.* Illg. Eng. Soc., 1911.

† Ives. "Some Home Experiments in Illumination," *Trans.* Illg. Eng. Soc., 1913, p. 238.

‡ Luckiesh. "Importance of Direction, Quality and Distribution of Light," *Proceedings* American Gas Institute, 1913.

‖ "The Effect of Variation of the Incident Angle on the Coefficient of Diffuse Reflection." Gilpin, *Trans.* Illg. Eng. Soc., 1910.

220. Various degrees of diffusion. See Par. **218.** Perfect diffusion of light is obtained within a hollow sphere whose inner reflecting surface is mat. Some plane-reflecting surfaces are nearly, if not quite, perfect diffusers of light. Perfect diffusion may be represented graphically by a circle, tangent upon the diffusing surface. Imperfectly diffused transmission or reflection may be represented by various curves having radials elongated in the direction of regular transmission and reflection, indicating correspondingly lesser distribution in other directions than is provided by perfect diffusion.* A variety of reflection characteristics is illustrated in Fig. 53, ranging from perfect diffusion to a combination of regular and diffuse reflection characteristic of glossy paper.

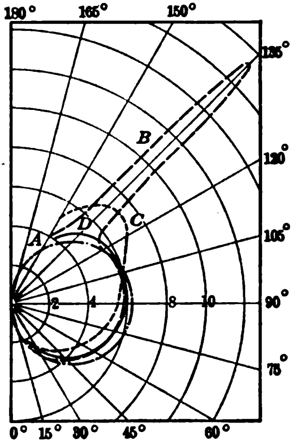

Fig. 53.—Various degrees of diffuse reflection. Light incident 45 deg. below horizontal, surface being vertical. A, perfect diffusion; B, reflection from glossy paper; C, reflection from semi-glossy paper; D, reflection from mat paper.

221. Need for diffusion. Diffusion tends to avoid glare and to soften shadows. Its accomplishment involves the substitution of secondary light sources which are relatively large and therefore of low brightness when compared with the source of light. Artificial lighting is usually inferior to natural light in respect to diffusion.† In practically every installation there is a real necessity for introducing artificial means of diffusing the light.

222. Color in its physical aspects has been treated in the discussion of the production of light (Par. **27**). The spectrophotometric values of light from the several common illuminants have been supplemented by color-sensation values as determined with color-mixing instruments. Referring further to the subject in its physiological relations, it may be noted that there are three primary colors, namely: red, green, and blue-violet, using pure spectral light. With these three colors, light of any desired color value may be produced. In his ability to modify the color of light, the illuminating engineer has at his disposal a means of enhancing the attractiveness of an interior as will be brought out more in detail under discussion of congruity in illumination, Par. **232**. It also is a field in which there is an opportunity for profiting by certain peculiarities of vision (Par. **206**).

PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF ILLUMINATION

223. Contrast. Once the correct general intensity of light (Par. **216**) is secured, all other aspects involved in direction (Par. **217**), diffusion (Par. **218**) and color (Par. **222**) as well as in the distribution of the light to produce various intensities, must be so manipulated as to secure the proper degrees of contrast. The more the subject of good illumination is considered, the more prominently does contrast force itself upon attention as a fundamental which must be served if an installation is to be successful. This applies both to contrast of light and shade and to contrast of color. Contrast of light and shade resolves itself into a question of varying brightness, embracing the range of brightness values from a brilliant incandescent-lamp filament or an arc, down to the deepest shades within view. The unshaded

* Nutting. "The Diffuse Reflection and Transmission of Light," *Transactions* Illg. Eng. Soc., 1912.
† Luckiesh. "Investigation of Diffusing Glassware," *Electrical World*, Nov. 16, 1912 and April 26, 1913.

incandescent lamp glowing outdoors in the daytime does not appear very bright against a background of sky, and may be viewed directly without discomfort. The same unshaded lamp burned at night in a room which is decorated in light colors, will prove annoying, while if burned in a room of which the decorations are of low reflecting quality, as dark woodwork, the lamp will prove positively intolerable. In the three cases the brightness of the lamp remains the same, and it is the varying contrast with its surroundings which explains in the one case, absence of discomfort and in the other extreme case, the most serious kind of ocular discomfort.

224. Need for concealing light sources. In Par. 31 brightness values for various unshaded light sources are given. It will be observed, for example, that these range from less than one candle-power per sq. in. for the Moore tube to 4,000 candle-power per sq. in. for the magnetite arc. This is, indeed, a wide range in brightness. When, however, it is remembered that the brightness of a very well-lighted wall, decorated in some light tone is of the order of 0.003 candle-power per sq. in., it will be seen that the variations in brightness of commercial light sources are small in comparison with the contrasts between any of them and the surfaces with which they are likely to be surrounded in practice. Herein lies the necessity for shading light sources in order to protect the eye against excessive contrasts. Entirely capable of protecting itself against excessive brightness, the eye is not able to see the objects of relatively low brightness and at the same time guard itself against the very high brilliancy of an exposed light source. There still remains the necessity for avoiding the intrusion of reflected images of the light sources in the ordinary field of view. A well-shielded light source may be exposed in the direction of a polished table top, the surface of which may reflect an image of the light source, subjecting the eye to almost as great strain as though the actual source were exposed. Glossy paper, shiny materials to be worked upon, polished woodwork, etc., are likely to introduce this sort of difficulty. Nature's surfaces as a rule are not shiny; artificial surfaces are likely to be shiny. In abolishing glossy paper, polished woodwork, etc., a long step is taken toward the elimination of excessive contrasts in artificial lighting. It is not possible, however, to abolish all such surfaces, and in other cases it is not done. It is, therefore, desirable to conceal the light source further. Accordingly, the improvement of a few years since in providing translucent reflectors which largely cover incandescent lamps and shield them from direct view, has been supplemented more recently by frosting the lower part of the bulbs of the lamps and the interior surfaces of the reflectors in order to soften and diffuse the light. Consequently, when reflected images are encountered, their brightness is rendered of as low an order as practicable. More recently still, bowls have been employed, either opaque or translucent, which intervene between any point of observation and the light source proper, softening and diffusing the light and directing a part or all of it toward the ceiling, whence it is further diffused and reflected downward.

225. Glare due to light source. Excessive brightness of surfaces or objects within the field of view gives rise to glare. Where the light source itself is within view, or a more or less imperfect image is viewed upon some shiny surface, the effect is much the same and is a manifestation of the same difficulty, namely excess of contrast (Par. 223). Glare or excess of contrast may actually reduce one's visual power temporarily; it may occasion discomfort and eye-strain; or, if continued long enough, may seriously impair visual organs. In the way of reduction in visual power, observations have been made of the extent of the effect.* Such studies are so complicated and difficult that definite results can be obtained only under very extreme conditions. In Fig. 54 is shown the reduction in visual power due to the presence of an exposed lamp in a dark room. The observers viewed a dimly illuminated test object. The presence of a 16-candle-power bare lamp 2 deg. from the test object, reduced the observers' ability to discern the test object to about the same extent as would follow a reduction in the illumination to 20 per cent. of that which was provided. As the light source was placed more and more distant from the observed object, its influence became less marked, falling off rapidly until the angle of separation was 4 deg. and thereafter at a slower rate until, at about 15 deg., the

* Sweet. "An Analysis of Illumination Requirements in Street Lighting," Journal of the Franklin Institute, May, 1910.

effect disappeared. Because of the very exaggerated conditions of dark surroundings and dimly illuminated test object, the results here obtained show diminished visual power far beyond that which would likely be experienced in practice. They illustrate the effect, however, and are suggestive of the need for concealing the light source. It is to be noted that, though no reduction in visual ability could be measured when the source was removed 15 deg. from the centre of the field of view, yet the discomfort and annoyance due to its presence were very severe.

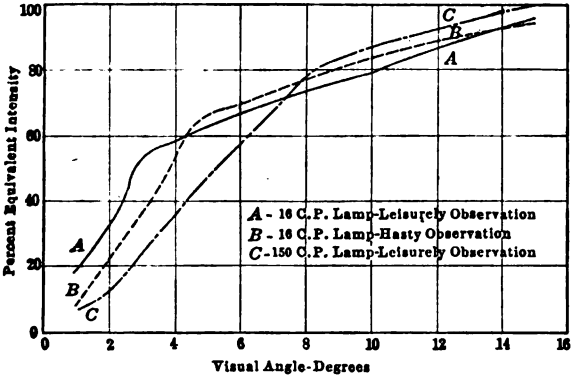

FIG. 54.—Influence of glaring light source in decreasing visual power.

226. Glare due to reflected image of light source. Glare due to images of light sources reflected from shiny surfaces is probably more productive of harm in the present stage of practice than is glare directly due to exposed light sources. While the imperfect rendering of the image by the usual polished surfaces decreases the brightness materially, yet the location of the reflected image is often so near the centre of the field of vision as to be much more serious than an exposed light source further removed. Viewing a glossy paper at the critical angle in which the image of the light source is reflected to the eye, it may be impossible to read print. This effect is diminished by altering the position of the object or of the observer, but, due to minute irregularities of the surface of the paper, there is still likely to be an appreciable regular reflection toward the eye. Likewise, paper which is only slightly glossy may reflect regularly toward the eye an appreciable section of the image of the light source without introducing so serious an effect as to prompt the observer to change position. Such conditions are the source of much discomfort and dissatisfaction experienced in artificial lighting. If they are to be avoided, light sources must be shielded both from immediate observation and from possibilities of reflection from glossy surfaces.

227. Coefficients of reflection. If it be assumed that softly diffused light is distributed generally throughout an interior producing uniform illumination, contrasts are dependent wholly upon the reflecting qualities of the illuminated surfaces. As these are usually less readily changed than the distribution and quality of the light, it is desirable to consider them before determining upon the degree of uniformity which should be achieved in light distribution. Uniform illumination with uniform decorations in an interior would be undesirable from every standpoint. Uniform illumination with heavily contrasted decorations and fittings may be acceptable. It is therefore of interest and value to obtain information on the coefficients of reflections of various surfaces, such are contained in Par. **228**.

231. Permissible contrasts. In general, authorities state that bright objects to which the eye is subjected should not exceed 4 or 5 c-p. per sq. in. (0.62 to 0.78 c-p. per sq. cm.) if physiological requirements are to be met. This applies to interiors at night. The limitation is relative rather than absolute. One authority,* while asserting the impracticability of fixing any standard, suggests that if the brightness of the object upon which the eyes are employed is of the order of 10 times that of surrounding objects, physiological requirements will be met satisfactorily.

232. Congruity. The requirements of esthetics are for illumination and an illuminating equipment which shall be pleasing to the senses and in harmony with the character of the premises illuminated. In buildings of notable architectural design the equipment should not only be suitable for its surroundings but the illumination should produce such combinations of light and shade, such contrasts, such color effects as will bring out in true proportions the important architectural features of the building, and will render its ornamentation in the manner conceived by the architect. In churches the illuminating equipment and the illumination must be of a character which is in keeping with the religious purposes for which the building is designed. In manufacturing establishments, effective illumination should be provided from simple, practical equipments. Incongruity of fixture, auxiliary, or illuminant; or unsuitability of light in quality, intensity, direction, etc., may mar an otherwise efficient illuminating system.

233. Pigmentary colors. Color of light, like color in decoration, is an aspect which affords many opportunities for skillful use by the illuminating engineer. In pigments, red, yellow, and blue of certain kinds and in certain proportions will produce white or any other desired color. They are sometimes referred to, therefore, as the primary colors, though, in a scientific sense, pure prismatic colors, respectively, red, green, and blue-violet, are the primary colors. The colors used for decoration are, however, dependent for their appearance upon the quality of the light by which they are illuminated.

It will be obvious, of course, that pigments which appear to the eye similar as regards color may be quite different physically, and that therefore their rendering under light of various colors may be markedly different from that here indicated. This is a field of application in which nothing may be taken for granted; only by trial can the appearance of a given pigment under a given light be determined. In decoration, therefore, a knowledge of the quality of the light employed is of first importance. It is essential that light be provided of such color value as will produce the effect desired in decoration.

234. Ultra-violet light. Some alarm has been felt by physiologists lest ultra-violet light from our ordinary illuminants should prove harmful to the visual organs. It appears to be quite clear, however, that nothing of this kind is to be feared. Recent investigations† show that little is to be apprehended on this score. The ultra-violet radiation from commercial illuminants is shown in Par. 235.

The data in this table arrange illuminants according to their ultra-violet, radiation. Luckiesh, studying the same subject at about the same time, arrived at the following conclusion:

"It appears that when glass is used over any commercial light source there can be very little harmful effect when moderate intensities are used. Considering the greater intensities of daylight, protection, if necessary in any case, is really needed against it rather than against artificial illuminants except in the case of special use of the latter light sources."

METHODS OF ILLUMINATION

236. Direct lighting. The fact that light sources are usually placed higher than the surfaces to be illuminated and that a downward direction of the light is rather generally desirable under such conditions, has led to the

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* Cobb. "Physiological Points Bearing on Glare," *Trans.* Illg. Eng. Soc., 1911.

† Bell. *Electrical World*, April 13, 1912.
Luckiesh. *Electrical World*, June 15, 1912.

room. Enclosing globes also are likely to produce results of much the same order. When the translucency of the semi-indirect bowl is so low that its brightness of transmitted light is not greater than that of the ceiling, the lighting effects are likely to be quite similar to those which obtain when indirect-lighting fixtures are employed.

239. Intermediate types of lighting equipment. In brief, opaque reflectors which allow little light to be distributed elsewhere than upon the working plane are distinctively direct-lighting equipments and form one extreme of a range upon the other extreme of which indirect-lighting equipments may be placed. Between these two extremes are a great variety of equipments, all of which distribute part of the light upon the ceiling and part of it downward. It is difficult to differentiate among these intermediate equipments from the standpoint of illuminating results. Most such equipments, however, may be located in one of three classes, namely: (a) inverted bowls or cones; (b) totally enclosing glassware; (c) translucent bowls.

240. Local illumination. The tendency in recent years has been to depend upon general lighting as far as possible and to supplement it by local illumination only where unavoidable. It is well to do so because with local illumination it is difficult to avoid glare either from the source directly or from the illuminated surface. When, however, it is necessary to illuminate locally some surface, which must be very brightly lighted, every precaution should be taken to avoid the evils just named. The application of diffusing media and care in locating the light source will go far toward accomplishing this; and satisfaction is doubly assured if, in addition, there is an ample general illumination supplementing the local illumination.

ILLUMINATION DESIGN

241. The purpose to be served. In laying out an installation a first step—so simple and obvious that its mention might appear unnecessary—is to determine the purposes to be served by the lighting installation. Usually one does not simply "light a room." He provides lighting in order to make a store attractive to the prospective customer and to promote the sale of goods; to illuminate the work on the machine and promote its prompt, accurate and safe accomplishment; to facilitate clerical work, promoting speed and accuracy without fatigue to the clerks; or to enhance the beauty and charm of a room in a residence. As a rule there are two or more principal objects to be attained in every installation. And the practitioner who familiarizes himself thoroughly with the conditions underlying the requirements established by these objects takes the first essential step in successful lighting design.

242. Choice of illuminant. Usually general conditions narrow the choice to two or three illuminants. In a residence any other illuminant than incandescent lamps would be unsuitable. In a steel mill the choice would probably be narrowed to Type C Mazda lamps and flame arc lamps. In a store either Mazda lamps or intensified carbon arc lamps would be employed, etc. In a street either magnetite or Type C Mazda lamps would probably be considered. Reliability, simplicity, efficiency, color of light, steadiness, cost (first, operating and maintenance) and size usually determine this choice.

243. Choice of auxiliary. Cost, ease of cleaning, ruggedness, efficiency new and maintained, light-directing qualities, diffusion, color, size and appearance have to be considered. Obviously, the importance of each qualification depends upon the nature of the installation.

244. Spacing and height. In industrial and commercial lighting it is generally considered that the spacing should be something like 50 per cent. greater than the vertical distance from the plane of illumination to the light source. This is a sufficiently good relation to form a point of departure in planning an installation. In large rooms it is useful to divide the floor area into squares or approximate squares. Desirable sizes of these squares are given in Par. 245.* One light source may be placed over the middle of each such square. Often, however, the squares or rectangles which form the unit of space to be lighted are established by the confines of the room or by the pillars or beams which make the division of the room into bays. In such cases it may be practicable to treat the space as a unit or it may be necessary

* "Handbook on Incandescent Lamp Illumination," General Elec. Co., 1913.

mination to be obtained apply methods of point to point calculation as described in Par. 198 and add a uniform increase of, say, 10 per cent. of the average, to represent the light reflected from ceiling and walls.

247. Illumination of several classes of installations. No attempt can be made here to discuss the special design features of the several classes of lighting installation. Those interested in the subject are referred to the Transactions of the Illuminating Engineering Society and to the technical press for descriptive articles. An index to some of the more important articles which may be consulted in this connection, is given in Par. 250.

COSTS

248. Calculation of total operating cost.*. "In determining the total operating cost of any system of lighting, three items should be considered: (a) fixed charges, which include interest on the investment, insurance and taxes, depreciation of permanent parts, regular attendance, and other expenses which are independent of the number of hours of use; (b) maintenance charges, which include renewal of parts, labor, and all costs, except the cost of energy, which depend upon the hours of burning; (c) the cost of energy, which depends upon the hours of burning and the rate charged.

"If data are compiled under these heads in convenient units, such as in (a) an annual charge, in (b) a charge per 1,000 hr. operation, and in (c) a charge per 1,000 hr. operation at unit cost of energy, the several items may easily be calculated for any given set of conditions, and the total annual operating cost of any lighting system obtained as their sum.

"Under fixed charges, the items of depreciation and attendance may be mentioned particularly. Depreciation should be charged on permanent parts only, and not upon parts the renewal of which is provided for in the maintenance cost. The rate for depreciation should, in many cases, be higher than the current practice, for obsolescence, rather than the wearing out of parts, determines the life of a lighting system. There are many installations in use to-day which are in good order and giving a fair measure of satisfaction, but which could be replaced at a large saving.

"Too much emphasis cannot be given to the desirability of regular attendance for those illuminants which do not require trimming from time to time. It is essential for satisfactory operation that such lamps and reflectors be cleaned at regular intervals, hence a fixed charge should always be included for this service. Lamps which require frequent trimming are cleaned at the same time, and the cost is included under the maintenance charge.

"The energy cost can usually be readily computed, but will, in the case of some electric illuminants, depend upon the voltage of the circuit, since this determines either the wattage or the power-factor. The effect of power-factor is seldom considered, although it governs the investment in generators, transformers, and wiring, and, in a small degree, energy required. To the central station or isolated plant, the volt-amperes required by a given lamp are perhaps as close a measure of the cost of service as the actual wattage consumed. When the consumer is purchasing energy on a kilowatt-hour basis this factor, of course, is eliminated so far as he is concerned."

Principles of cost accounting in illumination may be laid down and with discriminating application may serve to yield correct cost values. So largely, however, are costs in lighting dependent upon local conditions, and so greatly do these conditions vary, that it is unsafe to apply in one installation cost data obtained somewhere else, unless the differences in condition are first considered and allowance is made in the data for differences in such conditions. But little in the way of reliable impartial cost data has been published.

249. Cost of light in relation to other expenses. The total cost of artificial light as a part of the cost of living or as a part of the total cost of operation of a business enterprise is very small. In 1912 the Department of Commerce and Labor in a bulletin entitled "Retail Prices 1890 to 1911" shows that as an average of 2,567 workingmen's families in 1901, the average cost of lighting per annum was $8.15 out of a total cost of $768.54, or 1.06 per cent. expended in lighting. The report of the Commission of Labor for 1903, as presented at the 58th Congress, offers statistics compiled from the expenditures of 11,156 workingmen's families; these show that the cost of

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*Harrison and Magdsick. "The Analysis of Performance and Cost Data in Illuminating Engineering," Trans. Illg. Soc., 1911.

250. Selected list of reference pertaining to illumination designs.—*Continued*

Author	Where published	Title
Law and Powell	Trans. I. E. S., 1913, p. 515.	Distinctive Store Lighting.
Edison Lamp Works, G. E. Co.	Bulletin No. 43403, 1914.	Store Lighting with Mazda Lamps.
Edison Lamp Works, G. E. Co.	Bulletin No. 43500, 1914.	Lighting of Large Stores.
Shalling	Trans. I. E. S., 1913, p. 17.	Department Store Lighting.
Cravath	Electrical World, 1909, p. 53.	The Illumination Design of a Clothing Store.
Residence Lighting		
Vaughn	Elec. Review and Western Elec., 1912, p. 1061.	The Illumination of the Home.
Powell	Trans. I. E. S., 1914, p. 45.	Lighting a Simple Home.
Office Lighting		
Aldrich and Malia	Trans. I. E. S., 1914, p. 103.	Indirect Illumination of the Offices of a Large Company.
Ryan	Trans. I. E. S., 1912, p. 597.	The Lighting of the Buffalo General Electric Company's Building.
Street Lighting		
Way	Elec. Review and Western Elec., 1914, p. 371.	Elements of a Street Lighting Contract.
Ford	Univ. of Iowa, Bulletin 1, 1914.	Street Lighting.
Street Lighting Committee	Trans. N. E. L. A., 1912.	Report.
Street Lighting Committee	Trans. N. E. L. A., 1913.	Report.
Street Lighting Committee	Trans. N. E. L. A., 1914.	Report.
Millar	Trans. I. E. S., 1910, p. 653.	Some Neglected Considerations Pertaining to Street Illumination.
Bell	Trans. I. E. S., 1908, p. 400.	Street Lighting.
Miscellaneous		
Jones	Trans. A. I. E. E., 1912, p. 1127.	The Problems of Interior Illumination.
Higbie	Michigan Technic, 1911, p. 64.	Design of Illumination with Particular Reference to Interiors.
Powell	General Elec. Review, March, 1914, p. 318.	Interior Illumination.
Marks	Trans. I. E. S., 1908, p. 538.	Illumination of N. Y. City Carnegie Library.
Parsons and Smith	U. S. Naval Medical Bulletin, Vol. IV, No. 3.	The Illumination of Study Rooms.
Knight and Marshall	Trans. I. E. S., 1910, p. 553.	Public School-room Lighting.
Marks	The Brickbuilder, 1913.	Lighting Public and Semi-public Buildings.

and that the illumination of a plane surface varies as the cosine of the angle of inclination to the incident ray (Par. 201). These laws must be applied with discrimination and with strict regard for their practical limitations. The inverse-square law holds good only when the light source is relatively small with reference to the distance from the source to the illuminated surface. If the distance is less than five times the maximum dimension of the source, material divergence from the inverse-square law will result. The law may not hold good for relatively short distances when reflecting or refracting devices are employed to concentrate the light in a particular direction, as, for example, when a parabolic reflector is employed with an incandescent lamp or, as a more extreme example, a search-light. The cosine law applies to any plane surface insofar as the incident light is concerned. In many cases, however, the incident light is judged by the reflected or the refracted light. In such applications, the cosine law holds good only if the surface is a true diffusing surface, altogether free from regular reflection characteristics.

254. Ocular characteristics affecting photometry. In the comparison of lights of similar color, the process is not unlike other physical measurements since visual peculiarities do not affect the result. In heterochromatic photometry, in which lights of different colors are compared, ocular characteristics must be borne in mind, and the measurements must be carried out with due regard to the requirements which they impose. The three characteristics of greatest importance are as follows: (a) the Purkinje effect (Par. 255); (b) yellow-spot vision (Par. 256); (c) partial color blindness (Par. 257).

255. The Purkinje effect is the name applied to the greater sensibility of the human eye to blue and green light at very low intensities than to red or yellow light. In accordance with this characteristic, if a mercury-vapor lamp is adjudged equal in illuminating power to a tungsten-filament lamp when the two are compared at a distance of 10 ft., the mercury-vapor lamp would be adjudged of higher illuminating power than the tungsten lamp if the comparison were to be made at a great distance.

256. Yellow-spot vision. The central portion of the retina of the eye, the yellow spot, comprehends a visual angle of 6 to 8 deg., throughout which the eye is less sensitive to green and blue light than is the surrounding portion of the retina. If a comparison of a mercury-vapor lamp and a tungsten lamp of equal power were to be made upon a surface so small as to fall within a visual angle of 6 deg., the mercury-vapor lamp would be adjudged of lower illuminating power than the tungsten. While a relatively higher evaluation would be accorded the mercury-vapor lamp if the illuminated surface were to be enlarged so as to comprehend a visual angle of say 24 deg.

257. Partial color blindness is often encountered. Eyes of certain individuals are found to be less sensitive to light of a given color than are normal eyes. The characteristic sensibility of the eye to light of different colors and of a given intensity when plotted diagrammatically is known as the luminosity curve* (Par. 10). If an observer's sensibility to red is low, as shown by the luminosity curve for his eye, he would, of course, adjudge the illuminating power of a mercury-vapor lamp to be relatively high as compared with that of a tungsten lamp.

258. Psychology in photometry. In all photometry and especially in heterochromatic photometry, observers whose eyes may have quite similar characteristics sometimes secure markedly different results, due to the fact that they form different concepts of the appearance which two illuminated surfaces must assume when they are balanced. Usually, an observer forms a concept and adheres to such concept until persuaded that it is improper. This is a matter of memory, tradition, and, sometimes, of external influence. It is common experience that observers who work together in photometry tend to form similar concepts and to agree in their observations under all conditions. Sometimes the concept agreed upon by such observers is the probable correct concept reached as a consensus of opinion. On the other hand it may be the concept of one observer which another observer has been influenced, unconsciously, to accept.

* Ives. *Philosophical Magazine*, December, 1912.

comparison purposes must be verified occasionally and the repeated use of the working standards employed in such verifications in turn limits their period of constancy. A complete range of reference standards and working standards is important if comparison standards are to be relied upon for accuracy.

PHOTOMETERS AND PHOTOMETRIC APPARATUS

265. Physical or non-ocular photometers. In the measurement of radiant energy there are employed, at various times, the thermopile, the radiometer, and the bolometer. These are affected by radiation of various wave lengths in several characteristic ways, and, for some classes of physical investigation, have very important uses. The photo-electric cell, the selenium cell, and the photographic plate also have been investigated with a view to employment as substitutes for the eye in conjunction with a photometric device. In addition to characteristics which impose serious limitations to their use for practical work, these devices are open to the further objection that radiation within the visible spectrum does not affect them in the same proportions as it does the human eye. Their sensibility characteristics do not conform to the luminosity curve of the human eye. The photo-electric cell, for example, is most sensitive in the region of 0.44μ in the violet end of the spectrum; the selenium cell, on the other hand, is most sensitive to radiation in the region of 0.7μ, which is in the orange-red region of the spectrum. It is possible to correct these devices by employing color screens of such characteristics as to alter the sensibility curve to the desired extent. It is understood that those who are engaged in the study of these devices feel encouraged to hope that they may yet prove their value in some classes of photometric work. Up to the present time, however, they have been of scientific interest rather than of utility, in so far as ordinary photometry is concerned.

265. Photometric devices—ocular. It is a characteristic of the human eye, termed "**induction**" that a uniform dark surface placed next a lighter surface appears darker in the region immediately adjacent to the lighter surface than it does in the region farther removed. It follows that in bringing two surfaces to equivalent brightness, the contrast will appear more marked if the surfaces can be brought into close juxtaposition, and, if the contrast is more marked, equivalency can be established with greater

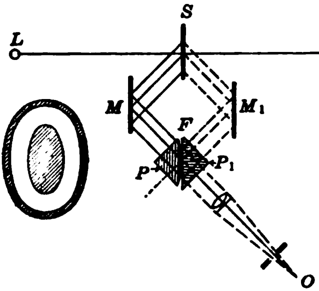

FIG. 55.—Lummer-Brodhun photometer, comparison type.

accuracy. Utmost precision in such adjustments is attained if the surfaces are made continguous and without distinguishable separation. A photometric device (sometimes called a sight box) is an appliance for promoting the brightness equivalency adjustment which is the essence of photometry. The more usual types may be classified as comparison devices, contrast devices, and flicker devices.

267. Comparison devices. For a description of many simple photometric devices which are of historic interest, see text-books.* The comparison

* Especially "Illumination—Its Distribution and Measurement," Trotter.

disc are essential to precision of operation. As in the Lummer-Brodhun contrast photometer, the Bunsen photometer presents to view two contrast fields. If properly constructed with mirrors of equal absorbing power, a condition of balance should bring equality of brightness and equality of contrast.

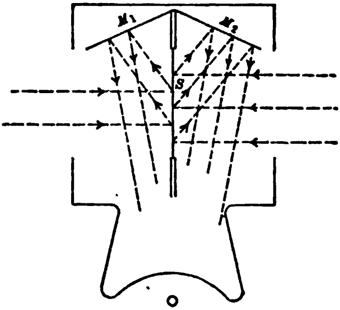

FIG. 57.—Bunsen photometer.

The Bunsen photometer is preferred by some for routine lamp testing where highest precision in individual measurements is not so important as good maintenance of accuracy throughout the day's work. It is inferior to the Lummer-Brodhun photometer in sensitiveness at low intensities. It is somewhat easier to make settings with the Bunsen photometer than with the Lummer-Brodhun photometer in comparison of lights of markedly different colors for the reason that the illumination of each surface of the disc is due in part to transmitted light from the other surface. Where colors differ, there is a tendency to blend and decrease the color contrast below the actual contrast encountered with a photometer like the Lummer-Brodhun, where the lights are not mixed.

270. Flicker photometer. In flicker photometry the criterion of adjustment is the disappearance of the flicker effect, or rarely, the equality of two flicker effects. The flicker photometer is used as a rule only where lights of markedly different colors are to be compared. Due to persistence of vision, the colors, though markedly different, tend to blend when presented to the eye in rapid alternation, and the color differences cease to be perceptible, while differences in brightness of the two surfaces are still visible. It is thus possible to make comparisons of markedly different lights with much less difficulty than when the equality-of-brightness method is employed, and different observers are much more likely to secure similar results, because the criterion rests upon a physiological effect and leaves room for less difference of opinion or less variation of concept than does the equality-of-brightness method. Ives, who has made the most recent and extensive investigations of the subject,* has found that with the flicker photometer, blue and green light is adjudged of lower illuminating power when compared at low intensities with red and yellow light. This is a reversal of the Purkinje effect (Par. **256**) which obtains in equality-of-brightness measurements at very low intensities. He concludes, as the result of his investigations, that the flicker photometer offers the best means of dealing with heterochromatic photometry, but its use should be limited by specifying a standard intensity at which comparison shall be made, a standard visual angle for the photometric field, and observers who are free from peculiarities of color vision. Incidentally, a similar prescription applied to any kind of photometry would do much toward standardization. Ultimately, heterochromatic photometry must be based upon the illuminating power as judged by some such criterion as equality of brightness or power to reveal detail. The disappearance of flicker cannot be considered as an ultimate criterion. However, a flicker photometer once verified and accepted in a given form as a reliable device for heterochromatic photometry, should prove very useful in that class of work because of the readiness with which settings can be made.

271. Forms of flicker photometer. Rood† devised the first flicker photometer, which consisted of a wedge, the two faces of which formed the photometric surfaces, which were viewed alternately through a revolving lens. The Whitman photometer is provided with a wheel, portions of whose rim are inclined in opposite directions. As the wheel revolves, it

* *Philosophical Magazine*, November, 1912.
† Science, Vol. VII, p. 757.

applications, any of the methods of varying the intensity which have been described, may be employed. The principles are the same and the applications differ only in accordance with the dictates of convenience and practicability.

277. Photometer bars. In the measurement of horizontal candle-power and in the measurement of distribution of light about a source, it is customary to employ a track upon which carriages supporting lamps or photometric devices, may travel smoothly and easily. The **Reichsanstalt bar** is an approved type which, with various modifications, may be procured from any manufacturer of photometric appliances.

278. Light-distribution apparatus. A considerable variety of appliances for facilitating the determination of radial distribution of light, is available. These appliances include the Dibdin photometer; devices employing respectively one mirror, two mirrors and three mirrors; the Matthews photometer, employing a ring of mirrors and apparatus in which the test plate is revolved about the source. For detailed description see text-books on photometry and manufacturers' catalogues. All such appliances are designed to facilitate the determination of the intensity of light at various angles in the vertical plane. Since the inverse-square law does not always apply strictly to light from reflectors at the short distances at which the light is utilized, it is good practice to maintain a fixed distance between the surfaces of the photometric device and the centre of the light source.

INTEGRATING PHOTOMETERS

279. General description. An integrating photometer yields in a single measurement the value of the total flux of light or the mean spherical candle-power of a light source. In general, most such devices, by optical or mechanical means, reduce the intensity of the light, at various angles to the vertical of the light source, in proportion to the area of the zone which the angle bisects, and provide a summation of such reduced intensities for the several angles throughout the vertical plane of the source. The **integrating sphere** intercepts and provides an indication of the total light produced by the source. Perhaps the earliest integrating photometer was **Blondel's lumeter.*** Kennelly† also devised an apparatus for mechanical integration. The instruments of Matthews and Ulbricht, and especially the latter, which are used at the present time are described in text-books.

280. Ulbricht integrating sphere. The integrating sphere devised by Ulbricht has been found to be the most accurate and practical form of integrating photometer It has been shown that if a light source be located within a hollow sphere having a diffusing inner surface and be screened from a given element of that surface, the illumination of such element, being due entirely to diffuse reflection, will be independent of the location

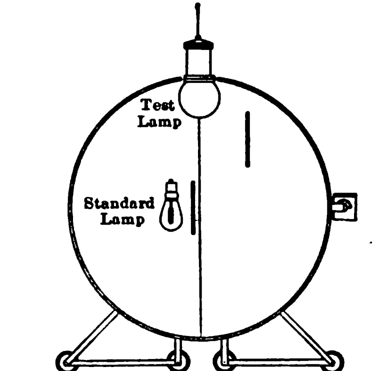

Fig. 59.—Integrating sphere for measuring total lumens or mean spherical candle-power.

* Blondel. "La Determination de l'intensite moyenne spherique des sources de lumiere," *Comptes rendus*, March and April, 1895 and *L'Eclairage Electrique*.

† Houston and Kennelly. "Electric Incandescent Lighting," p. 461.

Surfaces which conform most closely to this requirement are, however, not permanent in character. Also, any opaque surface is undesirable for some classes of work because it must be viewed from above, under which conditions it is almost impossible to avoid some obstruction of light by the photometer and the observer. The most satisfactory simple test plate for measurement of illumination under most conditions, consists of a thin milk glass which is free from selective absorption and provided with fine diffusing surfaces, and viewed from below, its brightness being judged by transmitted light. Such plates do not conform exactly to the cosine law of perfect diffusion, but the variation of the best plates from that law is immaterial in most classes of work. The broken line curve in Fig. 60 illustrates the variation of a typical translucent-glass test plate of a simple type.

283. Weber portable photometer. The Weber photometer, Fig. 61, was perhaps the first portable photometer embodying most of the features which have been found to be essential to this class of apparatus. In its latest form it consists of a rotating tube containing, at one end, the ocular aperture, *O*, at the centre a Lummer-Brodhun cube, *P*, and at the other end either an attached test plate or a diaphragm for use with a detached test plate, *T*. This tube revolves upon the end of a fixed horizontal tube containing at the other end the comparison lamp, *C*. A translucent glass, *G*, is moved along the axis of this tube, its brightness varying inversely as the square of its distance from the comparison lamp. Looking through the ocular aperture, one sees, as the centre of the photometric field, a portion of either the attached or the detached test plate, and surrounding it a portion of the comparison-lamp glass, the brightness of both being, of course, independent of their distance from the eye. The value corresponding to the location of the comparison-lamp glass, is indicated upon an external scale. This photometer is provided with some absorbing glasses to increase the range, and, in addition, has green and red glasses for insertion in the ocular tube in order to assist in heterochromatic photometry in accordance with a two-color method. This method of color photometry has very limited application.

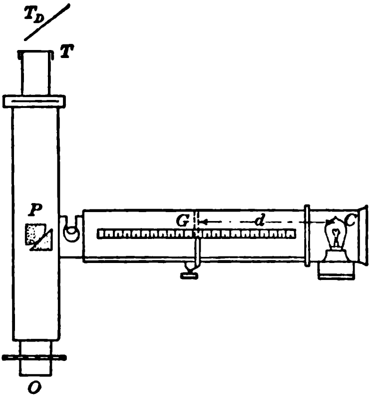

FIG. 61.—Weber portable photometer

284. Beckstein photometer. This instrument is semi-portable. It employs a Lummer-Brodhun cube, an incandescent comparison lamp, a variable sector disc, about which a beam of light is rotated (Par. 274), the prisms being driven by a small attached motor. It is provided with a multiplicity of attachments and adjustments which render it perhaps more suitable for academic purposes than for practical photometry.

285. Sharp-Millar photometer. This is the form of portable photometer which is most generally used in this country. It is available in three sizes, respectively 12, 24, and 39 in. long. Fig. 62 shows the essential features as embodied in the smallest size. The photometric device, *P*, consists of a Lummer-Brodhun cube or a microscope glass, mirrored except for a central aperture. Looking through this aperture from ocular aperture *O*, the observer sees either the attached test plate, *T*, which is upon the end of a rotating tube, or the detached test plate, T_d. The photometric surface, as seen through this tube, is surrounded in the photometric field by a portion of translucent glass comparison window, *W*. The illumination of window *W* varies inversely as the square of the distance to moving comparison lamp *C*. The values of a setting is indicated upon a direct-reading translucent scale, illuminated from spectrophotometry is liable to systematic and accidental errors, effects of stray light being notable among the errors of the former class. Results of spectrophotometric tests show relative intensities of light in the several wave lengths throughout the visible spectrum (Par. 27). These are difficult to comprehend and interpret unless one is well versed in such work. Usually it is necessary to refer spectrophotometric differences to differences in color with which one is well acquainted (as that between the Mazda and carbon lamps) in order to form a fairly good concept of magnitude.

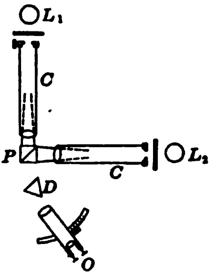

FIG. 63.—Scheme of spectro-photometer.

287. Colorimeter. It is generally considered that there are three primary color sensations (Par. 208). In colorimetry, three glasses corresponding to these sensations, respectively red, green and blue, are interposed between the light source to be studied, and a device which mixes the transmitted lights and brings the resultant combined light into juxtaposition with some comparison light for color match. Diaphragms, or variable-width slits, are employed to secure the proper relative proportions of red, green and blue light. In the Ives colorimeter* variable width slits are employed with the colored glasses. The adjustment scale for each slit is calibrated from 0 to 100. With each slit opened to the maximum, the resultant mixture appears white when average daylight is received upon the colored glasses. Color

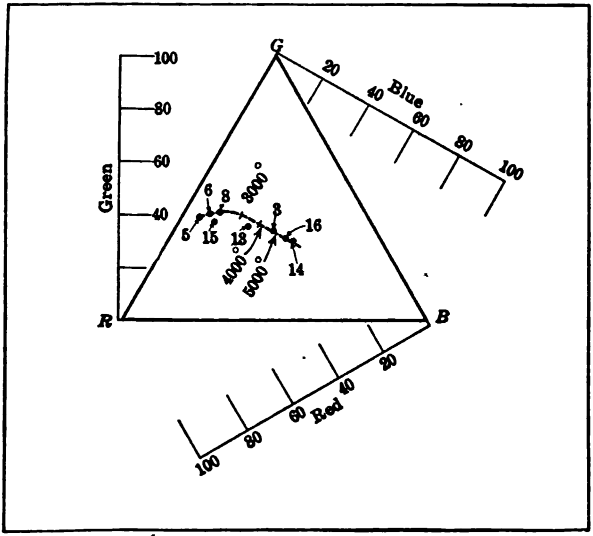

FIG. 64.—Color triangle. For key to numbers see Par. 27.

sensation values are expressed in terms of such maxima. The colorimeter may be employed in the study of light from line spectrum sources, whereas

* Ives. *Journal Franklin Institute*, 1907, p. 164.

293. Absorbing screens form a valuable adjunct to photometric equipment. Their transmission coefficient, however, is not accurately controllable, and a simple decimal value is therefore rarely obtained. Absorbing screens should transmit without diffusion, and should be free from serious selective absorption. Unfortunately, the usual absorbing screens having low coefficients of transmission, have considerable selective absorption.

294. Baffle screens. In practically all photometry it is essential to guard the photometric device against stray light. Opaque screens having suitably proportioned apertures are largely employed for this purpose. A series of these screens, painted black (for most precise work they may be covered with black velvet), is used, for example, on a photometer bar. Where the photometric device or the comparison lamp travels along a track, these screens must be re-located as occasion requires. A most satisfactory method is to so install them that they will be adjusted automatically to the movement of the lamp or photometer carriage. This may be accomplished by mounting them upon lazy tongs, as in several types of commercial lamp-testing photometers, or allowing them to slide upon the track, being pushed in front of the lamp as it approaches the photometric device, and drawn after the lamp by cords or otherwise as it recedes, as in the Sharp-Millar photometer. An alternative to the use of baffle screens is the employment of black velvet to cover all surfaces which may possibly reflect stray light to the photometric device.

295. Rheostats. The easy fine adjustment of the current or voltage of a lamp is important to precise work in photometry. Too much care cannot be expended in providing thoroughly satisfactory rheostats for this purpose. Step rheostats are unsatisfactory unless the steps are of such low resistance, in relation to the magnitude of the current, that the change per step is extremely small. A helix of resistance wire, with the coils well insulated, wound upon an insulated tube and mounting a sliding collar having a multiplicity of contact points, is the most generally acceptable form of rheostat for photometric work.

296. Lamp rotators. It is usually desired to obtain mean angular intensity of light rather than the light in some particular direction at a given angle. Wherever the nature of the illuminant permits, it is desirable, therefore, to rotate the light source during test, allowing the eye to integrate the intensities to obtain a mean. Most forms of illuminants can be rotated. The speed of rotation of course depends upon the extent to which the light distribution is asymmetrical. If the distribution is approximately symmetrical, a low speed of rotation will suffice. This being the case, it has been found practicable to rotate almost all types of illuminants, including most arc lamps and some forms of gas lamps. The lamp rotator therefore becomes a valuable adjunct in a photometric laboratory. It must be good both mechanically and electrically. As the moving electrical contact required for the supply of the lamp may involve some potential drop, it is customary in the best construction to provide auxiliary moving contacts either of the brush type or of the mercury-cup type, in order to allow the measurement of voltage immediately at the lamp terminals.

PHOTOMETRIC TESTING

297. The substitution method of photometry consists in calibrating a photometer by means of a standard lamp of as nearly as possible the same characteristics as the lamps to be tested, and substituting the lamp to be tested for the standard lamp. A skilled photometrist employing a photometer of exact construction which is perfectly screened and is used with correct electrical instruments for determining the electrical conditions of circuits which are free from potential drop, may obtain correct results in the practical comparison of a test lamp against a standard lamp. Whatever the methods employed, every care should be exercised to secure these favorable conditions for photometry, but if, in spite of care, some conditions exist which are not exactly as they should be, it is quite possible that the substitution method may result in cancelling the effect of such conditions and avoiding erroneous results. By using standard lamps of the same size and type as the lamp to be tested, the substitution method results in correcting both errors of illumination and errors of electrical measurement. If stray light from a 100-candle-power lamp adds 5 per cent. to the illumination of a photometric surface when a moving photometric device is set at 100 on a scale, it will have the same effect when a standard lamp of the same size is used. If then a comparison lamp be calibrated for temporary use by means of the 100-candle-power standard lamp, it will be adjusted 5 per cent. too high. When the 100-candle-power test lamp is measured, the light of the comparison lamp against which it is balanced and the light from the test lamp will both be 5 per cent. too high. The result will be a correct setting. If a voltmeter be employed which has an error of 1 per cent., the effect of the error will be cancelled in the same way if the substitution method is followed. Where considerable photometric work is to be done, the provision of an ample range of reference standard lamps, in order to permit the extensive application of the substitution method, is true economy.

298. Good practice in measuring illumination. It is well to be provided with reference standard lamps and a box equipped with baffle screens or black velvet to prevent stray light, in order to produce illumination of known intensities from the standard lamp upon the photometer test plate. It is well to have sufficient standardising equipment of this kind to permit of the verification of the photometer scale at a few points throughout its range and also the verification of photometer absorbing screens. The same equipment may be used in verifying the brightness calibration of the photometer, provided a standard surface of known qualities is obtained with the standard lamps. In such calibration, light of a known intensity is thrown upon the standard surface and the corresponding brightness of the surface is computed (Par. **205**), employing its coefficient of diffuse reflection.

In some illumination work it is sufficient to measure the intensity of illumination at certain points in a room, and it is usually sufficient to measure the brightness of certain objects in the room, as far as data on brightness are concerned. More frequently, however, it is desired to know the average maximum and minimum illumination intensities on certain planes, and to derive the coefficient of utilization (Par. **188**). In such instances it is customary to divide the plane of reference into rectangles, usually providing 20 to 30 such rectangles for the room, or for each bay in the room. A determination of the illumination intensity is then made at the centre of each such rectangle. The mean of such values is usually a fair approximation of the average intensity for the entire plane. Where a detached test plate is employed in the measurement of illumination on a horizontal plane or at any given angle of inclination to the horizontal, it is often desirable to employ an automatic-leveling test plate. In the measurement of horizontal illumination in interiors, a plane 30 or 36 in. above the floor is usually selected. A complete study of a room used, for example, for office purposes, should include the average horizontal illumination on such a plane; the uniformity of such illumination intensities; the brightness of the walls, light sources and other especially prominent objects within view; and measurements of either illumination intensities or brightness on desks to show depth and nature of shadows encountered.

299. Precautions for avoidance of error. The following suggestions are commended by experience, and, if followed, are likely to result in the avoidance of some of the most common errors.

Reduce color differences by the use of authoritatively calibrated color filters (Par. **290**).

Follow the substitution method (Par. **297**) as closely as practicable. Provide reference or working-standard lamps of the same size and type as the lamps to be tested.

Consult the characteristics of the light source under test and adapt practice accordingly. For example, allow an arc lamp or a large series incandescent lamp to burn for a short period in order to attain working temperature before making measurements. In testing arc lamps whose values vary through a cycle corresponding with the feeding period, make certain that results are average for such period.

Verify photometer-scale calibration by tests of standard lamps.

Repeat verification at reasonable intervals even though photometer has not been used in interim.

Verify indications of electrical instruments used.

Observe strict cleanliness of apparatus. Dust on transmitting glasses increases coefficient of absorption. Dust on black velvet reflects light.

Verify a few test results by tests upon other apparatus. It is relatively simple for an observer to repeat settings with a given photometer. Make certain that such settings are in accord with results determined by others employing different equipment.

In tests of reflectors make certain that the light source is strictly in accord with the manufacturer's standard of construction, both as to type and dimensions.

Assure correct location of the reflector with reference to the light source. Slight variation in any of these conditions may affect the result materially.

In tests for candle-power and in light-distribution tests, look along the photometric axis from the position of the photometric device to the test lamp and to the comparison lamp. Make certain that all of the light emanating from the light sources in the direction of the photometric device, reaches the photometric surface. Make certain that no other light reaches the surface, that is, avoid stray light.

300. Sampling. In sampling for test purposes, whether the samples be lamps, lighting auxiliaries, or illumination installations, it is important that the samples be unquestionably representative of the product which is to be judged by the results of the test. It is also essential that the samples be sufficient in number to guard against the exertion of undue influence upon the final result due to the presence of an eccentric individual among the samples. It is hardly possible to judge intelligently in these matters unless one is thoroughly acquainted with the characteristics of the product which is being sampled. No small part of expertness in testing lies in the successful sampling of the product to be tested. Lamps, reflectors, etc., are not uniform, and very misleading results may follow upon injudicious sampling.

301. Principles of comparison. In comparing illuminants it is important to bear in mind first, that some illuminants require more adaptation and suffer in efficiency more in adaptation for a given service than do other illuminants; and, second, that some illuminants deteriorate more largely in efficiency during life than do others. For example, a magnetite arc lamp as equipped is well adapted to street-lighting service, and its efficiency in the condition delivered by the manufacturer is substantially its service efficiency. On the other hand, incandescent lamps may have to be equipped with globe or reflectors or both before application to street-lighting service, and their efficiency as shipped by the manufacturer is materially higher than is their service efficiency. As another example, the candle-power depreciation of a 25-watt Mazda lamp is less during its life than is the candle-power depreciation of a 100-watt Mazda lamp. Conclusions based upon initial laboratory values should be modified where necessary before determining upon relative merit of two different kinds or sizes of illuminants for a given class of service. Likewise, lighting auxiliaries are not always directly comparable on the basis of their initial laboratory values. The deterioration of reflecting surfaces may be rapid. Some surfaces collect and retain dust more largely than do others, and, in consequence, their deterioration of light is greater in a given period.

302. Discussion of results. In discussion of test results it is rarely possible to draw unqualified conclusions as to relative merit between appliances or installations which are of more or less the same order of merit. In any test all that is demonstrated is that a sample or a set of samples or an installation has been found, in a given instance, to be superior in certain respects. It is dangerous to draw sweeping conclusions from tests. To do so may mislead when test data are applied to appliances or installations which have not actually been tested. In discussing results of tests and drawing conclusions from tests it is well to be cautious in accepting the basis of measurement as a final indication of value. The candle-power of an incandescent lamp is one direction or in one plane is not necessarily an indication of the illuminating power of the lamp. In the long run, the total light flux or the mean spherical candle-power is most nearly a correct indication, but even this measurement may fail to indicate the real value of an illuminant for a certain class of service. It may be shown that the minimum normal illumination intensities provided by two installations of illuminants for street-lighting service are equal, but this does not demonstrate that the two systems are of equal value. One may deliver twice as much light as the other upon the street. The mean horizontal illumination may be in the long run a reasonably good measure of street-lighting effectiveness, but even this measure may fail to indicate the facts for certain classes of service. In short, tests of illumination should be conducted and conclusions should be drawn from such tests in accordance with the dictates of common sense and good engineering practice.

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SECTION 15

INDUSTRIAL MOTOR APPLICATIONS

CONTENTS

(*Numbers refer to Paragraphs*)

SECTION 15

INDUSTRIAL MOTOR APPLICATIONS
MACHINE TOOLS

BY LEON P. ALFORD

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1. Definition. The term "machine tools" cannot be accurately defined. Broadly they are machines used to work and shape metals. A legal definition, taken from the Underwood tariff law, Par. 167, reads as follows: "Machine tool as used in this paragraph shall be held to mean any machine operated by other than hand power which employs a tool working on metal."

2. The two principal classes into which they divide are distinguished by the kind of motion of the work or cutting tools. This motion may be either rotating or reciprocating. In the former instance the speed is usually constant throughout each operation, and the energy absorbed is used in overcoming the friction of the machine and in doing useful work in cutting or forming metals. The exceptions are machines that accelerate during the cutting operations, such as squaring-up lathes and lathe-type cutting-off machines. In the second class the power is subject to great fluctuations during a working cycle. For, in addition to the friction losses and useful work done there are large, regular demands for energy with which to retard and accelerate heavy parts of the machine, or the pieces which are being shaped.

3. The friction losses in rotating machines, such as lathes, boring mills, drilling machines, milling machines, grinders, and the like vary almost directly as the speed, the gear ratio remaining constant. The loss in the gearing and feeding mechanism comprises the larger part of the friction losses.

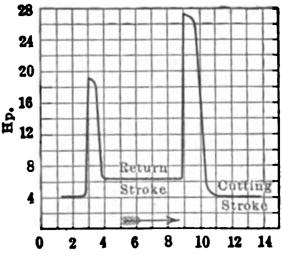

Fig. 1.—Power curve of a 60 by 60-in. planer.

4. The friction losses in reciprocating machines, such as planers, shapers, slotters, and the like, are very small in comparison with the losses due to inertia. In fact the inertia losses often exceed the useful work to such an extent as to determine the size of motor (this is especially the case with short-stroke machines). Fig. 1 shows a power curve taken by G. M. Campbell for a 60 × 60 in. × 20 ft. Pond planer. It shows the power input when running light plotted with time. The cutting-stroke speed was 25 ft. per min. (7.6 m. per min.) and the return-stroke speed 60 ft. per min. (18.3 m. per min.).

5. Group drive and individual drive. Motor applications to machine tools divide into two classes, group drives and individual drives. It is impossible to lay down a general principle to be followed in the selection of drive for a given case, for there are many modifying factors. Very large machines (those located under a crane) and all machines requiring variable-speed drive are commonly provided with individual motors. Small and medium-sized machines are usually arranged in groups and driven from a line shaft which in turn is driven by a constant-speed motor. If there are a number of reciprocating machines in the group, it is not uncommon to add a fly-wheel to the motor.

6. A comparison of lineshaft and individual-motor drives,* for machine tools is given in the following table:

Item	Lineshaft drive	Individual motor drive	Advantage of individual motor
1. Power consumption.	Constant friction loss in shaft, belts and motor, power for cutting.	Friction loss (motor and tool only) useful power only while working.	Less power required.
2. Speed control.	No. speeds = No. cone pulleys × No. gear ratios.	No. speeds = No. controller points × No. gear ratios.	More speeds possible; time saved in speed adjustments.
3. Reversing.	Clutch and crossed belt.	Reversible controller.	Time saved in reversing.
4. Adjusting tool and work.	Stopping at any definite point very difficult.	Can be started in either direction and stopped at any point.	Time saved in setting up and lining up.
5. Speed adjustment.	Large speed increments between pulley steps.	Small speed increments between controller steps.	Time saved by obtaining proper cutting speed.
6. Size of cut.	Limited by slipping belt; large belts hard to shift.	Limited by strength of tool and size of motor.	Time saved by taking heavier cuts.
7. Time to complete a job.	....	....	Much less time required as indicated for previous items.
8. Liability to accidents.	Slipping or breaking belt; injury to machine tools, cutting tool or prime mover.	Injury to machine tool, cutting tool or motor.	Much less liability to accident.
9. Checking economy of operations.	Close supervision required, very difficult to locate causes of delay.	Accurate tests possible by means of graphic meter which records automatically all delays and rate of cutting.	Causes of delay and remedies easily located without personal supervision.
10. Flexibility of location.	Location determined by shafting, and changes difficult.	Location determined by sequence of operation changes readily made.	Greater convenience in handling and increased economy of operation; more compact arrangement possible.

7. Motors for individual drives have been tentatively standardized by a committee of the National Machine Tool Builder's Association conferring with a committee of the American Association of Electric Motor Manufacturers. Although the design data were agreed upon in substance early in 1910, the motor manufacturers have failed to use it in the manufacture of their product. An abstract of the report of these committees appears in Par. 8.

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, page 182.

(e) **Axle lathes, wheel lathes and driving-wheel lathes** should be driven by direct-current motors.

(f) **Chucking lathes** usually are not motor-driven. If motors are used they should be of variable speed.

(g) **Automatic screw machines** in small sizes should be group-driven; in the larger sizes they should preferably be driven by variable-speed motors.

(h) **Sensitive drilling machines** in general should not be motor-driven. However, if machine is placed in an isolated location, a motor may be directly applied to the machine itself or the machine may be driven through a countershaft, from a motor on the floor.

(i) **Vertical and radial drilling machines** are usually group-driven unless they are isolated. If such machines are motor-driven, the variable-speed type should be selected. The motor may be direct connected to the machine itself or set up to drive the machine countershaft.

(j) **Boring machines,** if used for specialized work, are preferably belt-driven. If used for a variety of operations, a variable-speed motor is desirable.

(k) **Grinders** should be driven by constant-speed motors belted to the grinder countershafts.

(l) **Planers,** particularly those of small size, if located under a crane, should be driven by variable-speed motors. A recent development is the reversing-motor planer drive which is now being extensively tested, and promises to prove successful.

(m) **Shapers, slotters, etc.,** should usually be group-driven.

(n) **Knee and column-type milling machines** in the large sizes should be driven by variable-speed motors, especially if used in "gang" operations.

(o) **Planer-type milling machines** should be motor driven. Either the constant-speed or the variable-speed types will prove satisfactory.

10. Values of horse power required to cut metal*

Lathe-type tools

Material	Horse power required to remove 1 cu. in. per min.
Brass and similar alloys	0.2 to 0.3
Cast iron	0.3 to 0.5
Wrought iron Mild steel (0.30-0.40 per cent. carbon)	0.6
Hard steel (0.50 per cent. carbon)	1.00 to 1.25
Very hard tire steel	1.5

Drills

Material	Horse power required to remove 1 cu. in. per min.
Brass and similar alloys	0.4 to 0.6
Cast iron	0.6 to 1.0
Wrought iron Mild steel (0.30-0.40 per cent. carbon)	1.2
Hard steel (0.50 per cent. carbon)	2.0 to 2.5
Very hard tire steel	3.0

11. Determination of horse power required for machines under group drive. A table of power values for machine tools is given in Par. 12. These values are the result of tests made by the author under actual shop conditions, and apply to small and medium-sized machines only. The output of the factory where the investigation was made was light automatic machines. The parts operated on during the tests were iron and steel castings, drop forgings and bar stock. Manufacturing conditions were highly developed, and the degree of finish allowed was small. Because of these conditions the power values are still useful although they were obtained before the common use of high-speed steel in cutting tools. The values

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, pp. 199 to 209

have been checked by their application to a number of factories whose total power load was known. This showed that, for a group of machines, the sum of the power values given in the table is about 20 per cent. higher than the average working load. This is because of the intermittent service of tools for various reasons, or the departmental slip.

12. Power machine tools in groups (see Par. 11)

Kind	Size	Observed horse power; maximum	Observed horse power; average
Boring Machines:			
Bullard, single head	36 in.	0.78	0.52
Bullard, double head	42 in.	1.72	1.08
Cam Cutters:			
Brainard	No. 2	....	0.67
Brainard	No. 4	0.48	0.32
Brainard	No. 5	0.48	0.32
Lathe type, single head	....	....	0.32
Lathe type, double head	....	....	0.50
Cutting-off Machines.			
Hurlbut-Rogers	1$\frac{1}{8}$ in.	....	0.12
Hurlbut-Rogers	2 in.	0.28	0.14 to 0.18
Hurlbut-Rogers	3 in.	0.34	0.20 to 0.22
Drilling Machines:			
Prentice Bros. radial	No. 0	....	0.72
Prentice Bros. radial	No. 1	3.18	1.12
Woodward & Rogers	Sensitive single-spindle	....	0.31
Dwight-Slate	2-spindle	....	0.32
Woodward & Rogers	Sensitive 3-spindle	....	0.35
Woodward & Rogers	4-spindle	....	0.48
Woodward & Rogers	6-spindle	....	0.71
Prentice upright	16 in.	....	0.25
Prentice upright	18 in.	....	0.35
Prentice upright	20 in.	....	0.42
Prentice upright	22 in.	....	0.59
Blaisdell upright	24 in.	....	0.47
Blaisdell upright	26 in.	....	0.22
Blaisdell upright	28 in.	....	0.25
Blaisdell upright	30 in.	....	0.30
Blaisdell upright	34 in.	....	0.45
Blaisdell upright	36 in.	....	0.53
Blaisdell upright	46 in.	....	0.63
Blaisdell upright	50 in.	....	0.83
Gear Cutters:			
Brainard	No. 4$\frac{1}{2}$	....	0.15 to 0.32
Gould & Eberhardt	No. 3	....	0.20
Brown & Sharpe	No. 3	....	0.20
Grinders:			
Brown & Sharpe cutter and reamer grinder	No. 3	....	0.32
C. H. Besly & Co. Gardner grinder	No. 4	1.42	0.53
Brown & Sharpe plain	No. 11	....	0.80
Brown & Sharpe surface	No. 2	....	0.40
Brown & Sharpe surface	No. 3	....	0.50
Brown & Sharpe universal	No. 1	....	0.60
Brown & Sharpe universal	No. 2	....	0.76
Diamond wet tool grinder	....	3.29	0.97*
Leland & Faulconer wet grinder	....	....	0.41 to 0.82 †

* Carrying 1 20-in. wheel. † Carrying 2 24-in. wheels.

15. Bolt and nut machinery

Style	Size (in.)	Horse power
(a) Bolt cutters—motor A, B or C (Par. 13)		
Single	1, 1¼, 1½	1 to 2
	1¾, 2	2 to 3
	2½, 3½	3 to 5
	4, 6	5 to 7½
Double	1, 1½	2 to 3
	2, 2½	3 to 5
Triple	1, 1½, 2	3 to 7½
(b) Bolt pointers—motor B or C		
	1½, 2½	1 to 2
(c) Nut tappers—motor A, B or C		
Four-spindle..............	1, 2	3
Six-spindle................	2	3
Ten-spindle...............	2	5
(d) Nut facer—motor B or C		
	1, 2	2 to 3

16. Bolt heading, upsetting and forging machines

Motor A,* B† or C‡ (Par. 13)

Size (in.)	Horse power
¾ to 1½	5 to 7½
1½ to 2	10 to 15
2½ to 3	20 to 25
4 to 6	30 to 40

17. Boring and turning mills

Motor A, B or C (Par. 13)

Size (in.)	Horse power	
	Average work	Heavy work
37 to 42	5 to 7½	7½ to 10
50	7½	7½ to 10
60 to 84	7½ to 10	10 to 15
Size (ft.)		
7 to 9	10 to 15	
10 to 12	10 to 15	30 to 40
14 to 16	15 to 20	
16 to 25	20 to 25	

* Speed variation is sometimes desired when different sizes of bolts are headed on the same machine.

† Compound-wound, direct-current motor.

‡ Wound secondary or squirrel-cage motor with approximately 10 per cent. slip.

21. Drilling machines—multiple spindle

Motor A, B or C (Par. 12)		
Size of drills (in.)	No. of spindles	Horse power
1/32 to 1/4	6 to 10	3
1/16 to 3/8	10	5
1/16 to 1/2	10	7½
1/4 to 3/4	10	10
3/8 to 1	10	10 to 15
2	4	7½
2	6	10
2	8	15

22. Gear cutters

Motor A, B or C (Par. 12)	
Size (in.)	Horse power
36×9	2 to 3
48×10	3 to 5
30×12	5 to 7½
60×12	5 to 7½
72×14	7½ to 10
64×20	10 to 15

23. Grinders

(a) Tool, snagging, etc.—motor B or C (Par. 12)		
Wheels		
No.	Diameter wheel (in.)	Horse power
2	6	½ to 1
2	10	2
2	12	3
2	18	5 to 7½
2	24	7½ to 10
2	26	7½ to 10

(b) Cylindrical—motor A, B or C (Par. 12)

Dia. wheel (in.)	Length work (in.)	Horse power	
		Average work	Heavy work
10	50	5	7½
10	72	5	7½
10	96	5	7½
10	120	5	7½
14	72	10	15
18	120	10	15
18	144	10	15
18	168	10	15

26. Milling machines

Motor A, B or C (Par. 13)

Vertical slab milling machines	
Width of work (in.)	Horse power
24	7½
32 to 36	10
42	15

Vertical milling machines

Height under work (in.)	Horse power
12	5
14	7½
18	10
20	15
24	20

Plain milling machines

Table feed (in.)	Cross feed (in.)	Vertical feed (in.)	Horse power
34	10	20	7½
42	12	20	10
50	12	21	15

Universal milling machines

Machine no.	Horse power
1	1 to 2
1½	1 to 2
2	3 to 5
3	5 to 7½
4	7½ to 10
5	10 to 15

Horizontal slab milling machines

Width between housings	Horse power	
(In.)	Average	Heavy
24	7½ to 10	10 to 15
30	7½ to 10	10 to 15
36	10 to 15	20 to 25
60	25	50 to 60
72	25	75

31. Presses, hydrostatic wheel

Motor B or C (Par. 13)	
Size (tons)	**Horse power**
100	5
200	7½
300	7½
400	10
600	15

Presses for notching sheet iron or steel, motor A, B or C, ½ to 3 horse power.

32. Punching machines

Motor B* or C† (Par. 13)		
Dia. (in.)	**Thickness (in.)**	**Horse power**
[illegible]	[illegible]	1
[illegible]	[illegible]	2 to 3
[illegible]	[illegible]	2 to 3
[illegible]	[illegible]	3 to 5
[illegible]	[illegible]	5
1	[illegible]	5
1	1	7½
1¼	1	7½ to 10
1½	1	10 to 15
2	1	10 to 15
2½	1½	15 to 25

33. Rolls—bending and straightening

Motor B‡ or C§ (Par. 13)		
Width (ft.)	**Thickness (in.)**	**Horse power**
4	[illegible]	5
6	5/16	5
6	7/16	7½
6	[illegible]	15
8	[illegible]	25
10	1[illegible]	35
10	1½	50
24	1	50

34. Saws, cold and cut-off

Motor A, B or C (Par. 13)	
Size of saw (in.)	**Horse power**
20	3
26	5
32	7½
36	10 to 15
42	20
48	25

* Compound-wound motor.
† Wound secondary or squirrel-cage motor with approximately 10 per cent. slip on the larger sizes.
‡ Standard bending roll motor.
§ Wound secondary induction motor.

39. The direct-connected adjustable-speed reversing motor is the most recent development in motors for machine tools. It has been applied to planers, slotters, key-seaters, wire and tube drawing machines and large boring mills. Its advantages lie in increased production and saving of power. Figs. 2 to 6, inclusive show five planer drives.* These curves are drawn to the same scale and show the power required to drive "light" and with normal cuts, see Par. 38.

40. Power required by portable armature drills
(Andrew Stewart, before Glasgow Techn. College Sc. Soc.)

Size of tool	Spindle rev. per min.	Wt. of tool, lb.	Diam. hole, in.	Depth hole, in.	Time sec.	Metal	Watts	Watts per lb. metal per min.†
Breast	800	13	[illegible]	1.5	65	Cast iron	305	7,200
1 M 1	450	17	[illegible]	1.0	120	Cast iron	330	4,230
1 M 2	250	30	[illegible]	0.5	40	Steel	495	8,448
1 M 2	250	30	[illegible]	1.5	70	Cast iron	660	3,300
1 M 3	150	32	1	1.5	120	Cast iron	550	3,666
1 M 3	150	32	1	0.5	80	Steel	495	6,447
1 M 3	150	32	1¼	1.5	180	Cast iron	440	4,125
1 M 4	100	52	2	1.5	180	Cast iron	990	2,564
3 M 3	150	48	1¼	1.5	120	Cast iron	770	3,200
3 M 4	100	58	1¼	2.75	105	Cast iron	1,320	2,620
3 M 4	100	58	1¼	3.0	240	Cast iron	1,540	3,286
3 M 4	100	58	2	2.0	150	Cast iron	1,880	2,940
3 M 4	100	58	2 11/16	2.75	240	Cast iron	2,200	3,040
3 M 4	100	58	2	1.3	150	Mild steel	1,860	4,650

WOOD-WORKING MACHINERY

BY CHESTER W. DRAKE

Commercial Engineer, Westinghouse Electric & Manufacturing Co., Associate, American Institute of Electrical Engineers

SAWING

41. Band saws are replacing circular saws in most saw mills, since the saving they effect in the kerf much more than offsets their higher first cost, labor and maintenance charges. Band saws having wheels 8 ft., 9 ft. and 10 ft. diameter are in principal use and their power requirements vary widely with the kind and size of logs and the cutting speed.

42. Type of motor suitable for band saws. Induction motors, either of the squirrel-cage or wound-rotor type may be used for driving band mills, but special attention to the motor and control characteristics are necessary. The band wheels have a total weight of several tons, and when running at a saw speed of 10,000 ft. per min. have a very large fly-wheel effect. Consequently, a motor is required which has a high starting torque and is able to bring the mill to speed in about a minute. A squirrel-cage motor with a high slip (7 or 8 per cent.) will develop a high torque at starting, and besides this has the additional advantage due to its slip of allowing the band saw to slow down at times of heavy load, and give up some of its stored energy. In this way the load fluctuation on the motor and the system may be considerably reduced. A slip-ring motor gives a high starting torque, but with the secondary short-circuited has a low slip, and consequently the motor is subjected to all the instantaneous peaks of load. A permanent resistance may, however, be connected in the secondary circuit to give any desired slip. An advantage of this method is that the heat thus generated is external to

* Fair, Charles. *American Machinist*, Vol. XXXVIII, page 103.

† These figures include losses in the motor. Careful tests in which the motor losses were separated showed that the power utilized at the drill point varied from 3.13 to 4.1 kw. per lb. of mild steel per min. and from 1.57 to 2.69 kw. per lb. of cast iron per min., the low figures referring to 2-in. holes and the high ones to small holes.

Motor		Saws	Drive	Remarks
Horse power	Rev. per min.			
200	850	6–32 in.	Belted	
150	850	8–32 in.	Coupled	
75	1,700	8–24 in.	Coupled	Larger motor required for stock over 2-in. thick.
50	1,700	{ 4–18 in. 4–24 in.	Coupled	See test below
50	850	6–24 in.	Belted	Saws run 1,590 rev. per min.
30	3,480	2–6 in.	Coupled	Lath edger

Test on the above 50-h.p. coupled motor showed a friction load of 6 kw. With a feed of from 180 to 190 ft. per min., on hemlock stock, the following results were obtained:

4 cuts in 3-in. stock.................. 68 kw., peaks reaching 75 and 80 kw.
2 cuts in 6-in. stock.................. 68 kw., peaks reaching 75 and 80 kw.

47. Trimmers. The driving shafts of trimmers can be readily driven by coupled squirrel-cage motors and speeds of 680 to 850 rev. per min. are customary. The following are instances of successful applications.

Motor		Saws	Drive	Remarks
Horse power	Rev. per min.			
50	680	20–30 in.	Coupled	
50	850	21–32 in.	Coupled	Also drives transfer chains.
30	850	12–24 in.	Coupled	
5	1,120	2–18 in.	Coupled	Lath bundle trimmer

48. Slashers are best driven by standard squirrel-cage motors coupled to the saw shafts. The speed is determined by the saw diameter since it is not desirable to use a cutting speed much higher than 10,000 ft. per min. The following are typical installations.

Motor		Saws	Drive
Horse power	Rev. per min.		
50	850	14–40 in.	Coupled
40	580	6–36 in.	Belted
30	850	5–46 in.	Coupled
25	1,120	6–38 in.	Coupled
20	850	4–36 in.	Belted

49. Hogs. The rotating element of a hog is very heavy and the discussion of squirrel-cage versus slip-ring motors (Par. 42) applies here also.

Diamond Iron Works' hogs

No.	Style	Rotor		Capacity	Horse power
		Diam. (in.)	Rev. per min.	Cords per hr.	
1	B	60	650	16	65
1½	B	48	825	12	50
2	B	34	1,000	10	40
3	S	48	825	16	75

44-in. band rip and resaw. Berlin No. 282 44-in. × 4-in. wheel, 680 rev. per min., geared to a 15 h.p. 1,120 rev. per min. squirrel-cage motor. Friction load 4 kw. Resawing 6-in. to 8-in. poplar, 24 ft. per min.; average load, 12 kw.

54-in. band resaw. Mershon saw, 540 rev. per min., belted to a 20-h.p 1,120 rev. per min. squirrel-cage motor; friction, 5.5 kw. Resawing oak 4 in. to 6 in. wide, 70 ft. per min.; average load, 18 kw.; peaks, 21 kw.

Horizontal band resaw. Berlin No. 287 hopper feed, width of hopper 26 in.; belted to a 40 h.p., 850-rev. per min. squirrel-cage motor; friction load, 9 kw.; tests, sawing oak.

Width (in.)	Feed (ft. per min.)	Load (kw.)	
		Average	Peaks
13½	30	32	50
24	22	44	50

53. Circular saws

Cut-off saws		Combination benches, dado, etc.	
Diam. (in.)	Aver. h.p.	Diam. (in.)	Aver. h.p.
10–14	3	12–16	5
16	5	20	7½
*16	7½	....	....
24	7½	....	....
30	10	....	....
†32	25	....	....
36	15	....	....

Rip saws

Diam. (in.)	No. of saws	Feed (ft. per min.)	Aver. h.p.
12–14	1	Hand	5
16–20	1	Hand	7½
14–16	1	65–200	10–15
16	2	50–160	20
36	1	Hand	20
36	1	50–160	30

Self-feed rip saw. 13-in. saw, 2,250-rev. per min., belted to a 10 h.p., 1,700-rev. per min. squirrel-cage motor; friction load, 2.5 kw.

Stock	Feed (ft. per min.)	Aver. load (kw.)
1 in. oak	73	5
1 in. oak	116	7.5
1 in. oak	150	9.2
2 in. hemlock	150	12.5

Resaws

Diam. (in.)	Feed (ft. per min.)	Aver. h.p.
24–30	30–80	15
36–42	30–80	20
48	30–80	30

* Double cut-off or trimmer.
† Double automatic cut-off.

54. Jointers

Width (in.)	Aver. h.p.
8–12	2
16–24	3
30–36	5
Glue jointers	3–5

55. Surfacers

Capacity (in.) width and height	No. of feed rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
18×6	2	1	22–32	5
24×7	4	1	18–32	7.5
24×8	4	2	20–35	10
24×6	6	2	30–45	15
24×8	6	2	40–80	30
24×8	4	2	40–80	20
30×6	4	2	30–50	20
30×8	6	2	40–100	30
30×7	4	2	16–50	15

56. Planers, matchers and flooring machines

Capacity (in.)	No. of rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
9×6	6	4	40–80	30
15×6	6	4	40–102	40
15×8	4	4	30–45	30
24×6	6	4	59–104	40
24×8	6	5	40–80	40
30×8	6	4	40–80	40

Planers and matchers. Berlin No. 94 15-in. P. & M. with a 30-h.p., 1,120-rev. per min. squirrel-cage motor coupled to countershaft; friction load, 2 heads, 8 kw. Double-surfacing 12-in. wet oak at 60 ft. per min., reducing from 1¼-in. to ¾-in., required average of 30 kw., peaks 40 kw.

Hoyt No. 33 19-in.×8-in. P. & M. belted to a 30-h.p., 1,120-rev. per min. squirrel-cage motor; friction load, 2 heads, 8 kw.; 4 heads, 12 kw. Double-surfacing cypress 12 in. wide, reducing from 1-in. or 1¼-in. thick to ¾ in. thick, feed 50 ft. per min.; average load, 18 kw.; oak, same cut as above, 22 kw., peaks 32 kw.

57. Timber sizers

Cap. (in.)	No. of rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
20×12	8	4	25–85	50
20×16	6	4	25–85	40
30×20	8	4	25–85	50

For extra-heavy service, 75 h.p. is sometimes required.

58. Tenoning machines

	Aver. h.p.
Single end, hand feed, average duty....................	5
Double end, hand feed, average duty....................	10
Double end, power feed, average duty..................	15
Automatic blind slat tenoner...........................	3

59. Outside moulders or stickers

Cap. (in.)	No. of heads	Feed (ft. per min.)	Aver. h.p.
4×4	1 and 2	12–68	5
Sash	2 and 3	20–35	5 to 7.5
4×4	3 and 4	12–68	7.5
6×4	4	15–66	10
10×4	4	10–60	15
10×8	4	14–80	20
12×5	4	10–60	20
14×5	4	10–60	20

60. Mortising machines

Size of chisel or bit (in.)	Description	Aver. h.p.
[illegible] to 1	Hollow chisel sash	3
[illegible] to 1	Chisel mortiser with borer	3
[illegible] to 1¼	Horizontal automatic hollow chisel	5
Up to 2½	Vertical automatic hollow chisel	7.5
	Chain mortisers	3

61. Sanding machines

Drum sanders		
Face of drum. (in.)	No. of drums	Aver. h.p.
30	3	7.5
36·42	3	10
48–54	3	15
60–66	3	20
72	3	25
84	3	30
30–36	2	7.5
42–48	2	10
30–36	1	5
42	1	7.5

Sanders. Berlin 42-in. 3-roll Invincible belted to a 15-h.p., 1,120-rev. per min. squirrel-cage motor; friction, 3.2 kw.; sanding oak 6 in. wide, average load, 4 kw.; sanding oak 27 in. wide, average load, 8 kw., peaks, 9 kw.

Belt sanders

No. and width of belts	Aver. h.p.
2– 6 in.	3
1– 6 in.	2
1–14 in.	3
1–18 in.	5

Combination sanders

Drum and spindle	13 in.×16 in. drum 1½ to 4 in.×7½ in. spindle	Aver. 3 h.p.
Column, post or arm sanders		
8 in. diam. disc..............................		Average 3 h.p.
Disc sanders		
Two discs, 36 in. to 48 in. diam.................		Average 3 h.p.

74. Jib cranes comprise suitable jibs or booms, provided with motor-driven hoisting tackle. In some cases, also, a motor with suitable gearing is provided for swinging the jib into different positions.

75. Electric locomotive cranes comprise a jib or boom, usually carried by a turn-table which is mounted upon trucks. Frequently individual motors are provided for raising and lowering the boom, for rotating the boom, for hoisting the load, and for propelling the machine along the tracks. In other cases only a single motor is used, the different functions being set into operation through mechanical clutches.

76. Miscellaneous. Under this head may be mentioned charging cranes for open-hearth steel furnaces, skip hoists for elevating and dumping ore, coke, etc., into blast furnaces, also special cranes and unloaders for unloading bulk cargoes, such as ore or coal, from vessels.

77. Types of motors. The type of motor most commonly used for operating the various motions of cranes is the series-wound, direct-current motor. The series-wound motor is admirably adapted to the purpose because under heavy load it has the tendency to slow down, thus relieving the power station of a heavy load fluctuation; on the other hand, in the case of light loads, the motor speed increases, thus producing what is generally known as a "lively" crane. Compound-wound direct-current motors are used only in special cases. Where alternating current is available, and its conversion into direct current would entail a very considerable expense, alternating-current motors may be used. The preferable type of alternating-current motor for this service is the slip-ring type, in which resistance is introduced in the rotor circuit in order to obtain variation in speed. This type of motor affords much better results, as far as torque and speed variations are concerned, than the squirrel-cage motor, the torque of which decreases very rapidly as the voltage applied to the terminals of the primary winding is reduced. The speed range of both of these types of alternating-current motors is limited and hence they do not produce nearly so active a crane as one equipped with direct-current series-wound motors. In many large industrial plants, covering considerable areas, energy is generated and distributed in the form of alternating current. The motors which require but slight speed variation are operated directly from the alternating-current mains, while synchronous converters or motor-generator sets are installed to produce direct current for the operation of cranes, hoists, and other machines which must operate through a wide range of speed and under greatly varying load.

78. The selection of the proper normal rating of hoist motors* to be used is in general a difficult problem on account of wide variations in service requirements, particularly as to the matter of frequency of operation. As an illustration, two extreme cases may be taken: 1st, that of a crane installed in an engine room or pump house, the crane having been installed originally to assist in erecting the heavy machinery, being subsequently used only at varying and infrequent intervals for lifting parts of machinery when it becomes necessary to make adjustments or repairs; 2nd, the case of a traveling crane provided with a lifting magnet for handling pig-iron or other magnetic material in bulk, or equipped with a grab bucket for handling coal, sand, slag, etc. There are instances of the operation of cranes of this type four times per min., practically 24 hr. per day for indefinite periods, the lifted load being practically constant in value and almost equal to the rated capacity of the crane. It is obvious that in the first case cited, the heating of the motor windings presents a small problem, while in the latter case this item is of paramount importance. Of course the torque exerted by the hoist motor in lifting the maximum load which will be encountered, must be taken into consideration in both cases. If possible the cycle of operations should be considered as follows: 1st, the time required to hoist with maximum load; 2nd, the period of rest at the upper limit of travel; 3rd, the time of lowering; 4th, the period of rest at the lower limit of travel before the next cycle is started. The current required in lowering with a mechanical brake, or the current required in dynamic braking (Par. 83 and 464) must also be taken into consideration. These figures known, they may be plotted in terms of time and current, so that the square-root of the mean-square current may be

* See "Horse Power of Crane Motors," *Machinery*, Dec., 1913, page 286.

armature and the field are connected in separate circuits. On the first point of the controller, in lowering, the field is excited through a resistance which allows practically full-load current to pass through the field winding; also a considerable amount of resistance is included in the armature circuit. It will be seen that on the first lowering point the armature is shunted by the field winding and the brake winding. This naturally produces an extremely low speed. As the controller lever is moved from step to step, the resistance in the field circuit is increased, while the resistance in the armature circuit is decreased. Increase in resistance in the field circuit naturally reduces the field excitation and counter e.m.f., thus allowing the speed to increase. The resistance in the field circuit is ordinarily so proportioned that the speed can increase as much as 100 per cent. to 150 per

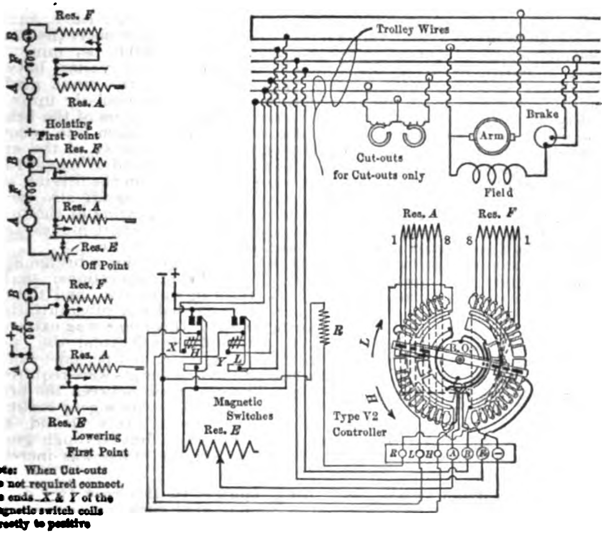

FIG. 7.—Face-plate type controller arranged for dynamic braking.

cent. above normal full-load speed. It will be seen that at all times the field is supplied with current from the mains, and at full speed this may amount to only half of the full-load current. On the other hand, the armature is also connected to the supply mains, and as soon as the counter e.m.f. reaches a value sufficient to overcome line voltage, current is actually returned to the line, so that the net current required in lowering the load is the difference between the current supplied to the field from the line and the current returned to the line by the armature. In lowering heavy loads the current returned to the line is greater than the current drawn from the line by the field, so that the lowering load is made to do useful work.

85. Slow-hoisting motor control. This type of control differs from the one illustrated in Fig. 7 only in the respect that a shunt is placed around the armature in order to reduce the speed, thus producing an extremely slow hoisting speed. This type of controller is frequently used in foundries where extremely slow speeds are required in lifting patterns from flasks, etc.

86. Limit stops are now customarily provided in connection with the hoisting motion of cranes and hoists. In the absence of a limit stop, the hoisting block, perhaps carrying a load, might be carried upward into

If, however, the overload relays continue to act when energy is applied, the operator must necessarily look for trouble in the mechanism of the crane.

90. Energy supply. In a plant in which a large number of cranes are employed, it is by no means necessary to provide generator capacity equal to the total rated horse power of all of the motors used. In a large industrial plant in which 127 cranes were installed, generator capacity corresponding to 25 per cent. of the total rated horse power of motors used on the cranes was found ample to care for the load. Where only a single crane is installed it is wise to provide generator capacity sufficient to take care of full-load on the hoist and bridge motions, leaving it to the overload capacity of the generator to take care of the current required by the trolley, in case all three motions of the crane should be operated at the same time. Naturally, the larger the number of cranes installed in a given plant where a definite cycle of operations is not carried out, the smaller may be the proportion of generator capacity to the total horse power of the crane motors.

ELECTRIC HOISTS

BY WILFRED SYKES

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91. Drums. Hoists are generally classified according to the shape of the drum. In general use are the cylindrical, the conical and the cylindro-conical drums, the last mentioned being a combination of the first two, part of the drum being cylindrical and part conical (Fig. 9). The object of the conical drum is to reduce the starting torque, as the load is exerted on the drum at a smaller radius when the cage is at the bottom of the shaft. The cylindro-conical drum is used with the same object. All other things being equal, the rope wear is less with the cylindrical drums than with other types of drums.

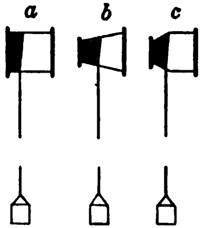

FIG. 8.—Unbalanced hoists.

92. Flat ropes. The above types (Par. 91) use round ropes. Flat ropes, generally about 0.5 in. thick, are sometimes used, the rope being wound upon itself on a reel, so that the radius at which the load is suspended gradually increases, the effect being similar to that of the conical drum. Flat ropes on reels are used only to a very small extent, on account of the excessive maintenance charges.

93. Balanced and unbalanced hoists. When running balanced the empty cage descends as the loaded cage ascends, the cages and cars balancing each other. When working unbalanced only one cage is used, and the load,

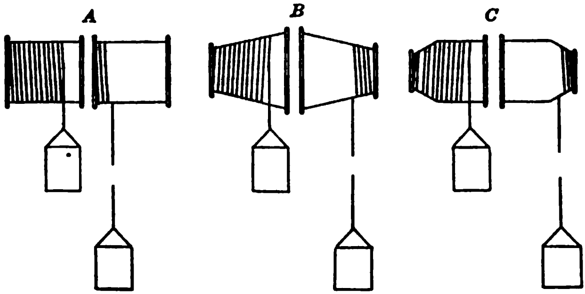

FIG. 9.—Balanced hoists.

100. Ilgner balancing system. The arrangement now most widely used, was devised by Mr. Karl Ilgner. As arranged for alternating-current supply, it consists of an induction motor with a wound rotor, coupled mechanically to a direct-current generator, which in turn supplies energy to a direct-current separately excited hoist motor. The motor-generator set is supplied with a fly-wheel of sufficient capacity to care for the peak loads. The field of the direct-current generator is separately excited, and a controller is provided so that the excitation and the polarity of the generator can be varied as desired. The field polarity of the hoist motor remains constant, so that by reversing the armature current the direction of rotation can be changed. By varying the excitation of the generator, the voltage applied to the armature of the hoist motor can be varied, and in turn the speed of the hoist.

101. Action of the automatic regulator. A regulator is provided for automatically inserting resistance in the rotor circuit of the induction motor, thereby reducing the speed of the motor-generator set, which causes the fly-wheel to give up part of the energy stored in it. The rate at which the speed is changed depends upon the difference between the input that is to be maintained on the induction motor and the power required to drive the generator. When the load on the generator is reduced below the value for which the automatic regulator is set, the fly-wheel speed is increased by automatically removing resistance from the rotor circuit, energy being stored in the fly-wheel in order to enable it to carry the peak load, due to the succeeding cycle.

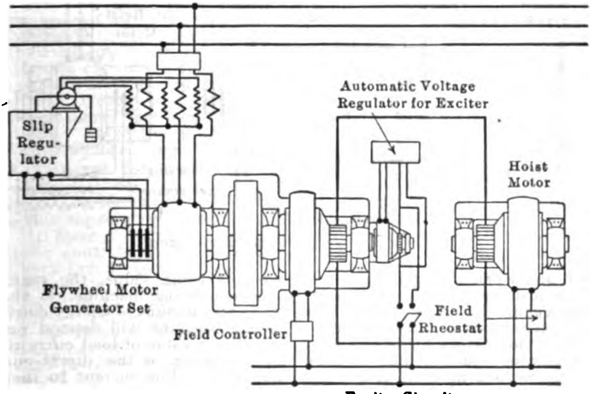

FIG. 10.—Ilgner balancing system.

102. Details of Ilgner balancing system. This system provides not only for power equalization, but also for the control of the hoist motor by the manipulation of the generator excitation, thereby eliminating rheostatic losses, and the difficulty of controlling large machines. The general arrangement of this scheme is shown by Fig. 10. In practice the speed of the fly-wheel set is varied from 15 to 20 per cent. during a hoisting cycle. High-speed fly-wheels with peripheral speeds reaching 25,000 ft. per min. are used in order to minimize the weight.

103. The losses with the Ilgner system are comparatively high, and it is seldom that an over-all efficiency of more than 50 per cent. is realized from the combined electrical and mechanical equipment. This efficiency decreases when the hoist is operated below its normal capacity, due to the constant no-load loss of the fly-wheel motor-generator set. However, for important hoists, the advantage of equalizing the input, and

and consequently the fly-wheels can be comparatively light. The machines of the converter equalizing equipment need be only large enough to deal with the load variations from the mean value, and under ordinary circumstances, the capacity need not be more than about one-half that of the motor-generator set for the same duty. The equalizing equipment is quite independent of the hoisting motor, so that it may be out of service without cessation of hoisting. However, in this event the peak loads will be felt on the line. With the Ilgner system the hoist is directly dependent upon the motor-generator set.

107. Significance of the starting method. The main difference between the two systems is that the Ilgner method provides for starting the hoist motor by voltage control without any rheostatic losses while the converter system makes no provision for doing so. When considering the economy of both systems, this difference must be taken into account as starting losses are often a large proportion of the total input. The question of starting is very important with large hoists, and on this account the Ilgner system is preferred for heavy work.

108. Control for alternating-current motors. Magnetic-switch controllers are used to a considerable extent. Liquid controllers for the rotor circuit are also used, and these have the advantage of providing smoother acceleration and of being simpler in construction.

109. Types of switches in use. For the control of the primary, both oil and air-break magnetic switches are in use. For circuits of 550 volts and under ordinary magnetic switches are quite satisfactory. For 2,200-volt motors, special air-break switches are in use, and when properly designed are preferable to other types on account of the accessibility of the contacts and their ability to withstand hard service. Oil switches are used to a considerable extent but for very severe service they must be very liberally rated, otherwise there is danger of explosion, due to the heat generated in the oil. Drum controllers can be used only for small hoists requiring motors not larger than 75 h.p., and are not at all suitable for severe operating conditions. Magnetic-switch controllers can be used for all sizes, but liquid controllers are used only for motors of about 300 h.p. and above.

110. Control for direct-current hoist motors. Drum controllers are satisfactory for direct-current motors under 100 h.p., providing the service is not too severe. Magnetic switches should be used for motors above this capacity. Liquid controllers are not satisfactory for direct current. In cases of very large hoists with peak loads of 1,000 h.p. and above, rheostatic control, for either direct-current or alternating-current motors is not very practicable. When power equalization is not required, a motor-generator set is used without a fly-wheel. In every respect the operation is the same as with the Ilgner system, except that the speed of the set is not varied. The efficiency of such an arrangement is often greater than that of the hoist with rheostatic control, and the maintenance is usually less than that of a large rheostatic controller, although the amount of apparatus involved is greater.

ELEVATORS

BY DAVID L. LINDQUIST

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111. Classification of electric elevators. There are two general classes of electric elevators, namely, those with winding drums, and those with traction sheaves. The drums of the former type are spirally grooved, the cables winding or unwinding as the elevator is raised and lowered. With elevators having winding drums it is advisable to restrict service to car speeds under 200 ft. per min. and for travels less than 100 ft. For elevators of the latter class, the sheaves are straight grooved for receiving the cables, the car being raised or lowered because of friction existing between sheave and cables. Elevators of this class, are especially adapted to service requiring car speeds of from 200 ft. per min. to 700 ft. per min. inclusive, regardless of length of travel.

112. Roping and counterbalancing of elevators with winding drums. Necessary connections are usually made between drum and car and counter-proportioned to approximately 70 per cent. of the actual weight of the car, the weight of the back drum counterbalance being equal to the difference between the total weight and that of the car counterbalance. Either method of counterbalancing imposes on the motor a net maximum load of approximately two-thirds the rated capacity of the elevator.

For car travels in excess of 100 ft. it is advisable to compensate variation of load on motor, produced by change in position of cables during run, by means of a compensating chain attached from the car to the middle point of the hatchway, as shown in Fig. 12, or attached from car to counter-balance as indicated in Fig. 13. The following formulas derive total compensating weight required, where h = weight of hoist ropes per ft.; dw = weight of drum counterbalance ropes per ft.; cw = weight of car counterbalance ropes per ft.; c = weight of compensating chain (or ropes) per ft. With compensating chain attached to car and middle point of hatch: $c = 2(h + dw + cw)$. With compensating chain attached to car and counterbalance: $c = (h + dw + 2cw)/2$. For installations employing the single counterbalance only; $cw = 0$.

113. Roping and counterbalancing of elevators with traction sheave From Fig. 14, which clearly indicates roping required by what is known as the 1 : 1 traction-sheave type, it will be noted that the single length of ropes used are directly connected to car and counterbalance at either end. By the use of a secondary or idler sheave these ropes are passed over the traction sheave a second time as a means for increasing rope contact, which, under the influence of the combined weight of car and counterbalance, provides the adhesion requisite to elevator service.

The foregoing arrangement corresponds to that used for the 2 : 1 traction-sheave type with the exception that the ropes, instead of being directly connected to car and counterbalance, are passed under traveling sheaves located at the upper end of both car and counterbalance; from this point they are extended vertically to the top of the hatchway and there securely and permanently anchored. This latter roping produces a decrease in car speed with a consequent increase in the lifting capacity. Fig. 15 represents the 2 : 1 roping arrangement.

One of the striking advantages resulting from this arrangement of ropes and method of driving them, is the total loss of traction obtained if either car or counterbalance is obstructed in its descent, or bottoms on its respective oil buffer, causing complete cessation of all car motion even though the driving member may continue to revolve. This property of the traction-sheave elevator constitutes an extremely important and effective safeguard by enabling the absolute fixing of the car travel between two given limits, inasmuch as with proper roping the car will be brought to rest on its oil buffer before the counterbalance comes into contact with the overhead work and *vice versa*. A further advantage of the traction-sheave elevator lies in the fact that the faces of the sheaves are entirely independent of the height of the building.

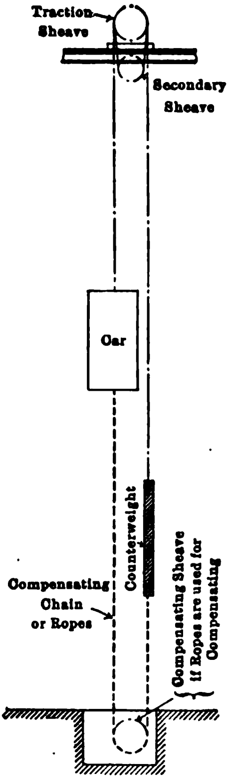
Counterbalancing must in all cases be proportioned for an equal margin of safety to counteract the tendency to slip on both up and down direction of travel under maximum load conditions. Where there is a considerable surplus of traction, however, the weight of the counterbalance should be made dependent upon the average loads in the car, which, for this type of elevator, usually range from approximately 33 to 45 per cent. of the maximum. Ordinarily, the total weight of the counterbalance should equal that of the car plus from 33 to 45 per cent. of the maximum load in the car.

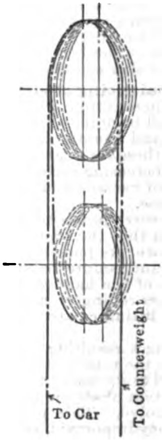
Elevators with traction sheaves should in all cases be provided with rope compensation and with connections arranged in accordance with Fig. 14; the weight per hatchway ft. of the compensating ropes should equal approximately the weight of the hoist ropes per hatchway ft. minus one-fourth the weight per ft. of the electric control and lighting cables.

114. Electric elevator machines. The machines used for driving the two types of electric elevators mentioned are distinguished by their methods of power transmission between motor and winding drum or traction sheave, namely, (a) worm gear; (b) worm and spur gear; (c) helical or herring-bone gear; (d) 1 : 1 gearless traction; (e) 2 : 1 gearless-traction machines. All of these machines are preferably arranged for location over the hatchway in each and every case, although, under certain conditions, they can be arranged for location at the base of the hatchway.

115. Worm-gear machines. These machines are used for both passenger and freight service and may be arranged with either winding drum or traction sheave. For the smaller sizes, known as dumbwaiter machines, duties ranging from 500 lb. at 100 ft. per min. to 100 lb. at 500 ft. per min. are possible, while in the larger sizes duties rarely exceed from 10,000 lb. at 100 ft. per min. to 4,000 lb. at 400 ft. per min.

In order to preserve alignment, all parts should be assembled on a ribbed bedplate extending underneath the entire machine. The armature shaft





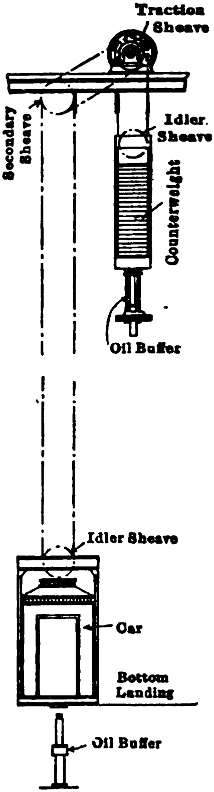


FIG. 14.—Roping arrangement for use with traction sheave.

FIG. 15.—Two to one roping arrangement.

of the motor is usually coupled direct to the worm shaft, the face of this coupling being utilized as the brake pulley. The worm and shaft should be solid and integral and of high-grade steel, the worm meshing with a bronze-rim worm wheel attached to a cast-iron spider. This spider, being directly and mechanically connected to the winding drum or traction sheave, renders power transmission at this point entirely independent of keys. Self-aligning ball thrust bearings are provided on the worm shaft.

116. Worm and spur-gear machines. The two types may be classified as safe lift machines and geared freight machines, the former being a special adaptation of the worm-gear machine when it is desired occasionally to lift loads greater than the normal and at considerably reduced speeds. This type is generally installed in office buildings, where, with the special arrangement applied to one or more of the ordinary passenger elevator machines, the handling of safes averaging from 4,000 lb. to 9,000 lb. in weight at a slow rate of speed, is greatly facilitated. To accomplish the increase in lifting capacity, a special provision is made for placing necessary gears in mesh between the armature and worm shaft, thereby reducing the car speed and increasing the lifting capacity in direct proportion to the ratio of the gearing inserted. By this method, therefore, and usually with a slight addition in counterbalance, the safe-lift loads are carried without requiring more current from the line than during normal operation. Geared freight machines differ from the worm-gear type by the addition of a single spur-gear reduction between the worm gear and the winding drum, thereby constituting them essentially slow-speed machines with relatively large lifting capacities.

117. Helical gear or herringbone gear machines. These machines, which can be arranged for use with either winding drums or traction sheaves, are provided with a single gear reduction to the motor by means of the helical or herringbone type of gear, usually made in accordance with the Wuest method. Such gears permit a larger ratio of reduction with greater efficiency than can be obtained with ordinary spur gears. The motor speeds usually range from 300 to 600 r.p.m.

118. Gearless traction machines, 1:1 ratio. This machine represents a combination of extreme simplicity, maximum economy and highest efficiency. Briefly, it is a two-bearing electric machine, the armature, traction sheave and brake pulley being contained on the same shaft, all parts being compactly grouped on a cast-iron bed. The motor is of the plain shunt-field, slow-speed type of about 60 r.p.m. transmitting energy direct to the traction sheave. Contrary to general belief, these motors have the remarkably high efficiency and a distinctive procedure has been to arrange design with a view to realising the highest efficiency (about 90 per cent.) at half rated capacity. This figure corresponds with the average loads for this class of service, the full-load efficiency being approximately 87 per cent. Frequently these machines are provided with ball bearings as a means for further increasing the efficiency and decreasing the space required.

Machines of this type should be located over the hatchway whenever it is at all possible. They are used for car speeds of from 500 to 750 ft. per min. with loads ranging from 2,000 to 3,500 lb. inclusive. To date only machines employing direct-current motors have been produced.

By means of a special arrangement, the regular machines can be converted so as to enable the lifting of safes weighing from 5,000 to 8,000 lb. This arrangement includes the placing of a second magnet brake in operation and also the adding of extra weight to the regular counterbalance. When lifting safes, maximum field strength of motor is utilized, producing a proportionately slow car speed.

119. Gearless traction machines, 2:1 ratio. All mechanical features of these machines correspond to those of the 1 : 1 gearless-traction type. They have been designed for traction sheave elevators requiring lower car speeds than obtained with the 1 : 1 machine without the necessity of gear reductions the car speed reduction being produced by the 2–1 roping arrangement previously described. The machines have been designed for direct-current service only, using shunt-field motors of from 80 to 140 rev. per min., with resultant car speeds of from 250 to 450 ft. per min., and they have been installed for capacities up to 11,000 lb. passenger load. By an arrangement similar to that with which the 1 : 1 gearless-traction machines are equipped, these machines can also be used for safe lifting.

120. A common characteristic of all elevator motors is that they must be specially constructed to withstand repeated stresses produced by frequent starting and stopping. In general, however, the performance of alternating-current and direct-current motors differ to such an extent as to necessitate their separate consideration.

121. Direct-current motors. This class of motors must be designed for sparkless commutation at starting, stopping and reversal of rotation under all fluctuations of load within their rated capacity, and be capable of exerting a heavy starting torque with minimum requirements as to starting current, especially where frequent starts and stops are made, in order to reduce the energy consumption and the reaction on the generating plant. Because of these requisite features, commercial motors are rendered generally unsuitable. As a means for reducing starting currents, those motors used for driving geared elevator machines, and usually operating at from 300 to 900 rev. per min., are arranged to start as compound-wound motors having a heavy series field which should be cut out, usually by a short-circuiting process, as the motor speed increases. At full speed, therefore, the motor operates as a plain shunt-field type.

Because of the high self-induction of the field winding required by motors used for driving the 1 : 1 and 2 : 1 gearless-traction machines, which generally operate at from 60 to 140 rev. per min., when at full speed, the fields are connected permanently across the supply lines, with reduced current when machine is at rest; this procedure shortens the length of time required to bring the field to full strength on starting. Such a method of field connection materially reduces motor starting current. For direct-current types of motors, starting torque and starting current are usually twice the rated torque, and not in excess of 125 per cent. of the current at rated capacity.

122. Polyphase slip-ring induction motors. This type represents beyond question the most satisfactory alternating-current motor for elevator service. The rotor, which is polar wound, is connected to a series of slip-rings, thereby permitting the insertion of an external resistance in the rotor circuit, resulting in large starting torque with reasonably low starting current. Since the resistance of a slip-ring motor is external, it may be adjusted for several values of starting torque, and good elevator practice, therefore, is to provide a larger external-rotor resistance than is required for necessary starting torque at full-load, thus limiting first inrush of current to a predetermined amount, with connections so arranged that if motor fails to start the imposed load, rotor resistance will be gradually short-circuited until required starting torque is obtained. As elevator loads are frequently considerably under full-load values, the maximum starting resistance allows the elevator to start with a current much lower than that required with full-load in the car. With the external rotor resistance it is possible to use a rotor winding of extremely low internal resistance, and since the external resistance is completely short-circuited when motor attains full speed, resultant slip and temperature rise are reduced to a minimum, and high running efficiency is obtained. The speed variation of this type of motor is very small, and it fulfills the best obtainable balance between the three values of starting current, slip and running efficiency, which are of extreme importance when applied to elevator motors.

123. Two-speed polyphase slip-ring induction motors. For car speeds in excess of 200 ft. per min., and where conditions demand accurate floor stops, it is advisable to use two-speed motors. These motors, which have been used successfully, contain double windings on both the stator and rotor. The switches governing them are mounted on the controller panel, being electrically and mechanically interlocked in order to prevent confliction. Starts are always made with the high-speed winding, and connections to the slow-speed winding, which is used for stopping purposes only, are so arranged that the motor is electrically retarded to a predetermined slow speed of usually $\frac{1}{3}$ to $\frac{1}{4}$ of full speed.

124. Polyphase squirrel-cage induction motors. Squirrel-cage motors are generally undesirable for elevator service except in the smaller sizes. With motors of this type, the rotor winding is permanently short-circuited, thus preventing the employment of external resistance at starting. In order to prevent the possibility of starting currents becoming excessively high, it is therefore necessary to wind the rotor with self-contained resistance, this method resulting in high slip, comparatively low efficiency and a high temperature rise, especially when the motor is operating frequently. Since rotor resistance is permanently fixed, the motor starting current rises to a maximum, with each start, irrespective of load. Motors of this class should only be used on a power line, where the high starting current required is not objectionable and where the service is sufficiently light to eliminate the possibility of danger from overheating.

125. Single-phase motors. Up to the present a type known as the repulsion-induction motor alone has proven successful and in sizes up to and including 15 h.p. These motors, which start as one of the repulsion type, are provided with a centrifugal governor, usually located within the armature core, so designed and adjusted that at about 80 per cent. of full speed the rotor winding is automatically short-circuited, and the motor operates as if it were of the simple induction type. These motors cannot be reversed while operating, as induction motors. Devices are required to prevent change of connections until speed has dropped below that point at which the repulsion connections are re-established in order that reversal of rotation may become effective. Although starting currents are comparatively high, this condition is not objectionable in the smaller sizes, and in the larger sizes the starting current may be appreciably reduced by an external resistance in the stator circuit so connected that it is effective at the moment of starting and during the first period of acceleration.

126. Brakes. All elevator machines are equipped with brakes for the purpose of assisting in stopping and holding the car securely at a landing, under any and all conditions of loads up to and including the maximum specified. The brakes, which must be so designed as to be equally effective for either direction of rotation, generally consist of two separate and independent shoes, lined with leather or asbestos preparations, and actuated by heavy helical steel springs. Brake release should be obtained by means of an electromagnet, as this method enables the making of such connections that the brake will be instantly and positively applied on failure or interruption of current supply. See Par. 459 to 463.

127. Methods of control. The controlling apparatus of an elevator constitutes one of its most important features, including devices for establishing direction, for producing proper acceleration, retardation, and speed regulation, and also including the necessary safety appliances. Usually slate panels bolted to floor standards are provided, the switches being mounted on its face with connections to these switches, and all resistances located on the rear. All contacts of the various safety devices are usually connected in circuit with the holding coil of what is known as a potential switch, and, since all current to the controller and machine is carried through the contacts of this switch, the operation of any one safety feature immediately interrupts all current to the equipment. This switch also constitutes a no-voltage circuit breaker and an excessive drop in voltage will cause the switch contacts to open. The motor circuits are completed by the reversing switches, two in number, one for the "up" and one for the "down" direction, respectively. The brake circuits are made simultaneously with the closing of either direction switch. In order to prevent conflict, reversing switches are generally electrically or mechanically interlocked.

128. Automatic starting. It is advisable, with direct-current elevators, to arrange the stepping-out of the armature starting resistance entirely independent of the operator, and by this process eliminate the damage which would result from a reduction of this resistance at too high a rate. As a means for reducing energy consumption, however, starting resistance should be stepped-out as rapidly as the load on the motor permits; this is accomplished by means of either series relay magnets or magnets dependent on the counter-electromotive force of the motor for operation. See article on "Motor Control" elsewhere in this section.

129. Dynamic braking. Except with the small-capacity machines, the wiring of direct-current controllers invariably includes a dynamic-brake circuit which is obtained by introducing a resistance across the armature terminals on stopping. The stopping field in some cases is obtained by having the shunt field (permanently in series with a limiting resistance) connected directly across the supply line. In other cases it is obtained by providing an extra low-resistance shunt field; in the smaller machines the residual magnetism of the field poles is sufficient. Although connecting the field permanently across the supply line slightly increases energy loss, an important safety feature is gained, for with such connections it becomes impossible to attain excessive car speeds either up or down should, for any reason, the machine brake fail to apply. By various methods stopping resistance is automatically stepped-out as the load on the motor permits, thereby strengthening the dynamic-braking effect. As explained, single-counter-weight immediately causes sufficient loss of traction to prevent further motion of the car and counterbalance.

136. Final hatchway-limit switches. To guard against the possibility of damage through disarrangement of the automatic terminal-stopping device, final limit switches are located, one each, beyond the terminal landings, and are operated by a cam on the car, in case the car overtravels to a point at which these switches become operative. The contacts of these switches are also placed in series with the holding coil of the circuit-breaker, causing immediate interruption of current to the machine when opened.

137. Governor switches. With high-speed elevators, regulating devices are usually provided, these being operated by a speed governor. These devices control car speed by means of field regulation of the motor, and are usually applied when the car speed exceeds normal by certain predetermined amounts. One or more speed-regulating switches are used, the number depending upon the average speed of the car, and, by their use, maximum speed variation is retained within certain predetermined limits. Governors should preferably be provided with a breaking contact adjusted to open at a car speed slightly lower than that at which the car safeties are set to operate. Therefore, connecting this contact in series with the holding coil of the potential switch or circuit-breaker, usually stops the elevator by interrupting all current to the motor, without the necessity of applying the car safeties.

138. Car safety switch. All electric elevators should be provided with a small enclosed switch, located within the car and so connected in the controlling circuits that current to the machine will be interrupted when it is opened. This switch is furnished for emergency purposes only.

139. Car-safety devices. The expression "car safety" is usually applied to that form of safety which is designed to bring the car to rest by locking it to the guide rails, in case excessive speed has been attained, irrespective of the cause. All elevators should be equipped with a device of this nature. The application of car safeties should be made dependent upon on a centrifugal or inertia governor, adjusted with a definite and fixed relation to the speed of the car and arranged to operate at approximately from 30 to 50 per cent. above normal car speed. The general practice is to support the safety device within the lower member of the car frame, with the governor substantially supported at the top of the hatchway, although, in some cases, specially designed governors are mounted on the car. With the governor located over the hatchway, it is driven by an endless rope attached to the car and safety mechanism in such a manner that, in case of excessive speed, the governor holds or grips this rope and the safety is applied, usually by means of a drum, sheave or lever arrangement.

Under certain building conditions, namely: where a room or vault is located directly underneath the hatchway, it is advisable to furnish a guide grip safety for the counterbalance as well as for the car, in order to prevent damage such as might otherwise occur through the breaking of the ropes. On all of the recent higher class installations counterbalance safeties have been furnished even where the foregoing condition has not existed.

140. The number of elevators required in a building depends on several conditions, namely: height of building, relation of area of building to its height, net rentable area in sq. ft. per floor, character of elevator service required by prospective tenants and relative location of building. In average office buildings it is not considered good practice to attempt to serve more than from 18,000 to 24,000 sq. ft. of rentable floor area per elevator. The mileage of each elevator in a modern office building ranges from 15 to 40 miles per day, depending on the character of service and type of elevators used.

141. General consideration of energy consumption. Usually, it is safe to assume that the loads distributed by an elevator to the different floors of a building are the same, approximately, as those loads returned to the starting point, and with such load conditions the work done consists merely of overcoming the friction. Of greater importance, therefore, in the energy consumption, is the power expended in imparting the kinetic energy required to bring the masses up to speed, and the machine which will register the lowest power consumption must have a low moment of inertia together with a low value of friction.

145. The average performance of some existing installations in actual service

Machine type	Specification		Rise	Class of service and building	Energy cons. kw-hr. per car mile
	Control	Maximum lifting capacity			
Worm-gear and drum...	Magnet, direct current	2,000 lb. at 300 ft. per min.	140 ft.	Hotel, passenger service	3.3
Worm-gear and drum...	Magnet, direct current	1,500 lb. at 275 ft. per min.	113 ft.	Small building, passenger service	2.35
Worm-gear and traction-sheave	Magnet, direct current	3,000 lb. at 300 ft. per min.	165 ft.	Large department store passenger service, stop at each floor	8.71
Worm-gear and traction-sheave	Magnet, direct current	3,000 lb. at 300 ft. per min.	170 ft.	Small office building passenger service	5.1
1 : 1 traction.........	Magnet, direct current	2,500 lb. at 550 ft. per min.		Large office building passenger service. Local service from 1 to 14 only.	4.0
				Express service from 1 to 25—no stops below 15.	2.85
2 : 1 traction..........	Magnet, direct current	3,000 lb. at 450 ft. per min.		Small office building passenger service	3.91

All of these readings are for direct-current elevators only. From 20 to 30 per cent. more power consumption will be required by alternating-current elevators under the same conditions.

POWER PUMPS

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GENERAL

148. Classification of power pumps. Power pumps for all practical purposes can be divided into two general classes—displacement pumps and centrifugal pumps. Displacement pumps may be further divided into reciprocating pumps and rotary pumps, while centrifugal pumps may be divided into turbine and volute pumps. As will be shown later, the two classes of displacement pumps differ radically in design and are really distinct classes, while the difference between turbine and volute pumps is a difference of detail of construction, rather than a difference of type.

149. Calculation of the horse power required, is based upon a consideration of the opposed head (expressed in ft. or lb. per sq. in.) the pump delivery (expressed in gal. per min. or cu. ft. per sec.); and the efficiency of pump and mechanical transmission. Pump efficiencies vary with the different types, sizes, and working conditions. See Par. **154**, **157**, and **165**.

The head will include the static head pumped against and also the head of pipe friction. A calculation of required horse power should always consider the latter component of total head if the pipe is of considerable length. **Friction head** may be calculated with reasonable accuracy by means of Eq. 3. Accuracy within 6 per cent. may be expected for new, smooth pipes, while accuracies within 20 per cent. may be secured by its use on practically all pipes met in common practice. This expression is a modification of the well-known "Exponential" formula for straight smooth pipe.*

$$h_f = 1.6\frac{G^{1.87}}{d^5}\left(\frac{L}{1{,}000}\right) \tag{3}$$

where G is the delivery in gal. per min.; L is the total length of the pipe in ft.; d is the inside diameter of the pipe in in.; and h_f is the friction head, expressed in ft., for the *whole* pipe length. The horse power required to pump a certain quantity of water through a given length of pipe of known diameter against a given head is expressed as follows:

$$\text{h.p.} = \frac{G \times H}{3{,}950 \times \text{Efficiency}} \tag{4}$$

where G is the delivery in gal. per min., and H is the sum of the static head and the friction head, both expressed in ft.

For use in these formulas it is well to note that 1 cu. ft. per sec. corresponds to 448.8 gal. per min.; also a pressure of 1 lb. per sq. in. corresponds to a head of 2.304 ft., for water weighing 62.5 lb. per cu. ft.

DISPLACEMENT PUMPS

150. Slip. In all displacement pumps, the volume of liquid pumped is always less than the piston displacement, or, in the case of the rotary pump (Par. **156**) the displacement of the rotating element. This difference is due, partly, to leakage past the piston (in the case of the reciprocating pump), or the rotating element (in the case of the rotary pump), and partly due to leakage through the valves. The difference between the displacement of the moving part (piston or rotating element) and the volume of water discharged, is called the slip, and is usually expressed in per cent. of the total displacement. This slip may vary from 2 per cent. in a new pump to 50 per cent. in a badly worn pump. Generally speaking, anything under 5 per cent. may be considered fairly good performance for pumps that have been in service any length of time.

151. Effect of speed on capacity of displacement pumps. Neglecting slip, the capacity of all types of displacement pumps varies directly with the speed, regardless of the head pumped against. For constant head, the horse power required varies almost directly as the speed and, therefore, as the capacity. This, of course, is not strictly true, for the pump efficiency

* Moritz, E. A. *Eng. Record*, Dec. 13, 1913.

fficiency increases with the capacity of the pump, for the same reason that he efficiency of similar pieces of apparatus increases with the size.

155. Reciprocating-pump types. Most displacement pumps are of he reciprocating type. In very small sizes, they are generally single-cylinder umps, while in the larger sizes they are more frequently triplex pumps. While most manufacturers of this type of pump build duplex pumps, the atter have not found favor to the same extent that the other two types have. ll simplex, duplex and triplex pumps are built in both the single-acting and ouble-acting pattern, *i.e.*, built to discharge only during one stroke of each evolution or during both strokes. It should be noted that in the case of he **single-acting pump,** the simplex pump gives one impulse, the duplex wo and the triplex three impulses per revolution, while in the case of the louble-acting type, the simplex gives two, the duplex four and the triplex ix impulses per revolution. Where uniformity of discharge and absence of pulsations is of primary importance, this feature will have a very direct bearing on the type of pump selected.

156. Rotary pumps in their essential parts consist of two rotating elements, sometimes called impellers or cams, enclosed in a casing. These two elements "mesh" in much the same manner as a pair of gears, bearing on each other in line contacts. Consequently, any wear that occurs cannot be compensated for by packing or by adjustment of the moving parts. The slip in this type of pump is caused by the leakage through the line contact of the impellers and through the clearance space between the ends of the impellers and the pump casing. While these pumps do not require priming, they frequently have a small connection from the discharge pipe back into the pump casing to "seal" the joints between the impellers, as well as the small clearance space between the impellers and the casing.

These pumps are primarily designed for low-head work and show their greatest efficiency at low heads. When used for high-head work, it is generally for intermittent service, such as fire-pump service. They probably find their greatest field, however, in pumping heavy oils, liquid tar, syrup and liquid food products of various kinds. The speeds are usually so low that motors of ordinary speed must be geared or belted to the pump shaft.

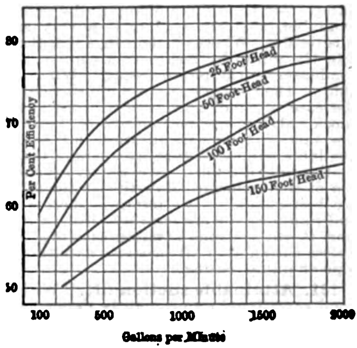

Fig. 21.—Efficiency curves of rotary pumps under various heads.

157. Efficiency of rotary pumps. Typical efficiency curves of this type of pump are shown in Fig. 21. These curves, like the curves in Fig. 20, do not represent the performance of a single pump, but rather the efficiencies of a series of pumps, designed for definite conditions of capacity and load, plotted in a single curve.

CENTRIFUGAL PUMPS

158. Mechanical construction. Centrifugal pumps for low heads are almost always of volute type, but manufacturers and designing engineers apparently differ as to the best practice to be followed for pumps discharging against higher heads. The turbine and the volute types of pump use substantially the same type of impeller. The difference between the two types lies in the design of the water passages of the casing. The volute pump, as its name implies, has these water passages built in the form of a volute, increasing in size toward the discharge opening. For the lower heads, the velocity of the water is comparatively slow and there is little or no "churning" and "eddying." Moreover, as this type of pump is cheaper to build than a turthe peripheral speed of the impeller increases, either on account of larger diameter or of higher rotative speed, the allowable head per stage increases correspondingly. When several centrifugal pumps are installed in the same station, they may be so connected that by the operation of a few valves, the pumps can be operated in series against a head aggregating the combined working heads of all the pumps, the capacity remaining the same as for one pump; or they may be operated in parallel, giving the total combined capacity, the limiting head in this case being the same as for a single pump.

163. The up-keep expense of centrifugal pumps is usually small for the reason that the only moving parts in contact are the shaft and bearings. The clearance between the impeller and casing is almost always greater than the permissible wear of the bearings, so that there is little likelihood of the two coming into contact. Even if they did, this would probably be detected and the pump shut down before any damage was done.

High-head conditions require high impeller velocity, which gives high velocity to the water leaving the impeller. In order to obtain good efficiency these conditions demand high velocities in the diffusion chamber (if there be one) and in the volute. High velocity of water results in rapid corrosion of cast iron, the usual material used for volute pumps. This corrosion occurs wherever the water at high velocity comes in contact with the iron, and particularly so wherever a sudden change in direction of flow occurs which will cause shock and the formation of eddies. However, it is often found that the efficiency of centrifugal pumps increases slightly after they have been in service for a time and this is due to the scouring action of the water on the surface of the water chambers.

164. Piping connections. From the principle of operation of centrifugal pumps and especially of turbine pumps, the velocity in the pump casing is very likely to be higher than good practice would permit for velocity of water in pipes, consequently the size of the pipe connection should be calculated on the basis of allowable velocity in the pipe rather than simply to make the connection of the size of the suction and discharge openings of the pump. To avoid shock, due to sudden change of section of the pipe, this change in size of pipe should be made by means of a standard "increaser" or "reducer," and this fitting should be installed at the pump opening. As already pointed out, the suction connections must be absolutely air tight if satisfactory operation is to be obtained. Incidentally, also, the packing glands must be drawn up tight, but only tight enough to prevent leakage, care being taken to avoid excessive friction on the shaft at this point. Some pumps have a connection from the discharge chamber to the glands in order to keep them under a "**water seal**" at all times. When this connection is provided, the glands should be loose enough to permit constantly a slight leakage.

165. Characteristics of centrifugal pumps. Fig. 22 shows typical curves of efficiency of standard centrifugal pumps designed for various heads and capacities. These curves may be compared with the curves of Fig. 20 of reciprocating pumps. Figs. 23 and 24 show the characteristic curves of typical centrifugal pumps. Attention is called to the slope of the so-called "capacity-head" curve in the two cases. In Fig. 23, the highest head is the "shut-off pressure" and the curve falls from this point on. In Fig. 24, the pressure rises at first above the "shut-off pressure" and then falls as the capacity is increased. While the shape of the curve depends primarily on the shape of the impeller vanes, it will be found in general, although by no means in every case, that volute pumps will show a curve similar to Fig. 23 and turbine pumps a curve similar to Fig. 24. With a head-characteristic curve similar to that in Fig. 23, the horse-power curve usually reaches a maximum slightly above normal capacity and then drops off. This feature is very important in the selection of a pump for service where the head is likely to be materially reduced at times, as it will prevent the motor from being overloaded. A pump with the characteristics shown in Fig. 24 should be used only where there is no likelihood of its being operated at heads greater than, equal to, or approaching the "shut-off pressure," or where the head is likely to be reduced to a value considerably below the normal working head. At heads equal to, or greater than the "shut-off pressure," there are two capacities corresponding to each condition of head. At these points, the operation becomes unstable with a probability that the pump will discharge intermittently, the water surging up and down in the discharge pipe. With

AIR COMPRESSORS

BY JOSEPH H. BROWN, JR.

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167. Rating. The rating of air compressors is made on the basis of the piston displacement of free air per min., and in designing a motor drive, the first problem which arises is the determination of the power output required of the motor for the compressor operating under the desired conditions.

168. Measurement of discharge. The relation between the piston displacement and the amount of air actually delivered, has been taken, in the past, from indicator cards, but this method is extremely inaccurate, since slippage due to leakage past the piston rings and leakage back into the cylinder through discharge valves, cannot be detected. As a matter of fact, these leakages tend to make an apparently better card and to increase the apparent volumetric efficiency. Recent tests have been made by discharging the compressed air through orifices and calculating the quantity of free air delivered per min. by Fliegner's formula (Par. 169).

169. Fliegner's formula may be stated as follows: $G = (0.53AP)/(\sqrt{T})$, where G = flow in lb. per sec., A = area of orifice in sq. in., P = absolute pressure (in lb. per sq. in.) of air behind the orifice, and T = absolute temperature (deg. Fahr.) of the air behind the orifice.

The weight of 1 cu. ft. of air is found by the following formula: $W = 1.325B/T$, where W = weight of 1 cu. ft. of air, B = barometer reading in in. of mercury, and T = absolute temperature (deg. Fahr.) at the compressor intake.

The delivery of cu. ft. of free air per min. then equals $G \times (60/W)$.

170. Efficiency. In practice it is found that compressors with mechanically operated rotary inlet valves show volumetric efficiency, varying from 91 per cent. at 100 rev. per min. to 88 per cent. at 188 rev. per min. Piston inlet machines at 100 rev. per min. give 88 per cent. efficiency, and at 188 rev. per min., 79 per cent.

The above figures may be used in determining the actual amount of air delivered by the compressor. The power required per cu. ft. of air depends upon the type of compressor, whether single-stage or multi-stage, and upon the method of driving, whether direct-connected, belted or geared (Par. 173 and 174).

171. Two-stage compression should be used for capacities over 200 or 300 cu. ft. per min., where the pressure is between 40 and 200 lb. per sq. in. Not only is there a saving in power of approximately 10 to 20 per cent., but the reduced terminal temperature permits better lubrication.

172. Theoretical power required to compress air. For the ordinary working pressure of 100 lb., the theoretical power required for isothermal compression of 1 cu. ft. of free air per min. is 0.131 h.p. To this must be added the power lost in friction and that given off as heat, during compression (Par. 175).

173. Test of a direct-connected compressor. In a test made in New York City in January, 1912, the power input to the motor was 23.26 h.p. per 100 cu. ft. of free air per min. compressed to 100 lb. per sq. in. gage pressure and actually delivered through orifices. The compressor tested was direct-connected to a 400-h.p., 188-rev. per min., self-starting synchronous motor with belted exciter. The low-pressure cylinder was 26 in. in diameter, the high-pressure cylinder 15.5 in. in diameter, stroke 18 in., and the displacement capacity 2,070 cu. ft. at 188 rev. per min. The volumetric efficiency at this speed as shown by the orifice test was 88 per cent. The horse-power input at full-load was 425, and the indicated horse power of the air cylinders was 350. The overall mechanical efficiency including motor, exciter and compressor was 82.3 per cent.

174. Comparison of direct-connected compressor with belted compressor. For the purpose of comparison with a belted compressor where the power is usually specified as that delivered at the compressor pulley, the efficiency shown in Par. 173 may be divided into 91.5 per cent. for motor and exciter and 90 per cent. for the compressor. This gives a motor output of 389 h.p., or 21.4 h.p. per 100 cu. ft. of air delivered. Compared of control is inefficient because a considerable amount of power is wasted in heat which cannot be regained, and there is also some leakage.

182. Regulation by use of an unloading valve. The most satisfactory and economical method of regulation is the combination of an unloading valve on the intake cylinder and an **atmospheric relief valve** on the discharge, or high-pressure cylinder. The unloading valve on the intake is connected to the air receiver, and a rise in pressure causes it to close. All air is then cut off, and as soon as the system is pumped out, the low-pressure piston operates in a vacuum. But there will be a slight leakage past the valve and around the piston-rod stuffing box, and provision must be made for allowing this air to escape. If this is not done, a small amount of air will be carried over into the high-pressure cylinder and compressed over and over again, resulting in dangerously high temperatures and waste of power. An atmospheric relief valve is therefore provided which is operated automatically after the unloading valve is closed. This relief valve shuts off communication between the pressure line and the high-pressure cylinder, and at the same time opens a free exhaust from the high-pressure cylinder to the atmosphere.

When the pressure in the receiver falls slightly, the intake unloader opens, then the relief valve closes, and the work of compression is again taken up. This cycle is secured without shock, as the operation is comparatively gradual and as an appreciable space of time is taken to fully load or unload. With this method of control the machine is either operating at its most efficient point (full-load) or else no work is being done except that necessary to overcome the friction of the moving parts.

183. A load factor of 60 per cent. may be taken as an average figure for compressor operation. In the test referred to above (Par. 178), the compressor was equipped with combination unloading valves and the power required at 60 per cent. load factor was 3.1 kw-hr. per 1,000 cu. ft. of free air actually delivered at 100 lb. pressure. A compressor of the same capacity and type, but fitted with clearance control, was also tested at the same time, and at 60 per cent. load factor the power required was 3.5 kw-hr. per 1,000 cu. ft., or 12.9 per cent. greater.

184. Starting. No special difficulties are encountered in starting, since the compressor is started without load and the load is not thrown on until the machine is up to normal speed.

185. Automatic starting and stopping. In cases where the demand for air is very intermittent and no air is required for long intervals, the compressor may be automatically stopped and started. The main switch is controlled by the air pressure and is thrown out when the pressure rises, and thrown in when the pressure falls. The unloading valve is controlled by a solenoid which holds the valve open when the compressor is running, but allows it to drop and close when the main circuit is opened. The compressor always starts unloaded since the solenoid is not energized until the motor is up to speed and the last contact has been made in the starter. On account of the effect of repeated starting on the electrical supply line, automatic starting is not recommended for large units, or for installations where the starting and stopping is at all frequent.

FANS AND BLOWERS

BY MERTON S. LEONARD

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186. Definitions. Fans will here include only **centrifugal fans** having inlet at centre and discharging at the periphery, either directly or through a casing which directs the air to the outlet; and **propeller fans** which move the air in an axial direction by propulsive force, similar to the propeller of a ship. **Blowers** will here include only **positive rotary blowers**, which, by the action of a rotating impeller or impellers in a very closely fitting casing, create pressure by direct compression.

187. Characteristics of fans and blowers. Fans and blowers, like pumps and unlike most other machines, may operate with equal efficiency since it is very likely to give trouble on account of its complexity and refinement.

195. Method of control (alternating-current). Any method of control which is adaptable to alternating-current motors in general is suitable for alternating-current fan motors. However, such motors are usually arranged to operate at only one speed, and are provided only with a starting device. If it is necessary to vary the volume or pressure of the fan or blower, it may be accomplished by throttling the air with a damper.

196. Methods of direct connection. Whenever feasible it is best to mount the fan wheel directly upon the motor shaft. This can usually be done with small centrifugal fans and with propeller fans up to about 60 in. diameter; however, the deflection and the critical speed of the shaft should be investigated to determine whether or not this is safe.

When it is not feasible to mount the fan wheel upon the motor shaft, it is best to provide the fan with two bearings and connect the motor by means of a flexible coupling. It is more common, however, on account of low cost and space economy to provide the fan with one bearing and connect the motor by means of a solid-flange coupling. If this is done, care must be taken properly to align the bearings, and to maintain the alignment.

197. If a fan handles hot gases, means must be provided for the protection of the motor from the heat. This is accomplished by cooling the shaft or the bearings with water, or by separating the motor and the fan with a long shaft extension, or by driving the fan with a belt or chain.

198. Suppression of noise. If there is danger of noise being transmitted through the air ducts, as in auditoriums, theatres, schools, churches and hospitals, it is often better to drive the fan by belt from the motor. This is particularly true of alternating-current motors.

199. Belt drive for fans. It is often possible to use a smaller and less costly motor by use of belt-drive, when the fan speed is lower than necessary for a motor of the same horse power. It is generally preferable to belt alternating-current motors, because the most desirable speed of a standard fan for a given duty is seldom the same as the available motor speed, making it necessary to build a special fan, and thus increasing the cost, if direct-connected.

It is desirable to drive by belt, when the required fan speed or the fan horse power is in doubt, as an inexpensive change in size of pulley will correct the error, if one is made.

200. Method of motor application to blowers. Blowers are essentially slow-speed machines. It is, therefore, almost always desirable to belt or gear the motor. If geared, the motor and the blower should be mounted on the same base to assist in maintaining alignment.

201. Approximate horse power of centrifugal fans. The horse power required to drive any centrifugal fan may be represented by the following formula:

$$\text{h.p.} = K\left(\frac{T}{1000}\right)^3 DW\left(\frac{w}{0.075}\right) \qquad (5)$$

Where K (Par. 203) is a constant depending upon the design and upon other conditions, T is the peripheral velocity or the tip speed of the blast wheel in ft. per min.; D is the mean diameter of the blast wheel in feet; W is the mean width of the blast wheel in feet; w is the absolute density of the gas handled, in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.

202. Approximate horse power of propeller fans. The horse power required to drive any propeller fan may be represented by an expression of the form,

$$\text{h.p.} = K_1\left(\frac{T}{1000}\right)^3 A\left(\frac{w}{0.075}\right) \qquad (6)$$

Where K_1 (Par. 204) is a constant depending upon the design and upon other conditions, T is the peripheral velocity or the tip speed of the wheel in ft. per min.; A is the gross area of the wheel in sq. ft.; w is the absolute density of the gas handled in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.

the main of unloaders, bucket-handling gantry cranes, car dumpers, self-propelled transfer cars and belt conveyors. Fig. 26 represents a stiff-leg unloader, with a gantry crane for stocking such ore as is not to be immediately loaded into cars. Fig. 27 shows a gravity-type unloader and a gantry crane.

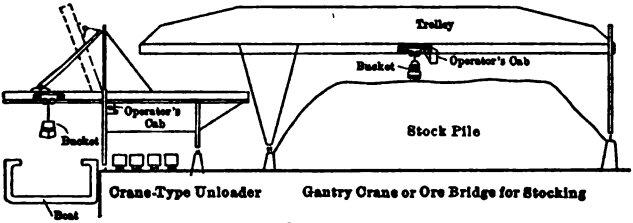

Fig. 27.

207. Motors for severe service are usually of the mill type with large shafts, fire-proof insulation, heavy frames, small moment of inertia of armature and great commutating capacity. Shafts are generally tapered at the pinion end to allow for easy removal of the pinion, and axle bearings are often used where a gear ratio of about five-to-one is desired. The frames are generally entirely enclosed, although many of the larger sizes are constructed with part of the upper frame cut away in order to facilitate the dissipation of heat. It is probable that in the future, forced ventilation will become common practice, as is already the case in electric locomotives.

208. Motors for light service where direct current is available, and of 25 h.p. or under, are usually of the crane type. This construction is much cheaper than the mill-type construction, yet is quite satisfactory for intermittent service where no severe overloads occur. The frames are entirely enclosed, as heating is not a consideration.

209. Motors for car dumpers, where there is usually abundant space available, and where the electrical apparatus is well protected from the weather, are often of the open type with commutating poles. The speed of rotation is preferably lower than for the mill motor, owing to the greater radius of gyration of the armature.

210. Motors for transfer cars are commonly either of the railway or mine type, the latter often being preferable on account of their low speed, high torque and large gear reduction. Standard drum-type controllers are ordinarily furnished with these motors.

211. Mill motors, where alternating current only is available, may be obtained for 3-phase, 25-cycle, 220-volt or 440-volt circuits. For a frequency of 60 cycles it is necessary to use an open type of frame, an outboard bearing being desirable for sizes above 25 h.p. Alternating-current motors should be of the slip-ring type, except for belt conveyors with light starting requirements, where squirrel-cage motors may be used. They should be of sturdy mechanical construction, and should be wound for high torque. Low rotor speeds are desirable as tending to keep the acceleration load at a minimum.

212. Controllers for heavy duty are always of the contactor or magnetic-switch type with overload and automatic acceleration relays. Dynamic braking for lowering buckets, etc., is now almost universal; not only is the energy of the lowered mass dissipated in resistors instead of brake friction, but the operator is given a very delicate control by means of his master controller instead of having to manipulate an air or hand brake. Where direct current is not available, dynamic braking is obtained by means of a small low-voltage generator set, which provides direct current for exciting the stator winding of the motor lowering the load, thus allowing it to become an alternating-current generator. Since only part of the winding can be used for this purpose, and since an induction motor possesses inherently a limited torque, this system of dynamic braking is not as reliable as where

218. Power required by transfer cars. In the case of transfer cars and the trolleys of unloaders and bridges, acceleration is the predominant factor. For loads of this kind, two motors are used as a rule, in order to obtain good traction; in such cases, series-parallel control is generally preferable. If the motors are permanently connected in parallel, it is safer to provide a separate set of reversing contacts for each armature. Armature-shunting points are occasionally employed to obtain very low speeds, and dynamic braking is sometimes provided in the case of a gantry crane or unloader trolley. To obtain dynamic braking for a series-wound trolley motor, it is necessary to connect the field in series with a resistance across the line, so that the characteristics of a shunt generator may be obtained. An air brake is generally preferable for trolley service, except when the operator is located at some distance from the mechanism, in which case the motor should be provided with a magnetic brake, preferably of the disc type, and the controller should give dynamic braking on or near its central position.

219. The frictional resistance of the ordinary trolley may be taken at 25 lb. per ton; for a transfer car with standard trucks, 15 lb. per ton is ample. The horse power for the final assumed speed should first be figured as follows: h.p. = friction force at rim of wheel multiplied by the speed in ft. per min. and divided by the efficiency (expressed as a decimal) and by 33,000. About twice the result should be taken as the nominal horse power required, this value being based on a rise of 75 deg. cent. in 1 hr. The performance of the trolley or car can then be easily worked out by means of the motor curves, the step-by-step method being used as explained in Par. **226.** It will sometimes be found that the motor chosen is too small; where there is any doubt, the moment of inertia of the armature should be obtained and should be translated into its equivalent weight at the trolley speed. The calculations should then be gone over more carefully; for slow trolley speeds, the inertia of the armature becomes a very considerable part of the whole.

220. The longitudinal drive of an unloader or bucket-handling gantry partakes of the nature of a trolley drive, but owing to the much lower speed and higher friction, inertia plays a smaller part, and dynamic braking is unnecessary. Friction may be taken at about 40 lb. per ton, although this figure is quite uncertain. The heating is not a factor in this class of service, but sufficient commutating capacity should be allowed to take care of a wind-pressure equivalent to one and one-half times the friction; this is merely a general rule, but is one which works well in practice. In some cases long gantry cranes are driven by independent motors at each end; this scheme is quite successful, even with series motors, although an automatic device should be provided to prevent one end from leading the other. With this type of drive, the motors should be provided with magnetic brakes, the disc type being preferable because the shock when stopping is less than with the post brake. For the ordinary gantry or unloader, one motor is generally connected by bevel gears to both trucks; a mechanical foot brake which is held in the released position by the weight of the operator is preferable to a magnetic brake in this case, since it can be applied more gently.

221. The gear efficiency of one reduction of cut spur gears in this class of work may be generally taken as 95 per cent.; for cut bevel gears, 90 per cent. For important motions, the cut herringbone gear is becoming popular; it should have an efficiency of at least 97 per cent. if properly erected. The **coefficient of friction** for the ordinary bearing will average about 0.05, while for sheaves it is better to allow a value of 0.07. These figures may be safely followed except in special cases, such as in gearing for longitudinal drives where there is decided likelihood of poor alignment of shafts and gears.

222. The calculation of power house or substation capacity for a dock is a long and tedious process, since it is a matter of some conjecture as to just how the peak loads, which are usually violent, will coincide. A 10-ton stiff-leg ore-unloader having a total capacity of 400 h.p. in five motors will show a momentary peak load of 1,200 amp. and an average load of 400 amp. Two such machines working together will occasionally take 1,800 amp. for 1 or 2 sec. One 15-ton stiff-leg ore-unloader with seven motors totalling 700 h.p. and requiring an average load of about 500 amp. will draw a peak of 1,800 amp. The maximum current for four such machines, however, will not exceed 4,000 amp. Gravity-type unloaders are likely to show a higher proportional peak load because practically all the work is done by a motor speed of 820 rev. per min.; then ft. per min. = (900/820) × rev. per min. = 1.1 × rev. per min.; also the force at the rim of the wheel will have the same ratio to the motor torque as the friction force has to the friction torque; or, force = (1,060/205) × torque = 5.17 × torque. Assume effect of armature weight equal to 1,500 lb. at 0.7 ft. radius; equivalent weight of one armature at trolley speed = [1,500 × 0.9 × (2π × 0.7 × rev. per min.)²]/(ft. per min.)² = ([1,500 × 0.9 × (2π × 0.7 × rev. per min.)²]/(1.1 × rev. per min.)² = 2,160 lb.; or say 5,000 lb. including gearing. Total weight per motor for acceleration = 85,000 + 5,000 = 90,000 lb. Assume that acceleration while short-circuiting the resistance is 2.5 ft. per sec. per sec., which is as high a value as the operator can endure with comfort; this initial rate of acceleration is determined by the rapidity with which the starting resistance is cut out. Since the force of acceleration = F_a = (wt. in lb./g) × acceleration in ft. per sec. per sec., then F_a = (90,000/32.2) × 2.5 = 7,000 lb. Since the friction force is 1,060 lb., the total force = 7,000 + 1,060 = 8,060 lb. Motor torque = T = 8,060/5.17 = 1,560 ft-lb. From the characteristic curve, when T = 1,560, h.p. = 119; rev. per min. = 402. Therefore ft. per min. = 402 × 1.1 = 442, and ft. per sec. = 7.4. This is the speed which is attained at the instant the last section of resistance is cut out. The time = t_1 = speed/acceleration = 7.4/2.5 = 3.0 sec. The distance = d_1 = average speed × time = (1/2) × 7.4 × 3.0 = 11 ft. After the starting resistance is cut out, the trolley will continue to accelerate at a diminishing rate, as long as the force supplied by the motors exceeds the friction force. Assume that the horse power has decreased to 60; then from the motor curve, rev. per min. = 560. Since ft. per min. = 1.1 × rev. per min., the ft. per min. = 616, or ft. per sec. = 10.3, and the increase = 2.9 ft. per sec. The average speed = (10.3 + 7.4)/2 = 8.85 ft. per sec. Referring again to the curve, T = 560, therefore F = 2,900 lb.; $F_a = F - F_f$ = 2,900 − 1,060 = 1,840 lb., acceleration = $A = g \times F_a$/90,000 = 0.66, average A = (2.5 + 0.66)/2 = 1.58, t_2 = (increase in speed)/(average acceleration) = 2.9/1.58 = 1.8 sec., d_2 = 8.85 × 1.8 = 16 ft., total time up to this point = t = 3 + 1.8 = 4.8 sec.; total distance up to this point = d = 11 + 16 = 27 ft. Assume the horse power has dropped to 35; then rev. per min. = 760, ft. per min. = 836, ft. per sec. = 13.9, increase = 3.6, average speed = 12.1 ft. per sec.; T = 240, F = 1,240, F_a = 180, A = 0.06, average A = 0.36, t_3 = 10.0 sec., d_3 = 121 ft., t = 14.8 sec., d = 148 ft. Assume trolley coasts for 1 sec. at 13.9 ft. per sec.; t_4 = 1, d_4 = 14 ft., t = 15.8 sec., d = 162 ft. Assume retardation = 2.5 ft. per sec. per sec.; t_5 = 13.9/2.5 = 5.6 sec., d_5 = 39 ft., t = 21.4 sec., d = 201 ft. The time originally allowed for a trip one way was 20 sec., but since the trolley will return light at a somewhat higher speed, the gear ratio originally assumed is close enough. If the heating is figured for the loaded trip and for one-half the cycle, the results will be on the safe side. Mean effective h.p. = $\{[(119^2 \times 3) + (119^2 \times 1/2 \times 1.8) + (60^2 \times 1/2 \times 1.8) + (60^2 \times 1/2 \times 10) + (35^2 \times 1/2 \times 10)]/[60 \times \frac{1}{3}]\}^{\frac{1}{2}}$ = 52. A fully enclosed mill motor can keep up this cycle for about 3 hr., but not indefinitely. If the crane will not operate for over 3 hr. at any one time, 80-h.p. mill-rated entirely enclosed motors should be used. For continuous operation use the same motors with the semi-enclosed frames, which will have a mill rating of about 90 h.p. and root-mean-square rating of about 70 h.p.; or if convenient, forced ventilation may be used with the totally enclosed motors. In any case, the armature, fields, etc., will be the same, the difference in rating being due to the different methods of cooling. The maximum loads to be commutated should not exceed those shown on the motor curve.

226. Calculations for bridge drive (Par. 223). Assume that the total crane weighs 1,200 tons, and that a 2-motor longitudinal travel drive is desired. Friction force per motor at 40 lb. per ton = 40 × 1,200 × ½ = 24,000 lb. Assume that a speed of 75 ft. per min. is desired, and that each motor has one spur-gear and two bevel-gear reductions. The efficiency would be approximately 77 per cent. The friction load per motor = 71 h.p. If 80-h.p. mill-rated motors were used, the friction torque read from the curve would be about 720 lb. at 1 ft. radius. Assuming the wind load = 36,000 lb. and acceleration at 0.25 ft. per sec. per sec. = 9,300 lb., the total maximum load = 69,300 lb. and approximate maximum torque = (69,300/24,000) × 720 = 2,080 ft-lb., which is well within the commutating limit of an 80-h.p. mill motor.

230. Energy supply, in the form of either direct or alternating current is communicated to the motors by conductors which lie parallel to the track, the contact being made by shoes or wheels. Sometimes storage batteries, suspended from the telpher or the carriage, are employed. On steep grades the telpherage traction, in some installations, has been assisted by supplementary cables, either fixed or movable.

231. Motors. The sizes of motors for telphers and hoists will depend upon the class of work to be done; the motors for telpher-tractors vary from 5 to 15 h.p., and for the hoists from 3 to 75 h.p., the loads being from 500 lb. to 30,000 lb. The load factor for the tractor motor is 0.25 and for the hoisting motor 0.16. The driving wheels and the motors may be connected by gears or by chain drive. The maximum service efficiency of the motors is that corresponding to the efficiency obtained between one-half and three-quarters full-load. The motors are of slow or medium speed.

Direct-current, 250-volt or 500-volt, series-wound motors are preferable for tractors and hoists although alternating-current motors afford satisfactory results. The motors should be dust and weather proof, and should have a 50 per cent. reserve in their rating. The average combined efficiency of the motors and gearing, for the tractor and hoist, is from 65 per cent. to 75 per cent.

232. Brakes. The telpher brake is of the mechanical type, and the hoist brake is of either the electro-mechanical or electro-dynamic types. Spur gears and chain drive on the tractor transmit the power from motor to track wheels, and either spur or worm gear is used to transmit power to the hoisting drum.

233. Trackage. Telphers either run in one direction on a closed track circuit (Fig. 30), or to and fro over a single line. On the single line the automatic telphers reverse themselves on completing their trips. The spacing between the cars is automatically regulated by a block system, and the cars are also automatically controlled at switches and crossings. The track consists of either a cable, or a T-rail supported on a wooden stringer, or upon the top or lower flange of an I-beam. There are also track rails of special section. The radii of the curves are from 8 ft. to 20 ft.

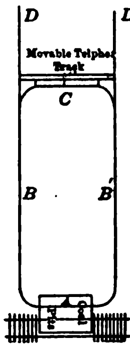

FIG. 30.—Typical arrangement of telpherage tracks.

234. Track supports. The track is supported on brackets attached to buildings, or is supported on "A" bents. Supports under straight track are spaced 20 ft. apart, and on curves the spacing is 8 ft. For long spans cables or trusses are used.

235. Tracks may be fixed or movable. In Fig. 30 the side tracks *B.B'*. are fixed, but *C* is movable, being attached to a travelling bridge. The speed of this bridge is from 300 ft. to 900 ft. per min. The motor driving this bridge would have a load factor of 0.16.

The telpher train passes from these side tracks *B'*, by means of a gliding switch, upon the movable track *C*. This track therefore may be placed anywhere over the area between the fixed side-tracks. The telpher returns by means of the track *B'*, to its starting-point. By the operation of this movable track, all the space can be served; this operation is called **transferage.** The minimum allowable radius of curves is 8 ft.

236. Performance. The loads hoisted and conveyed on telpher hoists have been as high as fifteen tons. The maximum speed of conveying on a straight level track is about 1,000 ft. per min. The running speed is reduced at curves, according to their radii.

237. For terminal work, the capacity of each hoist is 2 tons at 60 ft. per min. (18.288 m. per min.). Two hoists can be combined so as to raise 4 tons. The motors being series-wound, the speed of hoisting will increase as the load is diminished.

238. For freight handling, from two to four carriage hoists constitute a train which has a total maximum carrying capacity of 8 tons. Such trains are used for assorting as well as for distributing, according to consignments. Many telphers can be operated in one installation, the number being limited only by the design of the track layout. As the speed of man-telphers is greater than that of automatic telphers and the loads heavier, the capacity is greater for a given length of track.

239. Installation costs. The overhead trackage, made part of and attached to the building structure, costs the same in proportion as other structural steel. The weight, including the brackets, averages about 50 lb. per lineal foot. The steel is fabricated at the mill.

STEEL MILLS

BY WILFRED SYKES

General Engineer, Westinghouse Electric and Manufacturing Co., Fellow, American Institute of Electrical Engineers

240. Classification. Rolling mills are usually named after the material produced by them, although they are sometimes classified according to the layout of the mills. The principal types of mills are as follows:

(a) **Blooming mills,** rolling ingots, as cast, to blooms or billets. All material rolled in a steel mill must pass through the blooming mill or its equivalent, to be reduced to proper dimensions for handling in the finishing mills. The mills are built either two-high reversing, or three-high running continuously in one direction.

(b) **Slabbing mills** (modification of the two-high blooming mill) produce slabs with finished edges, which are afterward rolled into plates. Vertical rolls are provided for finishing the edges.

(c) **Billet mills** are usually of the continuous type, with rolls in tandem, and roll material from the blooming mill to a suitable size of billet for the finishing mills. Material passes directly from one stand to the other, the speed of the rolls being arranged to correspond to the reduction in area after each pass.

(d) **Plate mills** may be either two-high reversing, or three-high running continuously in one direction, and roll slabs to plates of various thicknesses. They are sometimes provided with vertical rolls for finishing the edges of the plates and are then known as universal mills.

(e) **Structural mills** are usually three-high and are used for rolling girders, heavy angles, channels, etc. In small plants such material may be rolled by the reversing-blooming mill.

(f) **Merchant mills** are used for rolling small angles, channels and all types of profiles. They are usually three-high, with the finishing stand sometimes two-high.

(g) **Bar mills** are usually three-high, and generally consist of roughing stand and a separate finishing stand. These are used for rolling bars of all sections and sizes.

(h) **Rod mills** are special types of bar mills, and are used for rolling small sections at high speeds.

(i) **Rail mills** generally roll blooms or heavy billets to rails of various sections, and are made two-high or three-high, according to the layout.

(j) **Sheet mills** roll 0.5-in. to 1-in. bars to sheets of all gages; they are always two-high, and generally have separate roughing and finishing stands.

In addition to the foregoing types, there are several other forms of construction, used for rolling certain sections of material, but their use is generally confined to one particular installation.

241. Arrangement of mills. The simplest type of mill, having more than one stand, is arranged on one axis, all stands being driven by one set of pinions in the middle or at one end of the mill (Fig. 31). This type of mill is generally used for rolling small sections only, but is occasionally used for heavy sections when transfer tables are provided to move the metal from one stand to the other.

The usual arrangement for rolling light sections is shown by Fig. 32, the roughing stand runs at a slower speed than the finishing stand, and usually has larger rolls to obtain greater strength, in order that large reductions can be made. The metal is roughed down to such size that it can be readily handled by the higher-speed finishing stands. The motor is generally direct-connected to the finishing stands, the roughing stands being rope driven. A better arrangement is to drive the roughing and finishing stands separately, so that the speed of each can be adjusted for different products to give the maximum output.

Occasionally the various stands are arranged on one axis, the finishing stands being separately driven to give the proper speed adjustment. The object of driving the finishing stands at different speeds than the roughing stands is to increase the capacity of the mill, and to finish the material at such a rate that it does not become too cool; this difference in speeds also makes it possible to work without an exceedingly large loop from one pass to the other.

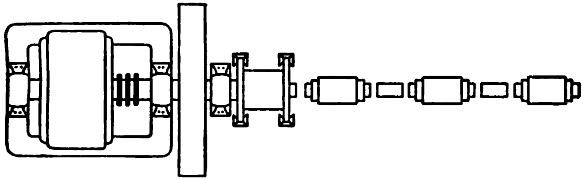

FIG. 31.—Simple mill for rolling light sections.

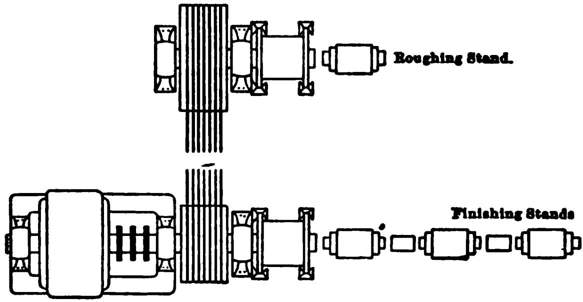

FIG. 32.—Mill with separate roughing stand.

242. Direct-connected drive. The best arrangement is to connect the motor direct to the mill, if the mill speed is such that this is feasible. In general, the lowest speeds possible for direct-connection at 25 cycles are as follows: 250 to 500 h.p., 125 rev. per min.; 500 to 1,000 h.p., 100 rev. per min.; 1,000 to 2,000 h.p., 85 rev. per min.; 2,000 h.p. and upward, 70 rev. per min.

243. Geared drive. The first cost of slow-speed motors is high, and if very large motors are not required, some speed-reducing arrangement is generally used for slow-speed mills. The low power-factor of the slow-speed motor is a serious objection. Gearing has been used extensively for connecting motors to mills, and the use of cut double-helical gears makes possible pitch-line speeds previously impracticable. Although the maintenance is increased, gears permit the installation of high-speed motor of good performance at low cost. The use of gears introduces losses and offsets the increased efficiency of high-speed motors, but the advantage of high power-factor is important. An important advantage of gear drive is that in the case of very slow-speed mills, the fly-wheel (Par. 247) can be located on the pinion shaft and run at such a speed that comparatively small weight is required. This is of particular importance in sheet mills, which run at approximately 30 rev. per min., as sufficient fly-wheel effect cannot be obtained to equalize the input properly if the fly-wheel is located on the mill shaft.

When connecting the motor to the mill, the fly-wheel (Par. 247) should be so placed that the shocks from the rolls are not transmitted to the motor.

as a general practice, the limit of peripheral speed in such cases is 6,000 ft. per min., because higher speeds are not considered safe, owing to the uncertainty of the shrinkage stresses. By special construction to avoid such stresses, cast-iron wheels for a peripheral speed of 10,000 ft. per min. have been built with success. For moderately high speeds, cast-steel wheels are commonly used, the usual limit of peripheral speed being 12,000 ft. per min.; but in special cases cast-steel wheels run at speeds up to 22,000 ft. per min. Such speeds are dangerous if the material is not homogenous and free from initial stresses, but with proper design and annealing, they have proved successful. For speeds up to 30,000 ft. per min. fly-wheels have been built from discs cut from single plates, the plates being riveted together to form a solid wheel.

248. Factors affecting power requirements. The power required by rolling mills depends upon the following factors: (a) volume of metal displaced in a given time; (b) manner in which the section is changed; (c) temperature of metal during rolling; (d) class of material; (e) size of rolls. The determination of the best arrangement of motor and fly-wheel for any particular mill necessitates the analysis of the power required for each pass. The

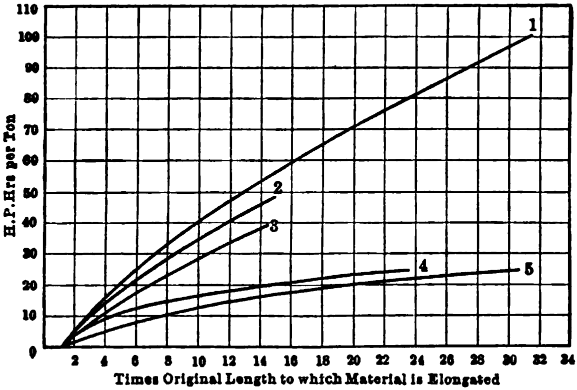

FIG. 34.—Curves showing average energy consumption of different types of mills.

Curve No. 1, rolling small billets of high-carbon steel to rods.
Curve No. 2, rolling billets to light rails.
Curve No. 3, rolling billets to flats and squares.
Curve No. 4, rolling ingots to billets.
Curve No. 5, rolling slabs to plates.

average output required can be obtained from Fig. 34, which shows **average energy consumption for different classes of materials.** The figures given are h.p. hr. per ton of metal rolled, plotted against elongation. To these figures should be added the friction of the mill, in order to obtain the motor load. The size of the motor may be determined from these curves, provided that the tonnage taken corresponds to the maximum that the mill will roll if working continuously, and that there is sufficient fly-wheel effect available to equalize the peak loads.

249. Motor rating and temperature rise. Rolling-mill motors are usually rated on a temperature rise of 35 deg. Cent. and they have a continuous overload capacity of 25 per cent. with 50 deg. Cent. rise and a 1-hr. overload capacity of 50 per cent. with 60 deg. Cent. rise. With the knowledge now available of the power requirements, a standard temperature rise of 40 deg. Cent. with a 25 per cent. overload capacity for 2 hr. is satisfactory, if the conditions are properly analysed.

251. Energy consumption per ton of material

Type of mill	Original cross-section (in.)	Finished product (in.)	Tons per hr.	H.p. hr. per ton
Reversing blooming mill.......	20×20	8×8	95	21
Reversing blooming mill.......	16×16	3×3	40	42
Plate mill....................	6×30	1/4×30	50	28
Plate mill....................	7×24	3/8×24	70	16.5
Sheet mill....................	7×30×[illegible]	0.025	8	165
Sheet mill....................	7×30×[illegible]	0.04	10	128
Rail mill.....................	4×4	40 Rail	75	20
Billet mill...................	4×4	1 1/4×1 1/4	50	20
Rod mill......................	1 1/4×1 1/4	1/4 Round	20	60
Bar mill......................	4×4	1×1	15	48

252. Types of motors adaptable to rolling-mill practice. Alternating-current motors are used almost exclusively for driving rolling mills, direct-current machines being adopted only in a few installations of comparatively small capacity, or where there are special speed requirements.

Special types of direct-current and alternating-current auxiliary motors for steel-mill service have been developed, the principal characteristics of these machines being high overload capacity without injury, and great mechanical strength. Accessibility is also an important factor in order to facilitate rapid repairs. Mill motors are built from 5 to 150 h.p., being usually rated on a temperature rise of 75 deg. Cent. after 1 hr. operation. They are equipped with heat-resisting insulation, because they are often located near furnaces where the temperature of the motor even without load may be very high. The maintenance cost of such motors is approximately one-fourth that of the modified railway motors previously used. Full particulars of these motors can be obtained from the publications of the manufacturers.

253. Control. It is becoming general practice to use hand-operated controllers only for auxiliary motors up to about 30 h.p., larger machines being provided with magnetic-switch controllers. The principal characteristics of steel-mill controllers are simplicity, reliability in operation and ability to stand abuse. The special construction necessary to meet these conditions increases appreciably the cost of steel-mill controllers as compared with controllers for ordinary industrial service.

For motors driving main rolls, magnetic-switch controllers are generally used, the resistance being so arranged that various running points up to 15 per cent. slip may be obtained, in order that the motor will slow down on heavy loads and allow the fly-wheel to give out a part of the energy stored in it. Automatic slip regulators are now being adopted, in order to regulate the rate at which energy is delivered by the fly-wheel, thereby obtaining better equalisation of the load on the motor. Liquid regulators are used on account of their simplicity and small maintenance, as well as quickness in action and sensitivity.

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portions of the plant, and is often from 80 to 85 per cent., based upon the ratio of average to maximum demand.

258. Motor characteristics. Induction motors only should be considered; already over 90 per cent. of the motors installed are of the alternating-current type, and the percentage is steadily increasing. The simplicity and ruggedness of the squirrel-cage motor make it admirably adapted for the severe and dusty service of cement mills. The bearings should be made dust proof. Ball and tube mills and others of similar type are very difficult to start, and motors which drive these machines should have a starting torque of not less than twice the value of full-load torque; friction clutches are unnecessary if proper motors are used. Slip-ring motors are often used for large gyratory crushers, which may become choked with rock and impose very severe starting conditions. Speed variation is sometimes desired on the kilns and dryers, but this requirement can be met easily by the use of slip-ring motors with resistance which will reduce the speed to one-half of normal.

259. Type of drive. For satisfactory service and long life, a motor should not be subjected to severe vibration. Either belts or flexible couplings are able to absorb the vibration of the grinding machinery, but the dust causes rapid deterioration of belts and, therefore, the best practice is direct-connection wherever possible. The countershafts of ball and tube mills rotate at about 160 rev. per min. and, on 25-cycle circuits, motors at this speed are connected through flexible couplings. Motors may often be placed in a separate room, the shafting extending through into the mill proper. For Fuller mills, or for other vertical-shaft mills, special belted vertical motors can be obtained which are more satisfactory than horizontal motors with quarter-turn belts.

260. Jaw crushers are often used for secondary crushing, or upon clinker, and the following are typical ratings.

Superior Jaw Crushers—Blake Type
(Power and Mining Machinery Co.)

Size of jaw opening (in.)	Weight of crusher (lb.)	Capacity per hr. according to size				Driving pulley			Horse power (aver.)
		Tons	In.	Tons	In.	Diam. (in.)	Face (in.)	Rev. per min.	
10×7	7,550	6	2	2½	1	24	7½	250	7½
15×9	12,000	16	3	8	1½	30	8½	250	10
20×10	21,500	38	4	19	2	36	13	250	20
24×15	38,000	60	5	25	2¼	42	16½	250	25
36×24	68,000	130	6	70	3	Pulleys to suit conditions		250	75
42×40	130,000	225	8	130	4½			250	100
60×48	205,000	290	9	180	5			200	150
84×60	400,000	450	11	280	7			100	200

Champion Crushers (American Road Machinery Co.)

Size no.	Size of jaw opening (in.)	Weight of crusher (lb.)	Tons per hr. according to material and feed	Driving pulley			Horse power
				Diam. (in.)	Face (in.)	Rev. per min.	
3	7½×13	5,500	8 to 12	38	8	170	12
4	9×15	8,800	12 to 18	48	9	155	15
4½	10×20	12,500	16 to 24	50	10	150	18
15	11×22	12,000	18 to 26	48	9	150	20
5	11×26	20,000	24 to 35	60	9½	140	25
20	18×50	60,900	70 to 100	72	12½	105	50 to 60

265. Kent mills. This mill (made by the Kent Mill Co.) is in very extensive use both as an intermediate and a fine grinder. Being of the roll and ring type it can be started with comparative ease, and a 40-h.p. motor is usually supplied to drive the mill with its elevator and screen. The pulleys on the mill are 36 in. × 8 in., and 64 in. between centres, running at about 200 rev. per min. Motors with double-extended shafts make a simple and satisfactory drive.

266. Tube mills of 5, 5.5 and 6 ft. diam. by 22 ft. long are now in common use in cement mills. The required power varies with the charge of pebbles and the feed, but averages 100, 150 and 200 h.p., respectively, for the above mills. For belt drive, motors from 480 to 690 rev. per min. are used, while for coupled drive 160 rev. per min. is customary. The F. L. Smidth No. 16 and 18 tube mills are usually driven by 100-h.p. and 150-h.p. motors, respectively. When "cylpebs" (short cylindrical pieces of steel) are added to a tube mill the power required is increased 20 to 30 per cent.

267. Fuller mills. The Lehigh Car Wheel & Axle Works have on the market three sizes of Fuller mills, known as the 33 in., 42 in. and 54 in. The smaller mill is used principally for coal, while the two larger sizes are adapted to pulverizing either raw material or clinker. The power requirements are given in the following table.

Size of mill (in.)	Pulley			Horse power
	Diam. (in.)	Face (in.)	Rev. per min.	
33	33	10	210	25–40
42	54	18	160	75–90
54	75	21	125	150–200

Vertical belted motors make the best drive for these mills.

268. Griffin mills. These mills, also of the vertical type, are manufactured by the Bradley Pulverizer Co. Since the driven pulley is above the mill, they are seldom individually driven, but such drive is made feasible by proper mounting of the motor.

Size	Pulley		Horse power
	Diam. (in).	Rev. per min.	
30 in.	30	190–200	30
36 in.	40	135–150	40
Giant	42	160–170	60–75

269. Bonnot pulverizer. Although this is a vertical mill, it has a horizontal pulley running at about 215 rev. per min. Only one size of mill is manufactured; this requires from 75 to 85 h.p. Either a belted or a coupled motor may be used.

270. Aero pulverizers. These reduce crushed coal to an impalpable powder, and blow it into the kiln, mixed with the correct amount of air for combustion.

Aero pulverizers						
Size no.	Weight (lb.)	Height (in.)	Floor space (in.)	*Normal capacity of soft coal (lb. per hr.)	Rev. per min.	Horse power
A	1,800	28[illegible]	61[illegible] × 27[illegible]	600	2,000	10
B	3,500	38[illegible]	77[illegible] × 29	1,000	1,600	15
C	4,200	51[illegible]	78[illegible] × 29	1,500	1,500	20
D	4,400	44[illegible]	78[illegible] × 29	2,000	1,400	30
E	5,600	46[illegible]	97 × 33	2,800	1,400	40

* The capacity may be increased 25 per cent. or decreased 50 per cent. without material loss of economy.

voltage of 500 has an advantage over 250 volts in that very much less copper is needed and greater distance can be covered. The danger is, however, considerably greater, and many states are legislating against the use of over 300 volts underground. Compounding is necessary due to the long lines that are required in reaching the workings. The type of load is such that heavy short-time peaks frequently occur.

279. Predetermination of generator capacity. When a mine is small and electric power is used for only one or two locomotives, the capacity of the generator will be determined entirely by the peak loads. For instance, if the load were to consist of two 10-ton locomotives each having two 50-h.p. motors, the conditions will be as follows: 1-hr. rating of motors, 200 h.p.; continuous rating of motors about 80 h.p.; maximum load with both locomotives starting 300 h.p. To compensate for the line drop and efficiency, 1 kw. should be allowed at the switchboard for every horse-power at the machine.

It will be seen from the above that on a heating basis, an 80-kw. generator can be used. This machine, however, could not take care of a load of 300 kw. The generator should have a capacity of not less than 150 kw. If old second-hand generators and engines are installed, it will be necessary to provide for a capacity of from 200 to 250 kw., as there would be a lack of overload capacity. The efficiency of power generation will not be very high, since the unit will be carrying a small load a considerable portion of the time. Excellent examples of load diagrams showing the low average and the high peak loads obtained at a coal mine power plant are shown in a paper presented before the A. I. E. E., April, 1913, by Wilfred Sykes and Graham Bright.

If we were to add to the above a third locomotive, a pump load of 50 h.p., a fan load of 50 h.p., and a cutting load of four 25-h.p. cutters, we would have the following conditions:

One-hour rating of motors............	300 + 50 + 50 + 100 = 500
Continuous rating of motors............	120 + 50 + 50 + 40 = 260
Maximum load of......................	400 + 50 + 50 + 100 = 600

For the maximum locomotive load, two locomotives can be considered as starting, each developing 150 h.p., and one running taking 100 h.p. There will, no doubt, be a diversity among the machines, so that the actual peaks will not be over 550 h.p. The generator capacity should be 300 kw., preferably divided between two units of 150 kw. each. From these figures it will be seen that, for the larger plants, the generators can be operated more nearly at their continuous capacity.

At larger mines, or where one company operates a group of mines, a central alternating-current generating system is frequently installed. Energy is generated at 2,200 volts, 3 phase, 60 cycles, and is either transmitted to substations at 2,200 volts, or stepped up to 6,600 volts or 11,000 volts. Motor-generator sets or rotaries are used at the substation to transform the alternating current to direct current. Motor generator sets are generally to be preferred to rotaries, as compounding is more easily obtained. In determining the capacity of the central plant, the machine and line losses must be taken into account in determining the size of the main generating units. These losses will average from 15 to 20 per cent. The capacity of the central plant will not be the sum of the individual substations, as there will be considerable diversity. The diversity factor will range from 1.2 to 1.5 to 1.

280. Design and advantages of mines using purchased energy. When central-station power is used, the power application is very much simplified. For haulage, cutting and inside pumping, a motor-generator set or synchronous converter is used. The motor-generator sets are generally of the synchronous type, owing to the high power-factor which can be obtained with the synchronous motor. This high power-factor will compensate for the lower power-factor obtained on the induction motors used for driving fans, pumps, and tipple or breaker machinery. The substation can be a very simple structure and, in a great many cases, the old generating room can be used. The care of a substation is an extremely simple matter when compared with an isolated plant. For fans, compressors, outside pumps, tipple and breaker machinery and machine or blacksmith shop drive, the squirrel-cage motor is best adapted, as regards first cost and upkeep. This apparatus can be operated at all times independent of the motor-generator set which, in many cases, operates only 8 or 10 hr. per day.

power is purchased, all outside motors can be of the alternating-current type, so that the motor-generator sets, or synchronous converters, need only supply the haulage, cutting, inside lighting and pumping. Where very heavy starting loads obtain, the wound-rotor induction motor with drum type controller should be used. Where only moderately heavy starting torques are required, the squirrel-cage motor is best adapted. The rotor characteristics of this motor will depend upon the character of the load. This is by far the simplest and most rugged motor built, the control also being very simple. Where starting requires a low torque, a low resistance end-ring can be used; where high starting torques are required, a fairly high-resistance end-ring should be used. The cast end-ring has solved all end-ring troubles which were once so prevalent.

288. Pumping. For inside pumping the reciprocating duplex or triplex pump is most used for the smaller sizes. The centrifugal pump will probably average a higher efficiency, but is not so well adapted for moving about and for use under various heads. The capacity of the motor can be readily determined by the amount of work to be done. See Par. 148 to 166.

289. Ventilation. Mine fans are inherently low-speed machines and are very well adapted for direct connection to a steam engine. For economy in first cost and operating cost an electric motor is inherently a high-speed machine, usually requiring some speed-reducing device in such an application. Belting seems to be the most popular method, although gearing, chain drive, and even rope drive, are used occasionally. See Par. 186 to 206.

290. Machine mining. Pick mining is a rather slow and laborious process of mining coal, although a large portion of the coal is still mined by this method. Machine mining has become a necessity owing to the increasing demand for coal and the limited supply of labor. Punchers and chain machines are the two types generally used. **Punching machines** were first driven by compressed air, and most of the machines of this type are still operated in this manner. The electric puncher is coming in rapidly; this machine consisting of a motor-driven compressor attached to the cutting mechanism, so that compressed air really is used to operate the puncher. This machine has the advantage of electric transmission, but is heavier and more expensive than the straight-air puncher.

The **chain machine** is the most rapid of all mechanical cutters. The chain cutter will require a motor having an intermittent rating of from 20 to 30 h.p., while the pneumo-electric machine will require a motor rated from 10 to 15 h.p. As a rule direct-current compound-wound motors are used to operate coal-cutting apparatus. Alternating-current motors are being introduced for both punching and cutting machines and have been very successful. They, however, require a separate power circuit consisting of two feed wires with track return. They possess the advantages of simplicity of construction and less danger of the workmen coming in contact with live parts.

LOCOMOTIVES

291. Locomotives for main haulage and gathering are of the direct-current type, designed to operate on 250- or 500-volt circuits. The series type of motor is invariably used as it has the best speed-torque characteristics for the service. The service is somewhat similar to street-railway conditions and the same general methods are used to determine the weight and capacity of the equipment.

Mine locomotives are built in weights ranging from 3 tons to 30 tons and gages ranging from 18 in. to the standard of 4 ft. 8.5 in. The wheels may be cast iron with chilled tread, steel tired, or rolled steel. Gathering locomotives are built to replace mules; these weigh from 3 to 8 tons with equipment varying from two 10-h.p. motors to two 40-h.p. motors.

292. Locomotive-adhesion and weight calculations. The cast-iron wheel will afford a running coefficient of adhesion of 20 per cent., and a starting coefficient of 25 to 30 per cent. when sand is used. The steel-tired or rolled-steel wheel will have a running coefficient of 25 per cent. and a starting coefficient of 30 to 33.33 per cent. with sand. The above figures are conservative and can be easily obtained with fair rail conditions. The weight of locomotive is determined by the following formula:

$$T(30+20G)+20GW = 400W. \text{ for cast-iron wheels,}$$
$$= 500W. \text{ for steel wheels.}$$

exceeded for satisfactory operation. The following table has been prepared by the Baldwin Locomotive Works and represents the best modern practice. If a heavier locomotive is desired than is shown in this table, tandem units are often applied.

297. Rating of locomotive motors. Although the motors of a mine locomotive are given a 1-hr. rating, it is the average heating that determines the capacity for all-day service. This heating is proportional to the square of the current. The average of the square of the current will give a squared value, the square-root of which is really the capacity of the motor for all-day service. This value is known as the square-root of the mean-squared current. It is obtained by finding the different values of the current for one motor throughout a round trip. These current values can be obtained from the characteristic motor curve of the particular motor used. After the weight of the locomotive has been determined, one of the standard motors for this weight is selected and calculations made to determine if it is of the proper capacity. The total tractive effort per motor is determined for each grade, allowing 20 lb. per ton for the friction of the locomotive. For each total tractive effort the current and speed are obtained from the curve, and the time is calculated. By squaring each current value and multiplying by the time, we have the sum of the products of various squared values of the current, multiplied by the time. This summation should be increased by from 5 to 10 per cent. to make allowance for acceleration and switching movements at each end. The final value is then divided by the total time, and the square-root extracted. The characteristic curve gives the continuous current capacity, which can be compared with the final result obtained.* The capacity of the equipment should not be based on h.p. per ton weight of locomotive, since the 1-hr. rating of the motor is no indication of what its performance will be under certain given conditions.

298. An electric reel is sometimes applied to a gathering locomotive so that it can be taken into rooms where no trolley wire is erected. This reel may be chain driven from one of the axles or motor driven from a small independent special motor which maintains a constant pull on the cable. This cable may be single-conductor or double-conductor, depending upon the track conditions. A No. 4 A.W.G. cable is generally used.

299. A traction reel can also be supplied on a gathering locomotive. It consists of a small motor-driven crab with from 300 to 400 ft. of steel cable. This type of reel is used where the room grades are very steep, and are driven to the dip.†

300. The storage-battery locomotive is rapidly coming to the front for gathering purposes. Until recently the storage battery was not rugged enough to stand the rough service that exists in mining conditions. Two types of battery are now available for this work, the lead-cell and the Edison. The iron-clad Exide is the most satisfactory type of the lead cells. The efficiency between battery and locomotive wheels will range from 60 to 66 per cent. In order to calculate the proper battery to use, the entire trip should be divided into as many sections as there are different characteristics. The car friction should be taken at 30 lb. per ton, and the tractive effort 20 lb. per ton for each per cent. of grade. The total tractive effort multiplied by *three* will give the watt-hours per train mile. The total watt-hours per round trip can thus be obtained. The total watt-hours divided by the voltage of the battery will give the ampere-hours of the battery. For a lead cell the voltage per cell will be 2, and to calculate the number of positive plates per cell, the ampere-hours should be divided by 31.5. The proper size of Edison cell can be selected from the ampere-hours required. Batteries for this kind of service are rated on a 4.5-hr. basis. The size of either type

* For a more detailed explanation of the determination of weight and equipment of a mine locomotive see article, *Electric Journal* of March, 1912, entitled "The Determination of Weight and Equipment of a Mine Locomotive," by Graham Bright. (This article gives an example with complete set of calculations.) Also see *Coal Age*, issues of March 6 and March 20, 1915.

† Additional information regarding gathering locomotives can be obtained from articles printed in the *Electric Journal*, Vols. VIII and IX, by G. W. Hamilton.

of battery can be reduced considerably if noon-hour charging, or other short-time boosting charging can be effected.

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REFRIGERATING PLANTS

BY AUGUSTUS C. SMITH

Sales Engineer, The Cataract Power and Conduit Co.

302. Motors adaptable to refrigerating service. Ammonia compressors and auxiliary apparatus in refrigeration plants may be driven either by direct-current motors or by induction motors. The flexibility of speed control of the direct-current motor offers an advantage, but the possibilities of speed control of the induction motor together with the characteristic advantages of this type are sufficient reasons to justify its selection where alternating current is available.

303. Motor speeds and speed control. Motors for the operation of ammonia compressors should be of the variable-speed type, so that where the operating conditions require it, suitable speed control can be secured. Compressors of 50 tons capacity, and over, are operated usually at about 70 rev. per min., so that a motor speed of 500 rev. per min. or less, is desirable.

304. Multispeed motors. With the two-speed motor, the compressor can be operated at full speed and at half speed; while with the three-speed motor, it can be operated at full speed, two-thirds speed and one-third speed. This method of speed control, however, provides for changes in the compressor at fixed and predetermined steps only, and does not, therefore, provide for the flexibility in speed control necessary to meet the usual requirements in the operation of refrigeration machines.

305. With the slip-ring type of motor and resistance speed control flexibility of operation equivalent to that of the steam compressor is attainable. The power-factor of this motor remains practically constant at all speeds, but the efficiency falls off with the reduction in speed; operating the compressor continuously, at reduced output, with this type of motor, is therefore uneconomical from a power-consuming standpoint.

306. Plant duplication. In plants where it is necessary materially to reduce the output, during certain periods of the year, it is desirable to employ more than one compressor unit. This is especially true in large refrigeration plants, where the total compressor capacity should be divided among individual units, properly proportioned according to the required operating conditions.

307. The standard rating for ammonia compressors is based on 15 lb. suction pressure, 185 lb. condensing pressure, and condensing water at 70 deg. Fahr. (21 deg. Cent.). The power necessary to drive a compressor varies directly with the operating pressure, the horse-power being determined by indicator card.

308. Power requirements per ton. Ammonia compressors operated at 15 lb. suction pressure and 185 lb. condensing pressure, having a rated capacity over 5 tons of refrigeration per 24 hr., require about 1.5 h.p. per ton of refrigeration; compressors having from 5-ton to 1-ton capacity, operated under like conditions, require from 1.5 h.p. to 2 h.p. per ton. Increasing the above pressures to 25 lb. suction, and 200 lb. condensing pressure, would increase the power necessary to operate the compressor about 16 per cent.

309. Varying pressures and output requirements. In the daily operations of a refrigerating plant, it is frequently necessary to operate a compressor at increased pressures. In some localities during warm weather the temperature of the condensing water will exceed 70 deg. Fahr. (21 deg. Cent.), and during extremely warm weather it may be necessary to force the compressor beyond its rated capacity in order to meet unusual requirements, all of which require increased power. For compressors of 50-ton rated capacity and smaller, about 25 per cent. additional motor capacity should be provided for these possible excessive operating conditions; for larger compressors,. from 15 to 25 per cent. additional motor capacity should be provided, depending upon the local and probable operating conditions of the plant.

310. Classification of ice-making plants. Ice-making plants may be divided into two classes: those making ice from **distilled water,** and those making ice from **raw, or natural water.** The former method uses the **can system,** while the latter may use either the can system, or the **plate system.** The compressor-room equipment for an ice plant of equivalent capacity is the same for all of these methods, except for the plate system, where about 15 to 20 per cent. more compressor capacity is required.

311. Operating data on 90-ton can-system ice plant using distilled water

Month	Maximum input (kw.)	Input (kw-hr.)	Tons of ice made
January	115	92,530	2,033
February	102	65,080	1,493
March	97	71,870	1,737
April	192	133,550	3,055
May	209	139,550	3,742
June	230	145,686	3,291
July	218	157,640	3,657
August	230	156,700	3,579
September	219	160,250	3,408
October	205	154,090	2,989
November	112	76,460	1,792
December	122	91,210	2,226
Total	....	1,444,616	33,002

312. Equipment of plant using can system. The compressor-room equipment in this plant (Par. **311**) consisted of two vertical 16-in.×24-in. double-cylinder single-acting ammonia compressors of 70 rev. per min., at full-speed. Each of these compressors had a rated capacity of 45 tons of ice per 24 hr., when operated at 15 lb. suction pressure and 185 lb. condensing pressure, with condensing water at 70 deg. Fahr. (21 deg. Cent.). Each was belt-driven by a 175-h.p., 500-rev. per min., 3-phase, 25-cycle, 2,200-volt, variable-speed, slip-ring induction motor. The speed control consisted of a 13-step drum controller, and iron-grid resistance of sufficient capacity to permit the continuous operation of the motor at any speed from full speed to one-half speed continuously.

the ice from the cans; 1 7.5-h.p. motor direct-connected to brine agitator. The distilled water used is furnished from a 10-h.p. boiler operated at from 10 to 15 lb. steam pressure.

318. Operating data on plant using centre-freeze system. The first complete month's operation of the above plant showed a total maximum demand of 125.8 kw., with an energy consumption of 91,056 kw-hr., and a production of 1,599 tons of ice. This is equivalent to a resultant maximum demand of 2.42 kw., or 3.24 h.p. per ton of ice, and 57 kw-hr. per ton of ice.

319. The Audiffren-Singrun refrigerating machine in its completed form, as placed on the market, is in reality a self-contained refrigerating plant, and is especially adapted for use in restaurants, butcher shops, clubs, apartment houses, and large residences, or where the average requirements may run from 10 to 100 lb. of ice per hr., or the refrigeration effect equivalent to the melting of from 15 to 100 lb. of ice per hr. The ideal method of drive is the electric motor, which can be of any type.

This machine operates on the compression system, using sulphur dioxide which condenses at a very low pressure, as the refrigerating medium. The principal element of this machine consists of a shaft on which two drums are mounted, and the driving pulley. One of these drums, located at about the mid-point of the shaft, contains the condenser, and revolves in a tank of running water which serves to carry off the heat absorbed. The other drum, in which expansion of the sulphur dioxide takes place, is connected to the condenser drum by a bronze pipe (which forms part of the shaft), and revolves in a tank containing either the brine or the water to be cooled.

The air is entirely exhausted from these drums, and, after having received the proper charge of sulphur dioxide and necessary lubricating oil, they are hermetically sealed, thus absolutely protecting all of the vital working parts from any outside element which might cause their wear or depreciation, and further making it impossible for any unskilled operator to tamper with the mechanism of the machine.

320. Rating and operating characteristics of the Audiffren-Singrun refrigerating machine, when operated under average conditions of brine at 27 deg. Fahr. (−2.8 deg. Cent.) and condensing water (at outlet) at 77 deg. Fahr. (25 deg. Cent.).

	Machine number			
	2	3	4	6
Capacity in B.t.u. absorbed per hr....	2,260	5,640	11,280	22,560
Capacity in pounds of ice per hr......	10.5	26.0	52.0	105.0
Hours necessary to produce refrigeration equivalent to melting 100 lb. of ice.	6.38	2.55	1.28	0.64
Horse power required...............	0.55	1.26	2.15	4.3
Horse power of motor recommended..	0.75	1.50	3.0	5.0
Kw-hr. required to produce refrigeration equivalent to melting 100 lb. of ice.	2.63	2.39	2.09	1.57
Kw-hr. required to produce 100 lb. of ice.	3.92	3.62	3.15	2.34
Water at 68 deg. Fahr. (20 deg. Cent.) required, in gal. per hr.	40.0	100.0	200.0	400.0

To obtain actual power and energy consumption of motor, divide the above power values by the efficiency of the motor.

TEXTILE MILLS

BY WILLIAM W. CROSBY

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321. Mechanical drive from steam plant. If the power plant can be centrally located, the mechanical drive with a belt or rope tower, is most efficient. By this arrangement energy is imparted to the shafting on each floor directly. The steam plant usually proves the most flexible of the stopped individually, doffing and empty bobbin replacing may be accomplished without stopping more than one frame at a time. Ring spinning and twisting may well be treated similarly to fly frames, although here again individual motors may be used.

330. Looms are perhaps the most susceptible to power variations of any textile machinery. The power to drive a loom varies with the speed of the loom, usually expressed as so many picks per min., a pick being one strand of filling left in the warp by a traverse of the shuttle. While there are so-called positive shuttle looms, most shuttles are thrown across the lay of the loom by a blow of the picking stick. As the shuttle enters the box at the end of its traverse, it pushes out one side of the box, called the swell, which operates a stop motion; when the shuttle does not properly enter the box, the swell is not displaced and this is called "banging off." The speed of the shuttle must therefore be sufficient to accomplish this, yet not so much as to cause rebound. The adjustments vary with the speed. The power to drive a loom also varies with the weight of goods, the beat-up, the number of harnesses and boxes in use.

331. Advantage of motor drive for looms. Overhead shafting and belts are objectionable on account of the damage likely to occur from flying slugs, oil, etc. As looms must be stopped and started continually, and as they start under full-load immediately, belts in weaving rooms require much attention if high efficiency is to be maintained. The shafting can be put below the floor, and long lines reduced by group drives, but the belt from shaft to loom remains. The individual motor obviates practically all of these troubles. It may be arranged to drive through a clutch or be geared directly to the loom. In the first case the motor is kept running all the time, while in the second case it is started and stopped with the loom. The shipper handle of the loom is connected with the control switch of the motor, so that the operative has nothing new to learn. A direct-connected motor must start instantly with full-load torque. The induction motor with small slip has, then, an advantage over belted drives in cleanliness and in constant speed. **Variations in angular velocity** are undoubtedly less in the case of direct electric drives than with belted drives, as shown by tachometer readings.

332. Power requirements for cotton-mill machinery.

Gins saw	10 saws per 1 h.p.
Gins roller 40 in.	1.25 to 3 h.p.
Bale opener	2.0 to 3 h.p.
Hopper feeder	1.50 to 3 h.p.
Thread extractor	2.0 to 4 h.p.
Single cylinder beater	3.0 to 4 h.p.
Two cylinder beater	6.0 to 8 h.p.
Top flat card	0.20 to 0.33 h.p.
Revolving flat card, 40 in. Production per hr.	
7 lb	0.75 h.p.
9 lb	1.0 h.p.
12 lb	1.25 h.p.
Sliver lapper	1.0 h.p.
Ribbon lapper	1.0 h.p.
Comber, 6 heads	0.50 h.p.
Comber, 8 heads	0.75 h.p.
Railway head	0.33 h.p.
Drawing frame, 1 head	0.25 h.p.
Drawing frame, 5-head metal rolls	1.0 h.p.
Drawing frame, 6-head plain rolls	1.0 h.p.
Speeders,	Spindles per h.p.
Coarse	30
Intermediate	42
Fine	48
Slubber fly-frame; spindles per h.p.	50

	Spindles per h.p.
Intermediate	60
Fine (roving)	90
Jack (fine)	110
Spinning-frame warp, 16's and coarser spindles per h.p.	70
22	75
40	80
60	90
80	100
Filling	
Spindles 8,500 rev. per min.	85
Spindles 9,700 rev. per min.	80
Twister sp. per h.p. 6,500 r.p.m.	80
Filling winder sp. h.p.	300
Spooler	200 to 300
Mule	100 to 120
Warper h.p.	0.25
Denn warper	1.00
Baller h.p.	0.50
Slasher (drum) h.p.	1.50
Plain loom narrow light	0.33
Fancy loom wide heavy	1.0
Reel 50 sp.	1.0
Brush and shear	3.0
Folder	0.25

PAPER AND PULP MILLS

BY JOSEPH H. WALLACE

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338. General application. Motors are generally well adapted for driving pulp- and paper-making machinery where the source of power is steady and reliable and will insure continuous operation of the plant. The choice of the grouping method (group drive), or the assembling of several machines to be driven by one motor through shafting and belting, and the unit method (individual drive), or the driving of each machine by its individual motor, will be determined by local conditions of layout and the probability of one or more machines in a group requiring operation while others in that group are shut down. Where machines can be assembled in groups that are easily served by short lines of shafting, the grouping method is more often to be preferred. The motor units then become larger, and being fewer in number, installation and maintenance costs are reduced, and speed reductions are more easily secured without the use of countershafts or gears. The unit method is preferable in case of large machines or where direct-connected apparatus can be used, and in places where points of power demand are scattered and would involve long lines of shaft to group the machines together. It affords convenience in locating machines in places desirable from the operator's standpoint, and is preferable where individual control of machines is frequently required.

339. Equipment adaptable to motor drive. In the equipment of paper and pulp mills specially suited to motor-drive can be included the following: flat and centrifugal screens, stuff pumps, suction-box pumps, white-water and effluent pumps, water-supply pumps, winders, rewinders, cutters, refining engines, elevators, exhaust fans, kollergangs, agitators, mixers, slushers, concentrators, savealls, wet machines, rotary digesters, rotary boilers, conveyors, shredders, chippers, supercalenders and beaters.

340. Jordan engines. The application of motors for driving Jordan engines is very successfully accomplished by direct connection. The motor is mounted on an extension of the Jordan base, and mechanical arrangements provided for the movement of the Jordan plug either by a coincident movement of the motor, or by a special form of coupling connecting the motor with the Jordan shaft. In the refinement of paper stock much depends upon the pressure put upon the Jordan plug as it rotates within its shell or casing. The power required is influenced by the pressure applied, and a good indication of what the refiner is doing is presented by the readings of a wattmeter placed in the feeder circuit to the motor. When power-factor correction is necessary or desirable, the direct-connected Jordan engine presents an excellent opportunity for attaching a synchronous motor large enough to provide for the required condensing effect. Jordan engines are started without the working load applied, and the friction load is usually within the capacity of self-starting synchronous motors.

341. Beaters. The question of driving beaters and other large units electrically will be largely affected by the elements entering into the generation of energy. Beaters are usually grouped, and driving can be economically accomplished through main line shafting. Considerable quantities of power are required within comparatively narrow limits, and conditions are often in favor of steam engine drive instead of motor drive, where the power can be developed in efficient slow-speed compound condensing steam engines located in close proximity to the beater room. This method is especially favorable where electric power is generated with steam-driven equipment. Mills deriving electric power from hydroelectric plants can usually adopt the motor drive for beaters with success.

342. Fourdrinier and cylinder paper machines that require variable speed, and steam for drying purposes, are driven best by variable-speed steam engines, using the exhaust steam for drying the paper. Pulp grinders are seldom driven by electric motors; the power requirements are so great that the method almost invariably accepted as the best is to attach the grinders direct to a water-wheel shaft.

343. Types of motor suitable. In general polyphase alternating-current (induction) motors give the best satisfaction in pulp and paper mill service where constant speed is desired. In cases where variable speeds are true in the case of beaters and Jordans, when a variety of product is made in the same mill. Loads will frequently vary 100 per cent. in the treatment of different stocks, and the most careful judgment is required in the selection of motors that will meet the maximum demand, as this condition may exist for much longer periods than the overload capacity of a motor for the average load would allow.

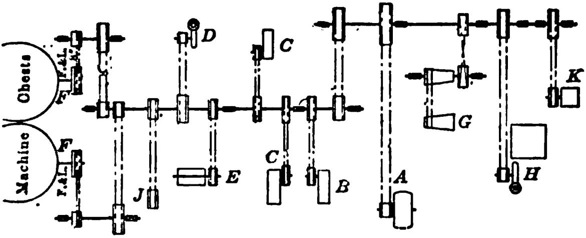

Fig. 36.

A—100-h.p. three-phase induction motor, 330 rev. per min.
B—16-in. by 18-in. vacuum (suction box) pump.
C—14-in. by 12-in. vacuum (suction box) pump.
D—8-in. fan pump (stock to screen).
E—10-in. by 10-in. triplex stuff pump.
F—Agitators in machine stuff chests.
G—Fourdrinier shake.
H—6-in. centrifugal for back water.
J—Three 12-plate screens.
K—Rotary vacuum pump for suction couch roll.

349. Power required by the constant line, operating in connection with a 104-in. Fourdrinier machine (Fig. 36). Power input was derived from wattmeter in feeder line to motor.

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficiency, 90 per cent.)
65	99	440	0.87	78.4 h.p.

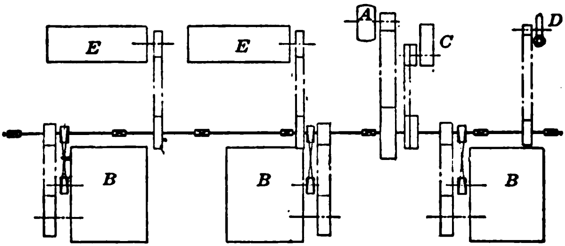

Fig. 37.

A—50-h.p. three-phase induction motor 570 rev. per min.
B—Three 72-in. wet machines.
C—14-in. by 12-in. vacuum pump.
D—Centrifugal pump.
E—Two 10-plate screens.

350. Test on group of wet machines (Fig. 37). Machines in operation—one wet machine, two screens, vacuum and centrifugal pumps and shafting. Power input derived from wattmeter readings in feeder line to motor.

355. Summary of approximate power required by paper-making machinery

Constant speed line or pump line on paper machine	40–125 h.p.	Stuff pumps	5– 10 h.p.
Fourdrinier paper machines (variable speed parts)	50–400 h.p.	Chippers	75–100 h.p.
Beaters	30– 75 h.p.	Crushers	25 h.p.
Jordan engines	50–300 h.p.	Barkers	10– 12 h.p.
Screens, flat platescreens	4– 6 h.p.	Grinders	250–350 h.p.
Wet machines	8– 12 h.p.	Centrifugal screens	10– 15 h.p.
		Supercalenders	50–100 h.p.

PRINTING, BINDING AND LINOTYPE MACHINERY

BY CHARLES E. CARPENTER

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356. Control. There is a rapidly growing tendency among the manufacturers of printing machinery to equip their motor-driven machinery with self-starters and self-starting, predetermined-speed-adjusting controllers, operated either directly from the line (service) switch or by the operation of one or more push-button or hand-control stations.

357. Job or platen presses, from the smallest to the largest size, on account of their large inertia, require a motor much larger to start than to operate them. In the following table the motor sizes are ample, although under normal printing conditions the machines require about half the rated motor horse power, or even less. The best practice is to obtain about 40 per cent. speed reduction below normal by armature resistance and about 25 per cent. increase above normal by field control. This is accomplished by the use of a predetermined-speed-adjusting self-starting controller, usually supplied with a self-contained line switch for starting and stopping (Fig. 38).

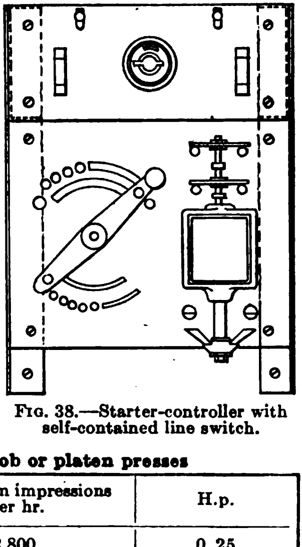

Fig. 38.—Starter-controller with self-contained line switch.

358. Power required by job or platen presses

Size: inside chase	Maximum impressions per hr.	H.p.
8 in. × 12 in.	2,800	0.25
10 in. × 15 in.	2,500	0.25
12 in. × 18 in.	2,250	0.33
13 in. × 19 in.	2,100	0.33
14 in. × 20 in.	2,000	0.50
14½ in. × 22 in.	2,000	0.75
17 in. × 22 in.	1,700	1.00
Automatic feed, high speed		
13 in. × 19 in.	3,500	1.5

press near the floor, convenient for operation from a point beneath the press. Where automatic feeders are used, a "Feeder clutch switch" should be attached to the clutch rod for automatically slowing down the press when the feeder clutch trips, and for automatically accelerating the press back to its predetermined speed when the feeder clutch rod is again thrown in, thus eliminating the necessity for operating push buttons or other starting devices. Reversal is only an occasional performance, and a double-pole two-way knife-blade switch for reversing the armature connections can be placed under the running board.

362. Power required by rotary lithographic presses

Size of sheet	Normal impressions per hr.	H.p.
Zinc or aluminum		
32 in. × 45 in.	2,000	4
42 in. × 53 in.	1,800	5
45 in. × 65 in.	1,500	5
50 in. × 65 in.	1,400	5
Offset		
22 in. × 28 in.	4,000	2
26 in. × 34 in.	3,000	3
30 in. × 42 in.	2,800	4
34 in. × 46 in.	2,500	5
38 in. × 52 in.	2,400	6
44 in. × 64 in.	2,000	10

363. Rotary typographical presses (not newspaper presses) are divided into two classes, sheet-feed rotaries and magazine rotaries. The sheet-feed rotaries range in power requirements from 5 h.p. to 10 h.p., and require non-reversing self-starting, predetermined-speed-adjusting push-button controllers, similar to those for rotary lithograph presses. On account of the high speed at which these presses are operated, it is essential that they be equipped with a very efficient quick-acting dynamic brake to prevent damage to the plates, etc., in case the feeder trips out for any cause. Magazine rotaries require from 7.5 h.p. to 25 h.p. motors, used in conjunction with push-button controllers. The smaller size may be used with a predetermined-speed-adjusting controller, Fig. 39, but a better equipment, especially for larger presses, would be a controller where the press may be accelerated or retarded from several interlocking (safety) push-button stations.

364. Embossing presses of various sizes require moderate-speed compound-wound motors from 1 h.p. to 15 h.p., arranged with from 25 to 50 per cent. field (speed) control, and should be used in connection with a self-starting predetermined-speed-adjusting controller without dynamic brake, controlled from one or two push-button stations for "run, stop and inch."

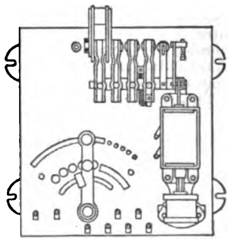

Fig. 40.—Controller for large folders.

365. Folders of the type generally used in printing offices require moderate-speed shunt-wound motors from 0.5 h.p. to 3 h.p., with combined armature and field control; 20 per cent. field (speed) control and 50 per cent. armature control may be considered good practice for ordinary requirements, without dynamic brake. For 0.5 h.p., 0.75 h.p. and 1 h.p. sizes the controller shown in Fig. 38 should be used; this may be controlled from the line switch. For larger sizes the controller shown in

372. Power requirements of individual machines

Mill proper			
		H.p. each	H.p. total
19	10×42 Style AA roller mills Corr.	17	324
20	10×36 Style AA roller mills smooth.	20	400
12	80 in.×77 in. vibromotor universal bolters	3	36
20	8-ft.×32-in. centrifugal reels	4	80
4	8-ft.×32-in. round reels	3	12
22	7-ft.×30-in. purifiers	2.5	55
10	7-ft.×32-in. purifiers	2	20
5	aspirators for 7×40 purifiers	0.5	2.5
4	8-ft.×32-in. flour dressers	3	12
6	No. 7 bran and shorts dusters	8	48
2	70-in. double steel plate fan	27	54
2	55-in. steel plate fan	15	30
1	40-in. single steel plate fan	8.5	8.5
53	elevators	1	53
25	dust collectors	0.33	9
	Total		1144

Wheat-cleaning department			
		H.p. each	H.p. total
1	No. 4 comp shake Dbl receiving separator.	8	8
2	No. 5 comp shake Dbl receiving separator.	10	20
8	No. 90 milling separator	10	80
1	No. 7 automatic magnetic separator	0.125	0.125
1	No. 8 standard aut magnetic separator	0.125	0.125
2	No. 10 standard aut magnetic separator	0.375	0.75
1	No. 8 2 high scourers	40	40
2	No. 9 2 high scourers	50	100
1	No. 31 dust collec. for grinder	0.33	0.33
3	No. 32 dust collec. for grinder	0.33	1
4	No. 33 dust collec. for grinder	0.33	1.33
1	No. 36 dust collec. for grinder	0.33	0.33
4	No. 46 dust collec. for grinder	0.50	2
2	32-in.×8-ft. round reels with drums	3	6
1	30-in. attrition mill	60	60
1	45-in. double steel plate fan	14	14
16	conveyors	....	6
	Total		340

BEET-SUGAR MILLS

BY WIRT S. SCOTT, M.E. IN E.E.,

General Engineer, Westinghouse Elect. and Manufacturing Co., Member, American Institute of Electrical Engineers

373. Power requirements. With electric motors properly applied, the total power consumption should not be over one-half of that required for steam-engine-driven factories. The machines of the types mentioned in Par. **374** to **392** inclusive, vary in size according to the individual requirements, but the examples cited will serve as a guide as to the average practice.

374. Beet lift. Sixteen feet diameter by 2 ft. wide, with 33 buckets 12 in. deep, making 4 rev. per min., driven by pinion meshing with 8 ft. gear on lift; 10 h.p. required, at constant speed, with high starting torque.

375. Beet washer. Six feet diameter by 18 ft. long, with thirty-two 24-in. arms or paddles. Shaft makes 14 rev. per min.; 7.5 h.p. required, at constant-speed and with a moderate starting torque.

376. Beet elevator. Thirty-four buckets, 22 in. wide by 17 in. deep, V-shaped; 70 to 120 ft. per min.; 10 to 20 h.p. required, at constant speed, with moderate starting torque.

377. Beet slicer. Capacity 50 tons per hr., 55 rev. per min.; 25 h.p. required, at constant speed, with high starting torque.

378. Cossette conveyor. Capacity 60 tons per hr., belt 12 in. wide by 125 ft. long; belt speed, 250 ft. per min.; 5 h.p. required, at constant speed, with light starting torque.

379. Sugar mixers. Shaft 50 ft. long, 12-in. paddles, speed 1.5 rev. per min.; 10 h.p. required, at constant speed, with moderate starting torque.

380. Tube mill or granulator; 6 ft. diameter by 30 ft. long, 10 rev. per min.; 10 h.p. required, at constant speed, with high starting torque.

381. Bagging machinery. Bag-sewing machine, requires 2 h.p.; bag stacker, requires 3 h.p.

382. Pumps. Hydraulic gasket pump, for operating doors on bottom of diffusion batteries, requires 5 h.p. Carbonation pump, 450 gal. per min., 50 lb. pressure, requires 25 h.p. Thick juice pumps, 450 gal. per min., 30 lb. pressure, requires 10 h.p.

383. Crystallizers. Ten feet diameter by 16 ft. long; paddles 4.5 ft. long secured to driving shaft which makes one revolution in 5 min. The power required varies considerably during the cycle of operation, the amount required at the completion of the operation being almost double that required at the start. For this reason the machines are best driven in groups of from four to eight, by one motor. For driving an individual machine, from 2.5 to 3 h.p. is required at the beginning of the cycle, and 5 h.p. at the end. Since the complete operation may require 60 hr., a motor must have sufficient capacity to operate at maximum capacity continuously, with individual drive. Where crystallizers are driven in groups of from four to eight machines, 3 h.p. per crystallizer will be sufficient.

384. Centrifugals. The sugar centrifugal is one of the most important machines in sugar making, the operating conditions of which are very severe due to the inertia of the load and the cycle of operation. The time required for the complete spinning process varies with the grade of sugar. Ordinarily one man can operate two centrifugals on granulated sugar and up to four centrifugals on white sugar. When these machines are to be individually driven the cycle of operation must be known, as the rating of the motors will depend upon the root-mean-square value of the power requirements, and the torque required for accelerating in a given time.

385. Average cycle of operation of group-driven centrifugals with fine granulated sugar. The average time required is as follows: filling, one-fourth speed, 30 sec.; accelerating, one-fourth to full speed, 10 sec.; full speed, 120 sec.; power off, retarding by braking, 20 sec.; revolving at about 25 rev. per min., 30 sec.; total time, 3 min., 30 sec.

386. Average cycle of operations of individually driven centrifugals with fine granulated sugar. Filling basket, revolving by hand, 10 sec.; accelerating, 100 sec.; full speed, 30 sec.; power off, retarding by braking, 20 sec.; stop, unloading by hand, 60 sec.; total time, 3 min. 40 sec.

387. Average cycle of operations of individually driven centrifugals with coarse granulated sugar. Filling basket, revolving by hand, 10 sec.; accelerating, 60 sec.; power off, retarding by braking, 20 sec.; stop, unloading by hand, 60 sec.; total time, 2 min. 30 sec.

388. Average cycle of operations of individually driven centrifugals with coarse white sugar. Filling basket, 25 sec.; accelerating, 100 sec.; full speed, 15 min.; power off, braking, 30 sec.; stop, unloading by hand, 145 sec.; total time, 20 min.

389. Group-driven centrifugal machines furnish a very satisfactory arrangement, whereas individual drive, although successful, has been used to a much lesser extent. The character of the load is very similar to that of a fly-wheel, so that with these machines arranged in a group and driven by one motor, the centrifugals in operation will help to bring the idle machines up to speed and maintain a uniform load on the motor. This can best be shown by the following data. A group of ten 40-in. centrifugal machines, driven by a 100-h.p. motor, with 1 machine starting, requires 20.5 h.p.; with 2 machines starting, and 1 at full speed, 40 h.p.; with 3 machines starting, and 3 at full speed, 52.5 h.p.; with 4 machines starting, and 4 at full speed, 60 h.p.; with 1 machine at full speed 5.5 h.p.

390. When centrifugals are individually driven, the peak load is about eight times the normal running load; for a 40-in. machine the peak is approximately 40 kw. input, corresponding to about 40 h.p. output. Since at the very start the speed is zero, the horse power is zero, therefore the power required at start should be stated in terms of pounds torque at 1 ft. radius. The starting torque, together with the root-mean-square horse power for the cycle, furnishes sufficient data for determining the motor required.

391. The speed of a direct-connected centrifugal machine increases very rapidly at the start and at a much lower rate as the motor approaches synchronous speed. The motors are usually of the squirrel-cage type with high-resistance end rings designed to give approximately 15 per cent. slip at full-load; but, since full-load is never attained except at starting, the maximum speed which can be attained by the centrifugal is almost synchronous speed, and in nearly every case the operation is completed before the machine has attained its highest possible speed.

392. The torque necessary for starting a loaded centrifugal machine, and accelerating it to a given speed in a certain length of time can be determined by the following formula:

$$T = 2\frac{Wr^2}{g} \times \frac{2\pi N}{60 \times S} \qquad \text{(ft-lb.)} \qquad (8)$$

T = pounds torque at 1 ft. radius, W = weight in lb. to be accelerated, R = radius of gyration of entire mass in ft., N = rev. per min. machine will attain in S seconds, S = seconds required for accelerating.

The above expression does not take into consideration friction and windage, and it will be necessary to increase the result thus obtained by 10 per cent. in order to obtain the required starting torque.

LAUNDRY MACHINERY

BY FRITZ BALZER

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393. Advantage of electric drive. The power laundry with its large number of different machines can employ electric drive to great advantage. The elimination of belts reduces the friction load of the plant, permits the convenient location of the different machines to reduce handling expenses, assures cleanliness and light, reduces danger of accidents and finally decreases the operating cost. From a number of tests all over the country this saving in operating cost appears to be from 25 to 30 per cent. Alternating-current polyphase induction motors are recommended wherever possible.

394. Use of steam in processes. When introducing electric drive in any laundry it must be kept in mind that a laundry requires a large amount of steam for drying and for the heating and boiling of water. This question is important in the controversy regarding the generation of electrical energy versus its purchase from a central station. In the latter event, steam must be produced independently of the source of power. A careful study of conditions must be made in order to determine which method is the more economical.

395. Classification. Laundries may be divided into three groups: (a) those doing family work only; (b) institution laundries (hotels and hospitals); (c) laundries doing railroad or steamship work only. Each of these groups has a different requirement for steam in amounts which can be expressed in terms of the horse-power requirements. Thus, for group (a) the number of pounds of steam used per hr. could be expressed as 1.2 times the horse power for that group; for group (b) 1.4 times the horse power; and for group (c) 1.8 times the horse power.

suitable double-throw switch, which makes and breaks connections with two relays of a contactor panel. The switch is so arranged, as to disconnect the relay between reversals, in order to allow the contactors to open the main circuit and permit the motor to slow down. The load factor of this group varies between 55 and 60 per cent.

402. Mechanical reversing devices for washers are best suited for group drive from one shaft by gear or chain. The reversals are obtained by clutches attached to two bevel gears which are driven by a third gear. The washer is so arranged that connection is shifted from one clutch to the other clutch. Three 36-in.×70-in. washers require one 7.5-h.p. motor of 900 rev. per min. Other sizes may be calculated from the data given above. The load factor is 75 per cent.

403. Extractors are machines employed to remove the water from the goods after washing. This is done by placing the pieces in a perforated basket and revolving the basket at a very high speed, whereupon the water is thrown out by centrifugal force.

404. Extractor speeds (Troy Laundry Machinery Co. Ltd.)

Basket diameter (in.)	Speed (rev. per min.)		
	Copper	Steel	Monel metal
20	1,400	1,600	1,800
24	1,200	1,400	1,600
26	1,100	1,350	1,500
28	1,000	1,250	1,300
30	900	1,150	1,200
32	800	1,000	1,100
40	700	900	1,000
48	600	800	900

405. The power required to start an extractor is from two to three times the normal motor rating, but after the basket reaches its proper speed the power consumption drops very rapidly to only a fraction of the motor rating. The table below gives the necessary data for Troy machines with copper baskets, if run at the above speeds (Par. **404**). The power required to start the machine varies exactly as the square of the rated full speed.

Basket diameter (in.)	Rating of motor (h.p. intermittent)	Horse power at starting	Horse power running	Acceleration period (min.)
20	1.0	2.5	0.33	0.75
24	2.0	4.2	0.5	0.85
26	2.0	4.7	0.65	1.0
28	3.0	5.5	0.85	1.1
30	3.0	6.0	1.0	1.2
32	5.0	8.0	1.5	1.5
40	5.0	9.0	2.0	1.5
48	7.5	10.0	3.0	1.5

The above data were compiled from the results of a large number of tests; different loading, maintenance and speed conditions will, however, change these figures. The average load factor is 35 per cent.

406. Starchers are built for both collar and cuff work as well as shirt work. A great many types are on the market, the commonest machines being enumerated below. All direct-current motors should be enclosed on the pulley end to prevent the entrance of spray starch. For direct-current as well as for alternating-current they should be of the constant-speed, non-reversing type. The load factor is about 50 per cent.

driven, while the small finishing machines are belted from a line shaft attached to the finishing table.

Collar and cuff ironers, for the most part, require no special motors. However, in the case of steam-heated ironers, it may be sometimes desirable to use variable-speed motors, in order to choose the speed best adapted to the steam pressure, should the latter be changeable. The load factor is 55 per cent.

412. Power requirements of collar and cuff finishing machines

Troy No. 5	Gas-heated, 3 rolls, 24 in.	1.0 h.p.
Troy No. 5	Gas-heated, 3 rolls, 40 in.	1.5 h.p.
Troy No. 5	Gas-heated, 5 rolls, 24 in.	1.75 h.p.
Troy No. 5	Gas-heated, 5 rolls, 40 in.	2.0 h.p.
Troy No. 14	Gas-heated	1.0 h.p.
Troy	Steam-heated, all sizes	0.75 h.p.
B. & E. No. 22	Steam-heated	0.75 h.p.

Finishing table. The motor, which is of 0.5 h.p. capacity, is of the non-reversing constant-speed type, and geared directly to the line shaft, from which the small finishing machines are belted. The load factor does not exceed 45 per cent.

413. Shirt finishing machines. These machines are used to iron or press the neckband, bosom, sleeves and bodies of shirts. For each of these operations a special machine is used, in some cases there are several types of machine for each operation. See Par. **414** and **415**.

414. Bosom ironers. Three distinct types of bosom ironers are in use; first, the reciprocating type, where the bosom passes back and forth under a revolving drum; second, the one-way type, where the bosom travels in one direction only under one or more heated rolls; and third, the presses.

Reciprocating ironers require a motor of 0.5 h.p. Reversals may be obtained by means of reversing switches, in which case direct-current motors must be compound-wound and alternating-current motors must have high-resistance rotors. Reversals may also be accomplished by means of mechanical-reverse devices, in which case non-reversing, constant-speed motors should be used. The reverse switch, as well as the mechanical device, is actuated by a foot treadle and lever connections. The load factor for reversing motors is 75 per cent., and for the mechanical reversing type 55 per cent.

One-way machines require motors of 1 h.p. capacity, without any special features. The load factor is 55 per cent.

Presses are built in two types. In one case a reversing motor operates a screw, and through it a toggle. This motor has a capacity of 0.5 h.p. Should it be a direct-current motor, it ought to be compound-wound; should it be an alternating-current motor, it ought to be equipped with a high-resistance rotor. Single-phase motors cannot be used unless some kind of mechanical reversing device is employed. The load factor is 75 per cent.

The other type of press is operated by a fluid (usually oil) under pressure. A constant-speed, non-reversing motor of 0.5 h.p. capacity operates the pump. The load factor is 55 per cent.

415. Neckband ironers. For this service, small motors of from 0.125 to 0.25 h.p. capacity are required. There are no special features, and the load factor is 55 per cent.

Sleeve and body ironers. These machines are almost identical, their only difference being in respective size. All modern machines are reversing and, like bosom ironers, are reversed either electrically or mechanically. The sleeve ironers require a motor of 0.25 h.p. capacity; the body ironers, 0.5 h.p. If the reverse switch is used the motors must be built for reversing duty (compound-wound if for direct current, or having high-resistance rotors if for alternating current). Single-phase motors cannot be used for this service. If the mechanical reversing device is employed, standard motors without special features should be used. The load factor of reversing motors is 75 per cent., of the others 55 per cent.

416. Flatwork ironers or mangles are used to dry and iron flatwork by passing the goods under pressure over heated rolls or chests. With rolls, one or more aprons may be used to insure perfect contact of the goods over the resistance, or with one or both of these features. Such motors are necessarily series wound and possess a speed torque characteristic in general similar to a series-wound direct-current motor. Consequently, their application is limited to disc types of fans, blowers, electric tools, etc.

420. Service rating of motors. Obviously a motor which is required to operate under load for short intervals will not attain the temperature reached when operating at a similar load continuously. Consequently, for intermittent service, smaller motors may be employed than for continuous service. However, where the motor is frequently started and stopped, though the aggregate running time is small compared to the idle time, the heating may become excessive due to the frequent inrush of current incident to starting. The simplest method of arriving at the proper motor capacity is by actual trial of a sample motor, subjecting it to a cycle of operations which will be equivalent to the most severe service conditions.

421. Split-phase motor characteristics. In analysing the speed-torque* characteristics and other features of split-phase motors for purposes of application, Fig. 41, will prove of use in the calculation of approximate value.

422. Calculation of full-load torque, knowing the horse power and the speed, may be illustrated by the following example: find the full-load torque of a 0.75 h.p. motor running at 1,700 rev. per min. at full-load (1,800 rev. per min. synchronous speed). Find in Fig. 41 the intersection of the vertical line through 1,700 rev. per min. with the curve marked 0.75 h.p. (560 watts), and horizontally opposite this intersection at the left is the torque 36.5 ounce-feet.

423. Starting torque. Since the starting torque and the pull-out or maximum torque of a small split-phase induction motor are limiting features, care should be taken that the motor selected will start the driven machine under the severest conditions of torque. The starting torque varies approximately as the square of the applied voltage, and any reduction in voltage caused by the inrush of current incident to starting, and possibly emphasized by insufficient wiring or transformer capacity in commercial circuits, reduces very materially the starting torque delivered by the motor. It is customary to select a motor which will start the driven machine at a voltage of approximately 80 per cent. of the normal circuit voltage.

The starting torque and the maximum running torque can be found by multiplying the full-load torque by the proper constants. For example, if the starting torque of the particular motor considered in Par. **422** is 1.5 times the full-load torque, its value will be $1.5 \times 36.5 = 55$ oz-ft. Likewise if the maximum running torque of the motor is 2.5 times the full-load torque, its value will be $2.5 \times 36.5 = 91$ oz-ft. These constants must be determined from the characteristic curves of the individual motor, Fig. 41.

424. The horse power at maximum torque can also be determined from the curve if the speed is known. For approximate results the slip of small split-phase induction motors at maximum torque can be assumed to be 25 per cent. In the case of the motor discussed in Par. **423**, the speed at maximum torque will therefore be approximately 1,350 rev. per min. Find in Fig. 41 the intersection of the vertical line through 1,350 rev. per min. with the horizontal line through 91 oz-ft. torque; this is near the line representing 1.5 h.p., which is the approximate power developed by the motor just before pulling out, or stalling.

425. Input. The problem is to find input in watts, when given the horse power and the efficiency. Assume for example that the efficiency of a 0.75-h.p. motor is 75 per cent. Find in Fig. 41 the intersection of the vertical line through 75 with the 0.75 h.p. curve, and horizontally across from this intersection is the value 746 watts.

426. Current per phase. Knowing the watts input, the power-factor and the voltage, the problem is to find the current per phase (or per terminal); for example, assume that the power-factor of the foregoing motor is 70 per cent. and the voltage is 220 volts. Locate in Fig. 41 the intersection of the 70 per cent. vertical power-factor line with the diagonal representing 746 watts. The horizontal line passing approximately through this point, repre-

* Torque measured with brake-arm and scales at 1 ft. radius.

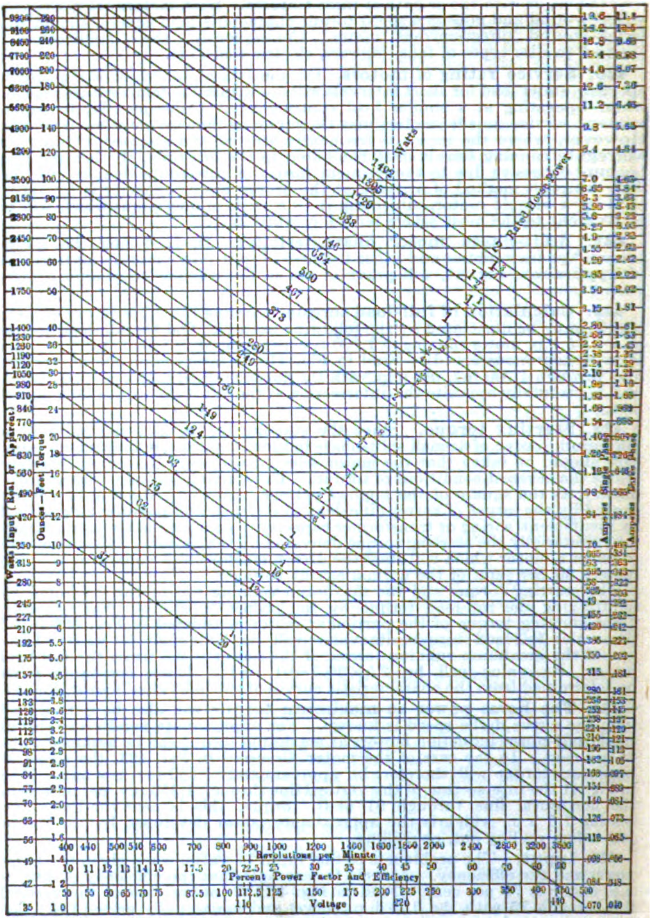


Fig. 41.—Characteristics of split-phase motors.

sents 1,050 apparent watts. Then from the intersection of the vertical line representing 220 volts with the diagonal representing 1,050 watts, the horizontal line representing amperes may be determined, namely, 4.8 amp. single-phase, or 2.8 amp. three-phase. The current per terminal in a two-phase motor is one-half that for a single-phase motor, and in this case would be 2.4 amp.

427. Approximate power requirements of small motor device machines used in the home, office and shop

Device		Motor			
Name	Capacity	Horse power	Starting condition	Rev. per min.	Belt
Air pumps	1 cu. ft. per min. air	1/4	Heavy duty	1,700	1 1/4 in. wide
Air pumps, 130 lb. pressure	2 1/4 cu. ft. per min	1/3	Heavy duty	1,700	1 1/2 in. wide
Air pumps, 130 lb. pressure	4 1/2 cu. ft. per min. air	1/2	Heavy duty	1,700	2 in. wide
Air pumps, 135 lb. pressure	6 cu. ft. per min. air	1	Heavy duty	1,700	2 1/4 in. wide
Bread mixers	Household size	1/6	Stand. duty	1,700	5/16 in. dia.
Candy mixers	Small sizes	1/3	Heavy duty	1,700	1 1/2 in. wide
Centrifuges	Small sizes	1/30	Light load	1,700	1/4 in. dia.
Coffee grinders	2 lb. per min	1/4	Heavy duty	1,700	1 1/2 in. wide
Coffee grinders	Household size	1/6–1/4	Stand. duty	1,700	1/4 in. dia.
Coffee roasters	25 lb. per min	1/6	Light load	1,700	5/16 in. dia.
Duplicating machines	Average size for office	1/6	Stand. duty	1,700	3/8 in. dia.
Egg beaters	Household size	1/8–1/4	Stand. duty	1,700	1/4 in. dia.
Envelope sealers	Average size for office	1/20	Light load	1,700	1/4 in. dia.
*Ice cream freezers	2 quarts	1/6	Stand. duty	1,700	5/16 in. dia.
Ironing machines	Rolls 7×26 in. long	1/6	Heavy duty	1,700	5/16 in. dia.
Ironing machines	Rolls 7×42 in. long	1/6	Heavy duty	1,700	3/8 in. dia.
Mailing machines	Average size for office	1/20	Light load	1,700	1/4 in. dia.
Meat grinders	Household size	1/6–1/4	Stand. duty	1,700	1/4 in. dia.
Revolving window table	Depends on display	1/12–1/4	Stand. duty	1,700	1/4 in. dia.
Sign flashers	Small size	1/20	Light load	1,700	1/4 in. dia.
Sign flashers	Medium size	1/12	Light load	1,700	1/4 in. dia.
Sign flashers	Large size	1/6 and up	Light load	1,700	5/16 in. dia.
Small water pumps	120 gal. per hour	1/6	Heavy duty	1,700	3/8 in. dia.
Vacuum cleaners	Average portable	1/6	Stand. duty	1,700	5/16 in. dia.
Vacuum cleaners	Small stationary 600 r.p.m.	1/4	Heavy duty	1,700	1 in. wide
Vacuum cleaners	Aver. stationary 600 r.p.m.	1/3 and up	Heavy duty	1,700	1 1/2 in. wide
†Washing machines	9 sheets	1/6	Heavy duty	1,700	3/8 in. dia.
†Washing machines	6 sheets	1/6	Heavy duty	1,700	5/16 in. dia.
Water pumps	60 gal. per hour	1/3	Heavy duty	1,700	1 1/4 in. wide
Water pumps	720 gal. per hour	1	Heavy duty	1,700	2 1/4 in. wide

* Speed of freezer about 175 rev. per min.

† Includes wringer.

resistance. A typical starter* of this class is illustrated diagrammatically in Fig. 42.

The **no-voltage release** which is usually a part of the direct-current starter consists of the resistance-controlling lever (Fig. 42) normally held at the extreme left or in the open-circuit position by means of a spring, and an electromagnet in series with the shunt field of the motor, adapted to hold

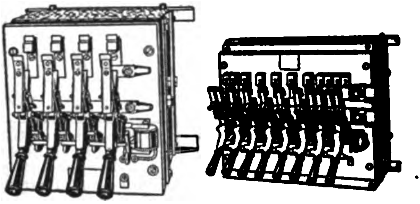


Fig. 43.—Direct-current starter for large motors.

the starting lever in the full-speed position as long as there is voltage on the line. In case of voltage failure this magnet will be de-energized, and the starting lever will return to its open-circuit position. This no-voltage release magnet is sometimes placed in the shunt-field circuit, and is sometimes connected across the line. The former arrangement is preferable because the motor circuit will be opened in case of failure of the shunt-field circuit.

In large capacities the use of a series of successively closed manually operated switches seems to be preferred by most controller manufacturers. Interlocks are usually provided which prevent the closure of such starting switches in any other than their regular order. Fig. 43 shows typical starters of this class.

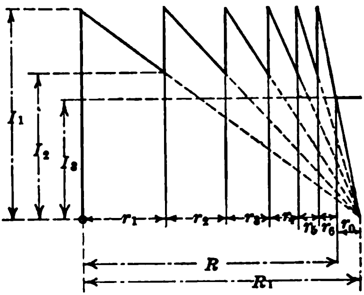


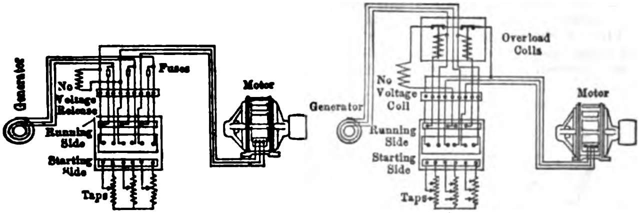
Fig. 44.—Direct-current motor starting current.

I_1 = Current peak.
I_2 = Current just before a step of resistance is cut out.
I_3 = Running current.
R_1 = Total resistance.
R = External or starting resistance.
r_o = Resistance of motor and its connections.
$r_1, r_2, \ldots, r_n$ = Resistance of starting steps.

431. Apportionment of resistance in direct-current starters. Fig. 44 shows the starting current required by a direct-current motor, it being assumed that a step of resistance is cut out each time the current falls to a predetermined value. For equal starting peaks the resistance must be divided unequally, the proper ratio between successive steps being a geometrical progression. The resistances of the steps, as well as the current peaks which will obtain, may be determined graphically from Fig. 44, where I_1 = initial inrush; I_2 = current at which a step of starting resistance is removed; I_3 = running current; r_0 = resistance of motor and its connections; R = external starting resistance. The ratios of progression with various numbers of starting steps, n, and for various values of a (which equals r_o/R) are given in the following tabulation:

* No. 27. Par. 468.

connecting the stator winding, first across reduced potential obtained from the starting transformer, then directly to the line. In large capacities these induction starters are often arranged to operate in three or more steps, thus reducing the current surges. For moderate-capacity machines they are generally designed to connect the stator first across transformer taps which deliver from 40 per cent. to 75 per cent. of line potential, and then to the line. Induction starters are almost invariably arranged to disconnect the starting-transformer windings from the line in all positions except the starting position.



(*a*) (*b*)

FIG. 47.—Induction starters for alternating-current motors.

Induction starters are also arranged to short-circuit the individual running fuses during starting. Sometimes the starting current is taken through auxiliary starting fuses of heavy capacity, but in most instances the motors are unprotected during starting. This class of starter is now almost invariably equipped with no-voltage release, and often with overload release which replaces the fuses. The overload release generally takes the form of overload relays which are adapted to open the circuit containing the no-voltage release magnet; this allows the switching mechanism to open the motor circuit. Where overload release is employed, the overload relays are individually short-circuited during starting. Fig. 47a is a connection diagram for a typical induction starter with no-voltage release and protected with fuses, while Fig. 47b shows the same device supplied with overload release.

In large plants one bank of starting transformers is sometimes employed for starting all motors, and a five-wire system is installed. Where this arrangement is employed the motors are first connected to a common line and two starting lines, and then directly to the distributing mains. Fig. 48 shows the arrangement described.

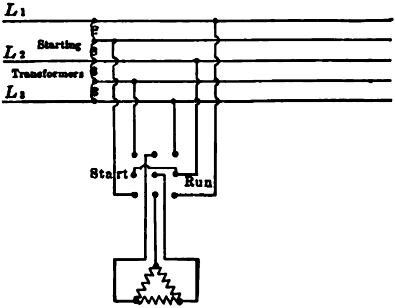


FIG. 48.—Five-wire system of starting alternating-current motors.

435. Secondary-resistance starters for alternating-current motors are used in connection with alternating-current slip-ring motors for the purpose of increasing the secondary impedance during starting, and are of the same general type as primary-resistance starters. Since slip-ring motors almost invariably have their secondaries wound polyphase, it is quite important that the starters used with such motors be designed to keep the secondary circuit as nearly in electrical balance as possible, for any unbalancing of this circuit reduces the starting torque which it is possible to obtain with a given line current. Generally speaking, unbalancing the secondary circuit 10 per cent. will reduce the possible torque by approximately 15 per cent.

In order to be quick acting and positive in operation, direct-current contactors should have coils which are capable of closing the switch with potential equal to 75 per cent. of normal impressed at the coil terminals, when the coils are at the operating temperature.

438. Alternating-current contactors are almost invariably called upon to handle two circuits simultaneously and are, therefore, almost invariably of the double-pole type. They are generally of the clapper form, but the magnetic circuit is necessarily laminated. Particular care should be taken to insure the holding of the laminations with sufficient rigidity to secure a permanent structure. The pull exerted by an alternating-current magnet is proportional to the square of the voltage impressed at its terminals, consequently it is not practicable to make alternating-current contactors which have the same operating range as direct-current contactors.

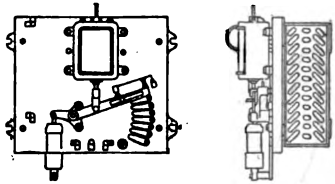


FIG. 50.—Direct-current time-acceleration starter.

It is practically impossible to obtain sufficient sealing pressure with alternating-current magnets to allow the use of laminated contacts, and, as a result, most alternating-current contactors depend upon butt contacts of copper for opening the circuit and for carrying the current when closed. Alternating-current contactors designed for voltages up to 550, are almost invariably equipped with magnetic blow-outs, and those built for higher potentials are generally arranged to open the circuit under oil. Air-break contactors have been made, however, for potentials up to 2,200 volts. These high-potential contactors are equipped with horn-type arc gaps, which permit the arc to increase in length until it reaches the point of disruption.

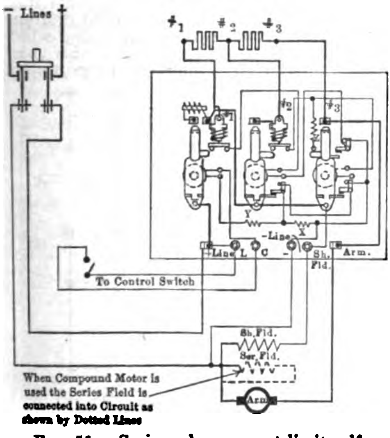


FIG. 51.—Series-relay current-limit self starter.

439. Time-acceleration self-starters are designed to accomplish the necessary starting operations in a predetermined and adjustable period. The timing may be accomplished in many ways, but a solenoid whose action is retarded by an adjustable dash-pot, is perhaps the most widely used device. A typical direct-current time-acceleration starter is shown diagrammatically in Fig. 50.

440. Current-limit self-starters are devised to halt the starting operation whenever the required starting current exceeds an adjustable predetermined value, the starting operation being resumed when the current falls below this limit. There are several forms of current-limit acceleration self-starters, and only those which are most widely used will be described.

441. A series-relay current-limit self-starter is shown in Fig. 51. It will be noted that the starting resistance is removed from the motor circuit by a series of successively energized magnetic switches or contactors. The motor circuit is initially closed by operating a control switch, thus from the positive line through the shunt-field windings, "f," to the negative line; also from the positive line through the armature, "A," the series field, "F," the resistance sections, "V_3" "V_2" "V_1," and the operating coil, "C_1" of the first series accelerating switch, to the negative line. If the initial current inrush is in excess of the value at which "C_1" locks open, no resistance will be cut out until the accelerating current has fallen to the point which will permit "C_1" to lift its plunger. When "C_1" lifts its plunger, switch "S_1" is closed, thereby short-circuiting resistance section "V_1" and including the winding "C_2." The operation of these series switches is progressive. When "C_3," the last of the accelerating windings, closes its switch "S_3," windings, "C_1," "C_2" and "C_3," are short-circuited and the shunt winding, "H_3," is connected in circuit directly across the lines. Winding "H_3" serves to hold "S_3" closed during running, thus guarding against the dropping out of the accelerating switches should the motor operate under light load.

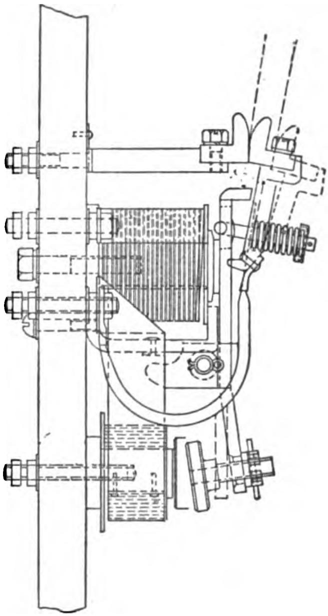


Fig. 54.—Magnetic lock-out switch.

443. The magnetic lock-out switch, illustrated in Fig. 54. is applicable to direct-current motors. It is a clapper-type switch of conventional form, operated by a series winding instead of shunt, and having a second series winding, separately mounted, adapted to act on a downwardly projecting extension of the switch clapper, and to hold the switch open as long as the force exerted by this secondary winding exceeds that of the closing coil. An adjustment is provided by which the air gap between the secondary or locking-out coil and its armature can be varied; thus the current above which the switch will be locked in an open position can be adjusted through a wide range.

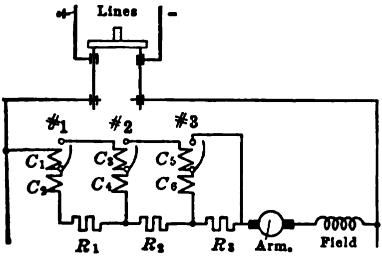


Fig. 55.—Starter comprising three magnetic lock-out switches.

Referring to the diagram, Fig. 55, which covers a simple starter consisting of three magnetic lock-out switches, it will be noted that when the line circuit is closed, the motor current passes from the positive line through the two windings of the first magnetic lock-out switch, thence through three sections of starting resistance to the armature of the motor to be started. As long as the current passing through these windings is in excess of a predetermined and adjustable value, the restraining force exerted by the lower or locking-out magnet will exceed the attractive force exerted by the upper or closing magnet, and the switch will maintain an open-circuit position. When the current has fallen below this predetermined value, the upper or closing magnet will develop sufficient pull to overcome the lock-out winding. As soon as the contacts of the switch engage, one section of the starting resistance is removed, and, with this section, the lock-out coil, so that any tendency which this coil might have to hold the switch in an open-circuit position is entirely removed. No. 1 accelerating switch, in closing, not only short-circuits a section of the resistance and its lock-out coil, but also automatically includes both windings of the second accelerating switch, which in turn locks open until the starting current has

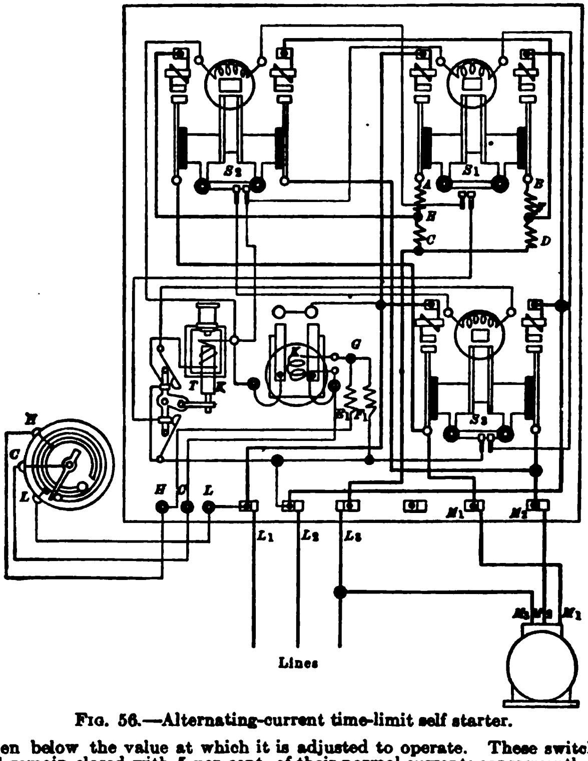


Fig. 56.—Alternating-current time-limit self starter.

fallen below the value at which it is adjusted to operate. These switches will remain closed with 5 per cent. of their normal current; consequently no shunt winding is ordinarily required for the last switch.

444. The counter-e.m.f. starter for direct-current motors is in reality a current-limit starter. In this device the starting resistance is removed by a series of magnetic switches whose operating windings are connected across the motor armature; these switches close successively as the counter e.m.f. of the motor increases with the speed.

445. Alternating-current induction self starters may also be of either the time-limit or current-limit type. In the former the primary windings are connected to the starting transformer for a predetermined length of time, and are then thrown directly on the line. Fig. 56 shows a typical starter of this class. A very similar starter is employed for the control of secondary starting resistance, the removal of the starting resistance being accomplished after a predetermined time interval. Both induction and primary-resistance self starters of the current-limit type are manufactured, but have not proven as satisfactory as the time-acceleration type on account of the low starting torque of squirrel-cage motors, and the possibility of their being so loaded that they will not accelerate sufficiently to enable a current-limit type of starter to change from starting to running position. Fig. 57 shows a current-limit acceleration controller for use in connection with an alternating-current slip-ring motor. This controller consists of a primary contactor and two

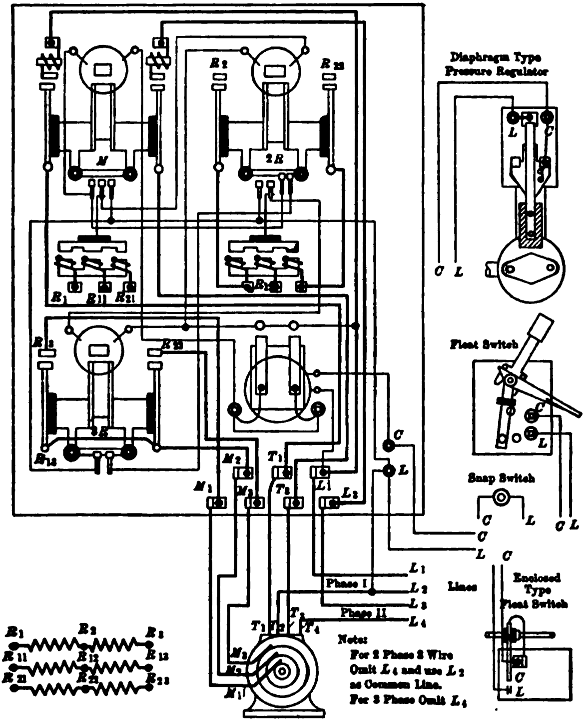


FIG. 57.—Alternating-current current-limit self starter.

secondary resistance contactors, all of which are double-pole type. The operation of the primary contactor may be controlled by a pressure regulator, a float switch, or a simple snap switch. The secondary resistance switches are arranged for successive operation, and are governed by two 3-phase, secondary series relays, which are arranged to halt acceleration whenever the motor current exceeds the value for which they are adjusted.

SPEED REGULATORS

446. Direct-current speed regulators. The speed of direct-current motors may be varied in two ways: first, by varying the potential impressed at the armature terminals, the field strength remaining constant (the speed

110 and 220, or 125 and 250 volts at the motor armature. To obtain reasonably small speed increments throughout the entire speed range, these three-wire systems require a motor whose speed may be varied by field control through a wider range than is required where a motor is operated on the four-wire system.

449. The field strength of a motor may be varied by electrical or mechanical means. When this is accomplished electrically, the field strength is generally varied by a field-regulating rheostat. Field regulation is effected mechanically by changing the air gap and consequently the reluctance of the field circuit. Either method produces the same results, the former having the advantage that the regulating rheostat can be conveniently located at some distance from a motor, also that the field strength can easily be increased to normal during starting.

The extent to which the speed of a motor can be varied by field control depends upon its design. Generally speaking, a standard machine will seldom commutate well if its speed is increased in this manner more than 20 per cent., while specially designed inter-pole motors have been built for speed ranges as great as 10 to 1. On account of their good inherent regulation and their high efficiency at all speeds, field-control motors are almost universally employed where speed control of direct-current motors is required.

450. A combination of armature-resistance and field control may be used to advantage where reduced speeds are required for comparatively short periods, and the expense of installation can be materially reduced by such procedure. It will also be found where a wide range of speed is required in connection with the Ward-Leonard system (Par. 468, No. 18), Fig. 56, that it will be advisable to regulate the field strength of the motor as well as that of the generator.

451. Self-starting speed regulators. In machine-tool practice, self-starters are used to start and stop machines whose speeds are adjustable by a regulator controlling the motor fields. Such self starters may be equipped with a vibratory field-regulating relay, the winding of which is connected in series with the motor armature. When the armature current reaches a predetermined value this relay will short-circuit the field rheostat, thus increasing the motor field strength to normal. The field strength is continued at normal until the armature current decreases sufficiently to allow the relay to drop, thus inserting the field resistance and increasing the armature current because of the reduced counter e.m.f. Increase in armature current causes the relay again to short-circuit the field rheostat, and the relay continues to vibrate, alternately short-circuiting and cutting in the field resistance, until the motor has accelerated to such an extent that the field resistance may be left in circuit without causing the armature to take a current in excess of the relay setting.

452. Series-parallel control of two motors is a convenient and efficient means of obtaining two speeds, one speed being one-half the other. Such a control system has the added advantage of reducing the current required to produce a given starting torque. This system of control is most widely used in railway work (also see Par. 468, No. 10).

453. Speed control of squirrel-cage motors may be accomplished in two ways: first, by changing number of poles; second, by varying the combined voltage and frequency impressed on the primary. The number of poles may be changed by the use of separate windings and selective energization, or by regrouping the windings to change the number of poles. The former method is employed where more than two speeds are required. To obtain a 1 to 2 ratio the windings are generally connected as shown in Fig. 60. It should be particularly noted that in changing from the star, or half-speed connection, to the double star, or full-speed connection, it is necessary to reverse two of the incoming lines in order to prevent the motor from running in a reverse direction.

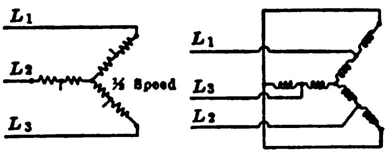


Fig. 60.—Two-speed squirrel-cage motor.

tends to oppose the first ("A"). See also Par. 468, No. 6. The synchronous speed for each of the concatenated connections can be determined as follows:

$$S = \frac{\text{cycles} \times 120}{P_1 \pm P_2} \quad \text{(rev. per min.)} \qquad (9)$$

where S is the synchronous speed in rev. per min.; P_1 is the number of poles of motor "A"; P_2 is the number of poles of motor "B." The plus sign should be used when the motors are in direct concatenation, and the minus sign when in differential concatenation. The diagram in Fig. 61 shows the connections for a cascade system.

There are so many methods by which the speed of one or more slip-ring motors can be varied (see Par. 468, No. 6, 7, 15 and 26), that it is impossible to cover them all in the limited space available.

457. Single-phase motors of the repulsion type may have their speed varied either by the use of primary resistance, or by shifting the brushes. The results obtained by various motor manufacturers are so widely diverse as to make it almost impossible even to outline the limitations of such systems.

458. Synchronous motors are not susceptible of speed control; see Par. 468, No. 22.

ELECTRICALLY OPERATED BRAKES

459. Classification. In the control of electric motors it often becomes desirable to provide a brake which is electrically released and applied by a spring or weight. Such brakes are made in three types—the multiple-disc, the band and the shoe type.

460. Band brake. In one type of band brake, a wheel is attached to the shaft to be braked, and this wheel is encircled by a band lined with a suitable friction material. Normally the band is brought into frictional engagement with the wheel by means of a spring; a solenoid is provided for the purpose of compressing these springs and relieving the brake band. The band brakes are manufactured for either alternating-current or direct-current service.

461. A multiple-disc brake is illustrated in Fig. 62. This typical form of brake is manufactured only for direct-current service. It consists of

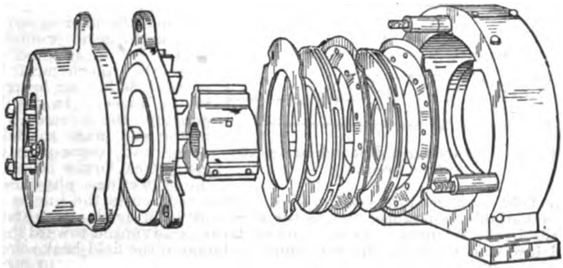


FIG. 62.—Exploded view of multiple-disc brake.

a hub which is mounted on the shaft to be braked, to which hub are keyed one or more discs and a stationary frame, in which are carried, by means of keys, two or more stationary discs. Normally the rotating discs are clamped between the stationary discs by the action of a spring, and by means of an electromagnet this spring can be compressed and the pressure on the friction discs relieved.

462. Shoe brake. A typical shoe brake differs from the band brake only in that the movable friction face is in the form of a shoe rather than in the form of a band. These shoe brakes are also made for alternating-current or direct-current service.

463. Advantages of the various types. The disc brake has the advantage, over either other type, of imposing no side strains on the shaft to which connecting a fixed step of resistance across the terminals of the motor armature after the line circuit is interrupted. As a result of this procedure the motor acts as a generator and serves to retard and stop the machine which it drives. While it is possible to effect a quicker stop by this method than if it were not employed, it does not provide for the quickest stopping that can be obtained; it is obvious at once that as the motor speed decreases, the potential generated by its armature correspondingly decreases, and the reduction in current which the armature will send through the fixed step of resistance results in a gradual diminution of the braking force, until it reaches zero when the armature stops.

Inductive resistance is often employed in the braking circuit for the purpose of prolonging the period during which the braking current remains at high value, and quicker stoppage can be effected by its use. Where the quickest possible stop is desired, a variable resistance should be connected across the motor armature; this resistance should be reduced by a series of magnetic switches, the successive closure of which will be halted whenever the braking current exceeds a predetermined value. With such an equipment, the braking current can be maintained at a high value throughout the entire stopping period, and much faster results obtained than are possible by any other method. In the interest of economy the starting resistance and the accelerating switches are generally employed for graduated dynamic braking. Thus the same apparatus which is used to limit the current of acceleration, serves also to limit the current of retardation.

467. Alternating-current motors can be used for dynamic braking only when direct-current is available for their excitation; the method is seldom used, for this reason. For quick stopping, the reversal of the primary and the inclusion of a high resistance in the secondary is equally effective and does not require direct current. For the retardation of descending loads it has not been very popular, largely on account of the general unpopularity of alternating-current motors for this class of service, direct-current machines being better adapted on account of their inherent characteristics (Par. 468, No. 11).

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SECTION 16

ELECTRIC RAILWAYS

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TRAIN RESISTANCE

4. Tests. Careful experimental tests, carried out during the past few years with electric locomotives and motor-cars, have thrown new light on the much discussed question of train resistance at the higher speeds. Without, in any way, disparaging the care taken in tests made with steam locomotives, it was not until electrical methods of measuring power introduced greater accuracy than was possible by use of the steam indicator, that consistent results became obtainable with light trains operating at very high speeds.

The electric motor was the means of introducing the single-car train operating at speeds up to 70 miles per hr. At that time no data were extant concerning the operation of single-car trains. It was soon found that such a car operating alone required an input out of all proportion to the power required to propel a train composed of several such cars operating at the same speed, consequently new adjustments had to be made in train-resistance formulas then existing.

During the spring of 1900, a series of tests were made by Mr. W. J. Davis, Jr., on the Buffalo & Lockport Railway, which consisted in running a 40-ton electric locomotive alone and with trailers at speeds approaching 60 miles per hr., as a maximum. These tests probably constitute the first consistent attempt to utilize the benefits of greater accuracy which electrical methods of recording afford. Since then other tests, taken under better conditions and with various classes of equipment, afford data from which it is possible to predict, with a considerable degree of accuracy, the total resistance (wind, bearing and rolling) opposing the movement of cars or light trains up to speeds of 100 miles per hr.

5. Train resistance may be expressed in pounds tractive effort exerted at the rim of the driving wheels of the prime mover of a train. It includes all losses in bearings, losses due to rolling friction, bending rails, flange friction, etc., and the wind-resistance loss. The last item is made up of head-on resistance, skin or side resistance and eddy currents caused by the suction at the rear of the car or train. All these variables depend upon the condition of bearings, design of trucks, condition of the road-bed, shape and cross-section of cars, direction of wind, etc., so that any tests, to furnish authoritative data, must be sufficiently comprehensive to eliminate the errors of purely local conditions. As no such elaborate series of tests have yet been made, any formulas predicated on the data available must at best be approximate.

Data are available on the performance of locomotives and cars of modern construction as follows: Buffalo and Lockport experiments in 1900; Zossen high-speed tests in 1902-3; tests on New York Central type locomotive at Schenectady, 1905-6; tests on car No. 5 at Schenectady, 1906; tests made by the Electric Railway Test Commission, on the test car "Louisiana," 1904-5; New York Subway tests, 1905; Dynamometer car tests by Prof. Edward C. Schmidt, University of Illinois, 1910.

Many isolated tests have been made from time to time other than those mentioned above, but either the data was not sufficiently complete or the conditions were too unfavorable to justify using the results obtained as applying to other than local conditions. The data comprised in the tests given above are sufficiently general, as they include the operation of trains varying from a single 35-ton car, to a train of 532 tons, and at speeds up to 130 miles per hr. in the Zossen tests.

6. Frictional resistance. The laws governing the **friction of journal bearings** are fairly well understood, and such bearing friction opposing the motion of a train, need introduce no undetermined factors in a calculation of train resistance. Such friction losses decrease with the pressure on the bearings and are a function of the speed. Hence, the expression, $f' = A' + B'S$, where f' is bearing friction expressed as lb. per ton, A' and B' are constants determined by experiment (see Par. 8) and S is the speed expressed conveniently in miles per hr. **Rolling friction** (see Par. 22) is due to the friction of metal rolling on metal where the surfaces are not perfect; the bending of rails due to insufficient support, or meager cross-section of rail; and flange friction between rail and wheel flange. All these factors are proportional to speed, and hence may be represented by a straight line function of speed. As bearing and rolling friction are both approximately proportional to the speed they may constitute the first two terms of a train resistance formula,

$$f_1 = A + BS \qquad \text{(lb. per ton)} \qquad (1)$$

tory experiment and previous experimental train tests by Davis in 1900. Hence, that portion of train resistance which results from the effect of wind may be given by the relation

$$f_3 = \frac{CaS^2}{w} \qquad \text{(lb. per ton)} \qquad (3)$$

where f_3 is the wind resistance in lb. per ton, C is a constant, a is the projected area, and W is the train weight in tons. This equation leads to the third term of Eq. 4.

Values of C (*Kernot*, 1894)

$C = 0.004$ for flat surfaces, $C = 0.0020$ for cylinder,
$C = 0.0024$ for octagonal prism, $C = 0.0014$ for sphere.

11. Method of making wind resistance experiments. The simplest and most accurate is the coasting method, where a moving train is allowed to drift until it reaches standstill, the rate of speed decrease and elapsed time being accurately noted. The efforts of most experimenters have been directed toward securing such data during periods of no wind in order to eliminate this troublesome feature. However, a series of runs taken with and against a wind of known velocity offers much data not otherwise available, and affords a ready means of solving directly for the coefficient of the second and third term of the train resistance formula (Eq. 4).

For example, given a wind of 20 miles per hr. velocity, a series of runs made with and against such a wind will, at say 50 miles per hr. train speed, correspond to a wind pressure at 30 miles per hr. with the wind and 70 miles per hr. against the wind, the rolling friction being constant at the value obtaining at the train speed of 50 miles per hr. As the wind pressure varies as the square of the speed, such a series of tests affords a means of determining the coefficient of S^2 for the particular type of equipment used.

12. The shape of the car end has a large influence upon the coefficient of S^2, such a result being reasonably expected from the results of experiments by Goss, Kernot and others: in fact, Davis checked up the values of 0.004 found by Kernot for flat surfaces. As a matter of fact, no cars or locomotives used for high-speed service have perfectly flat ends, and hence, all experimental values of C have been found to be less than 0.004.

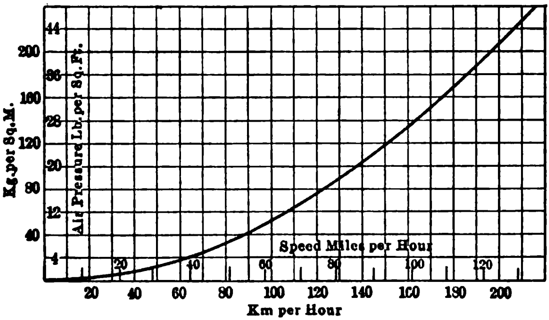


FIG. 1.—Wind-resistance test (Berlin-Zossen).

Little attempt has been made to construct cars for least wind effect, owing largely to a lack of full understanding of the benefits to be secured thereby. The cars used for high-speed suburban service and all electric locomotives, with few exceptions, are provided with partially rounded ends, with the result that the effective wind pressure is considerably reduced. A notable example of the extreme type of pointed nose design is the steel gasolene motor-car No. 7, of the Union Pacific Company, and such construction is a step in the right direction.

Values of C vary from 0.004 with perfectly flat ends to 0.0015 with noses

It is very possible that the higher values obtained at the maximum speeds were influenced by reason of the track being not rigid enough for speeds of 120 miles per hr., and hence increasing the value of B.

15. A consideration of trains of several cars makes it necessary to introduce an additional factor in the third term of the proposed train-resistance formula that shall express the effect of the wind resistance upon the sides of the succeeding cars. The head-on wind resistance is borne by the leading car, and hence additional cars only introduce the additional skin friction offered by a train of greater length.

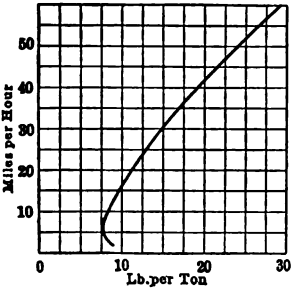


FIG. 4.—Train resistance (General Electric tests); weight 63,000 lb.

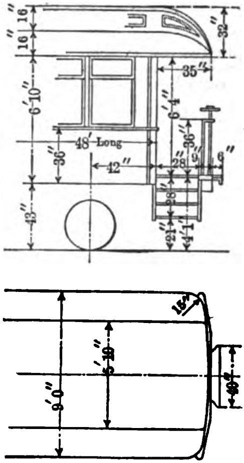


FIG. 5.—Elevation and plan, car No. 5 (General Electric tests).

16. The most reliable and exhaustive series of tests made with trains composed of a different number of cars is offered in the experimental runs of the New York Central locomotive No. 6,000, during its 50,000-mile endurance run, hauling trailers up to a nine-car train. Over 140 runs under different climatic conditions are condensed in the series of curves shown in Fig. 6, where the train resistance is expressed in pounds per ton weight of total train including locomotive. This set of curves indicates very plainly the reduction in train resistance per ton of train with the increase of train weight, such a reduction being largely due to the fact that the head-on wind resistance remains constant for any composition of train, being influenced only by the shape and cross-section of the locomotive.

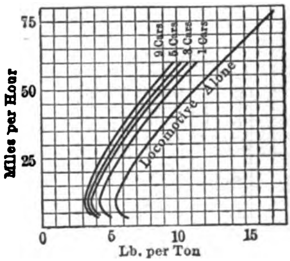


FIG. 6.—Train-resistance runs (N. Y. C. locomotive and train).

17. The increase in skin friction along the surface of succeeding cars corresponds closely to 10 per cent. of the value of wind resistance as expressed by Eq. 3, and for a train of several cars the expression for wind resistance becomes,

$$f_3 = \frac{CS^2a}{W}\left(1+\frac{n-1}{10}\right) \qquad \text{(lb. per ton)} \qquad (5)$$

where n represents the number of cars in the train. This may be substituted for the third term of Eq. 4.

The results of a series of dynamometer car tests conducted by the Engineering Experiment Station of the University of Illinois, are given by Prof. Edward C. Schmidt in a paper read before the A. S. M. E., May 14, 1910. These tests covered a wide range of car weights and train speeds; Fig. 14 gives the results thereof.

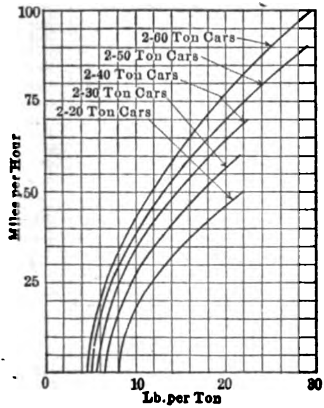


FIG. 10.—Train resistance, two-car train.

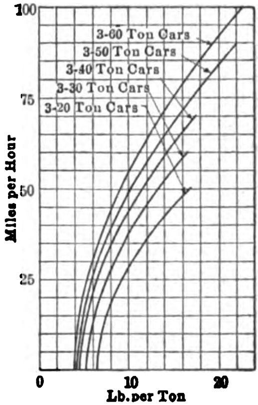


FIG. 11.—Train resistance, three-car train.

20. Track curves are usually expressed in degrees; a 1-deg. curve is taken arbitrarily as one in which a 100-ft. chord will subtend an arc of 1 deg. or, which is the same thing, will subtend a 1-deg. angle at the centre. Hence the radius of a 1-deg. curve is approximately $(100 \times 360)/(2\pi) = 5{,}730$ ft. Similarly the radius of any curve in feet is approximately 5,730/No. of deg.

21. Curve location. This custom of rating curves by degrees instead of by radius has undoubtedly arisen from the facility offered for laying out a curve in the field with a transit. For instance, a transit is set up at the point of curve, *PC* (Fig. 15), and several angles, *BAB*, *BAC*, etc., each equal to one-half the degree of the curve are laid off. In the first of these directions 100 ft. is measured off and a stake driven. From this stake another 100 ft. is measured off and lined in by the transit in its second position. One-hundred-foot chords are thus laid off until point of tangent *PT* is reached. As indicated in Fig. 15, this point is seldom at an even station, but is always indicated by a stake marked as shown, *PT*. Sta. 102+80. Likewise with the point of curve, *PC*. In case the *PC* is not at an even station, the first stake of the curve is driven at an even station so that the remaining stakes of the curve will come at

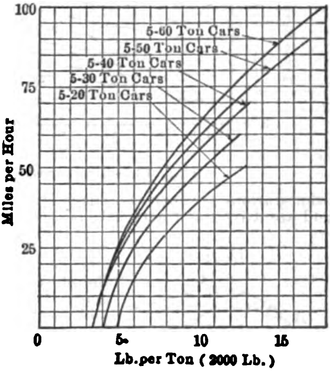


FIG. 12.—Train resistance, 5-car train.

resistance calculations except in the calculation of locomotive constants assigned to mountain grade service, where both sharp curves and heavy grades occur.

23. Grades are expressed in percentages, being the ratio of the distance the train is raised to the distance travelled, in other words, the ratio of the ordinate of a right-angled triangle to the hypothenuse. A grade of plus 1 per cent. is one where the train is raised vertically 1 ft. for each 100 ft. travelled; a minus 1 per cent. grade is one where the train falls 1 ft. for every 100 ft. of distance travelled. It follows that a plus 1 per cent. grade calls for a tractive effort of 20 lb. per ton, while a minus 1 per cent. grade is equivalent to delivering a tractive effort of 20 lb. per ton to the train.

Where gradients are small it is not necessary to consider the reduction in train weight due to the angle of direction of travel to the true horizontal in calculations of friction (Par. 6) and adhesion (Par. 28). However, with the excessive grades, it is necessary to correct for effective train weight.

Grades are divided in railway parlance into virtual grades and ruling grades.

24. Virtual grades are of limited length and are so called as they express the equivalent grade, a value always something less than the true grade. A train running at constant speed can surmount a certain grade as determined by the maximum tractive effort available. The moving train however may be compared to a fly-wheel, and has stored in the moving mass a large amount of energy, which is usually expended in heating the brake shoes during the period of stopping. This stored energy may be used to furnish the extra tractive effort required to ascend a heavier grade than the available locomotive tractive effort alone would permit, but in such a case the grade must be of short length. Hence, the actual grade may be considerably in excess of the virtual grade, provided it is so short that the inertia of the moving train can supply the additional energy required to ascend it.

25. The ruling grade means the maximum grade encountered on a given section of track and may be the actual grade, where such is of long extent, or the virtual grade, where the inertia of the train may be used to advantage in overcoming a heavier short grade. The ruling grade of freight hauling roads should be limited to 2 per cent. or less when the topography of the country will permit, in fact, on a modern freight road any grade exceeding 1 per cent. maximum would be considered excessive, and would demand the use of helper locomotives. While low grades are not so important on electric suburban railways where the income is largely derived from passenger receipts, the future possibilities of freight traffic over these lines makes a low gradient desirable whenever possible.

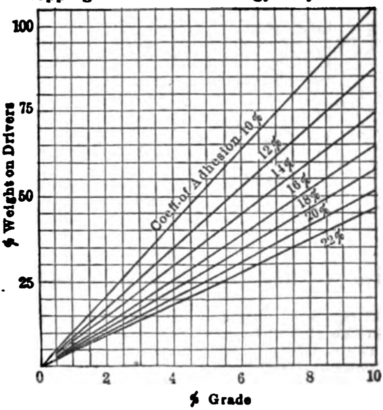


Fig. 16.—Relation between per cent. weight on drivers and per cent. grade.

26. Coefficient of adhesion expresses the ratio between total tractive effort and weight on drivers. Coefficient $= F_e/W$ where F_e is the maximum possible tractive effort in lb., and W is the weight on the drivers in lb.

This is expressed in per cent. and is a variable depending upon the condition of track and composition of wheel. See Par. 27.

It is good practice to design the motive power of a car or locomotive so that it can slip the wheels on a dry rail, this practice not being strictly foltotal tractive effort on grade is expressed by the sum 4+10+(20×per cent. grade), in lb. per ton.

Based upon above formula, Fig. 17 is made up, giving the **weight of locomotive required** to operate trains from 500 to 3,000 tons gross weight on any grade. It is assumed that all the locomotive weight is on the drivers, an assumption that may hold true in slow-speed freight service if the alignment is good. Where pony or bogie guiding trucks are necessary for safety in rounding curves or to prevent "nosing," divide the values of locomotive weight as obtained from Fig. 17, by the percentage of weight on drivers to total locomotive weight obtaining in the design of locomotive required.

SPEED-TIME CURVES AND MOTOR CHARACTERISTICS

31. Acceleration. The many problems connected with train acceleration can be treated either analytically or graphically. As will be shown later, there are so many variables entering into the consideration of train movements at variable speeds that the analytical method becomes somewhat complicated and difficult to follow. The graphical method is equally as accurate, much easier to work with, and the final results are given in such form that they are of general application without calling for the familiarity of terms and symbols made necessary by the analytical treatment.

There are several terms used in connection with train acceleration phenomena which are defined in Par. 32 to 38.

32. Tractive effort is the torque in pounds developed at the rim of the wheels, divided by total train weight in tons. This term is usually expressed in pounds per ton of train weight and includes train resistance losses.

33. Braking effort, also expressed in pounds per ton is the opposite of tractive effort, expresses the force tending to retard the motion of the train and bring it to rest.

34. Rate of acceleration is the increment expressing the rate of increase in speed of train, and may be expressed in feet per sec. per sec., or miles per hr. per sec.—usually the latter.

35. Rate of braking is the increment expressing the rate of decrease in speed of train. Both rate of acceleration and rate of braking may vary considerably during successive periods of time, depending upon type of motive power and brake rigging used.

36. Train resistance a variable, expressed in pounds per ton and tending to retard the motion of the train (Par. 4 to 30).

37. Speed-time curves express the relation of the above variables in curve form, generally with speed in miles per hr. as ordinates, and elapsed time in seconds as abscissas.

38. Energy curves show the energy consumption, generally expressed as watt-hours per ton mile, for different rates of acceleration, braking and train resistance, for various elapsed times over a given distance run.

39. Curves of free acceleration. A better understanding of the possible movements of a car or train operating at different speeds over different distances, is obtained by eliminating the type of motive power and brake rigging used, and assuming straight-line acceleration, coasting and braking curves. The results so obtained are fundamental, and may be applied to examples, considering any type of motive power using a correction factor, which will be treated later, known as the efficiency of acceleration.

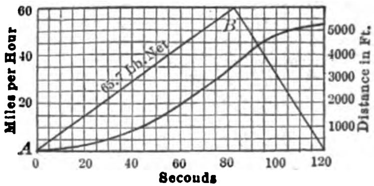


FIG. 18.—Typical speed-time-distance curve (no coasting).

40. The problem of train acceleration deals with the movement of a given weight over a given distance within a specified time. As it is impracticable to start and stop the train instantaneously, it is necessary to deal with some finite rate of acceleration and braking, thus giving rise to the simple form of speed-time curves shown in Fig. 18. The speed-time curve is here duction of friction occasions a falling off of speed during the coasting period proportional to the friction value taken, which for the sake of simplicity is here assumed to be constant at all speeds.

The speed-time curves shown in Fig. 18 and 19 both indicate the completion of the run of 5,280 ft. in 120 sec., although in one case the rate of acceleration was that produced by 65.7 lb. per ton, and in the other case by 100 lb. per ton. These curves are of equal area, as the distance in each case is 5,280 ft. Thus, it becomes possible to produce any number of speed-time curves, for a given distance and elapsed time, by varying the rate of acceleration with consequent variation in time of coasting.

A more extended set of curves is given in Fig. 20, for the same distance of 1 mile covered in 120 sec., the rate of acceleration varying from 0.713 miles per hr. per sec. as a minimum to an infinite number of miles per hr. per sec. as a maximum.

A train resistance value of 15 lb. per ton is assumed constant at all speeds and the dotted curve, *A*, *B*, is described by the loci of the maximum speeds reached with the different rates of acceleration. The highest maximum speed required is obtained with no coasting, and the minimum speed is obtained with an infinite rate of acceleration. The pounds per ton corresponding to the different accelerating rates are given as including 15 lb. per ton train resistance, hence the net tractive effort values corresponding to the rates of acceleration indicated are 15 lb. per ton less than the figures given.

43. Application of unit-distance speed-time curves. Instead of plotting similar curves for distances other than 5,280 ft., advantage may be taken of the fact that the area enclosed by the speed-time curve is proportional to the distance travelled and the coordinates are proportional to the square root of the enclosed area. It is convenient, therefore, to plot a full series of curves for one distance, preferably one stop per mile, that is, a distance of 5,280 ft. run, and to apply the results so obtained for any other distance by using a factor expressing the relation of the square roots of the distance travelled. This is shown in Fig. 21, where *A*, *B*, *C*, *D*, represents an area of 1 mile, or one stop per mile, *A*, *F*, *I*, *L*, two stops per mile with a factor of $1/\sqrt{2}=0.707$; *A*, *E*, *H*, *K*, four stops per mile with a factor of $1/\sqrt{4}=0.5$, and *A*, *G*, *J*, *M*, one stop in 1½ miles with a factor of $\sqrt{1.5}=1.225$.

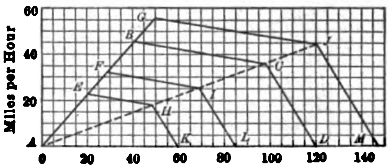


FIG. 21.—Similar speed-time curves (varying distances).

Referring to Fig. 19, it is obvious that a similar sheet could be prepared for any elapsed time other than 120 sec., using the same train resistance and braking values of 15 and 150 lb. per ton respectively.

44. Imposed time limits. In Fig. 22 is shown the time limits imposed by 15 lb. per ton train resistance, and 150 lb. per ton braking for any length of run and any rate of acceleration. The dotted curves indicate the loci of the several maximum speeds reached with different accelerating rates for a run made in a given elapsed time. Thus the dotted curve terminating at 80.7 lb. per ton is a reproduction of the similar dotted curve, *A*, *B*, given in Fig. 20, and gives the maximum speed reached with any rate of acceleration for a run of 5,280 ft. in 120 sec. with 15 lb. per ton train resistance and 150 lb. braking effort. Similarly, the dotted curve terminating at 100.4 lb. per ton gives the limiting maximum speeds reached, with any rate of acceleration, when a run of 5,280 ft. is accomplished in 110 sec., using the same values of train resistance, braking, etc.

45. Time limits with and without coasting. The full line *C*, *D*, gives the angle made by a coasting line when the rate train friction is 15 lb. per ton. Thus, in a run completed in 120 sec., the minimum accelerating rate corresponds to 80.7 lb. per ton (gross), with no coasting introduced, for here braking commences as soon as acceleration ceases.

Example: Given a distance of 8,000 ft., train resistance 15 lb. per ton, braking effort 150 lb. per ton, tractive effort gross 67.4 lb. per ton (including 15 lb. per ton train resistance), what is the minimum time required to perform the run and what maximum speed is reached?

Solution: From Fig. 22, minimum elapsed time with 67.4 lb. tractive effort is 130 sec. with no coasting. Ratio of distances $= \sqrt{8{,}000/5{,}280} = 1.23$. Hence for 8,000 ft. time of run $= 130 \times 1.23 = 160$ sec.; maximum speed for 5,280 ft. = 55.6 miles per hr.; hence for 8,000 ft. speed $= 55.6 \times 1.23 = 68.5$ miles per hr.

47. In actual practice, a certain amount of coasting is necessary; hence, the run of 8,000 ft. (Par. 46), would be made in somewhat more than the minimum possible limit of 160 sec., or else the tractive effort should be increased to allow for a higher rate of acceleration that would permit of some coasting. Fig. 22 is of universal application as it is not limited to any particular type of motive power, having its own peculiar speed characteristics. Moreover, the values of 15 lb. and 150 lb. chosen for train resistance and braking effort respectively are conservative operating values obtaining in practice.

48. The maximum speed reached during the performance of a service run will be little influenced by the type of motive power and its curve characteristics (See Par. 42). The values indicated in Fig. 22 will hold approximately true in service operation with series motors of either the alternating-current or direct-current types, and hence, the curves given constitute a set of fundamental data by means of which it becomes possible to attack any acceleration problem and determine the data required.

49. Electric motors used in railway service are of the following types:

(1) Series-wound direct-current motors,
(2) Single-phase alternating-current motors,
(3) Polyphase alternating-current induction motors.

In addition to the above, there have been several attempts at operating shunt-wound direct-current motors, but as such motors have not come into even partial use, owing to the superior qualities of other types, the shunt-wound motor will not be discussed.

50. Direct-current series-wound motor characteristics and applications. The direct-current series motor has the general characteristics shown in Fig. 23. Applying this motor characteristic to the performance of a car, it becomes necessary to reduce the motor voltage during the starting or accelerating period of the car in order to limit the tractive effort to a value that will not slip the driving wheels. In other words, if full voltage were to be applied to the motor at standstill, the resulting current would be enormous, would produce a torque that would slip the wheels, and would far exceed the safe commutating capacity of the motor. Hence, the necessity of introducing external starting resistance in successive steps during acceleration, with the result that the starting current is maintained practically constant at the full-load rating of the motor.

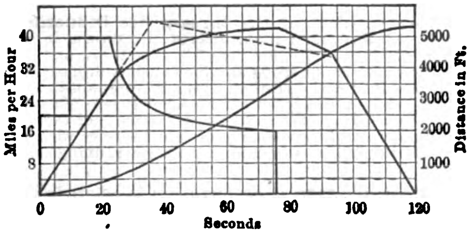


FIG. 24.—Typical speed-time curve with motor-curve acceleration.

51. A speed-time curve with direct-current series-wound motor is shown in Fig. 24, indicating a constant current input up to a speed of 28 miles per hr. At higher values of speed, the motor has full voltage applied

58. Table of accelerating rates

Locomotives	
Steam locomotives, freight service........	0.1 to 0.2 miles per hr. per sec.
Steam locomotives, passenger service.....	0.2 to 0.5 miles per hr. per sec.
Electric locomotives, passenger service....	0.3 to 0.6 miles per hr. per sec.
Motor Cars	
Electric motor cars interurban service....	0.8 to 1.3 miles per hr. per sec.
Electric motor cars city service	1.3 to 1.8 miles per hr. per sec.
Electric motor cars rapid transit service...	1.5 to 2.00 miles per hr. per sec.
Highest practical rate..................	2.00 to 2.5 miles per hr. per sec.

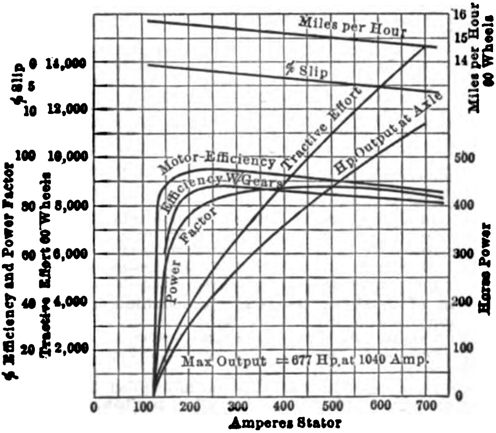


Fig. 26.—Typical polyphase induction motor performance.

59. Limits of acceleration rate. The rates given in Par. 58 apply only to that part of the accelerating period during which the current is maintained practically constant by means of cutting out successive sections of the external starting resistance. The higher rates from 1.0 to 2.5 miles per hr. per sec. demand a gradual increase to those values in order to avoid the discomfort to passengers that would surely result from a sudden application or cessation of such rates.

The coefficient of adhesion (Par. 26) also determines the accelerating rate by limiting the available tractive effort, thus giving rise to the values given above for locomotive practice. As the practice is common to run locomotives very close to the limit of adhesion for full-speed operation, it leaves but a small excess of tractive effort available to accelerate the train. High acceleration demands that all axles shall be equipped with motors, and if trains are run, that all cars must be motor cars, that is, no trailers are permissible when extreme accelerating rates are required to make the schedule desired.

60. Limits of braking rate. The limits reached in acceleration hold equally true in braking. As a matter of fact, acceleration may be at a higher rate than braking, for two reasons: first, discomfort to passengers is greater during braking of cross-seat cars, as the inertia of the passenger tends to carry him away from his seat and he lacks the supporting back that prevents discomfort during rapid acceleration when his body is pressed backward; second, in braking a train to standstill, it is necessary for the operator to stop within a distance of a few feet of a fixed spot, and the skill shown in judging speed and distance will determine the braking rate. During acceleration no such limit exists; the motorman has absolute freedom; in fact, a

67. The relation between schedule and maximum speed with arying frequency of stops is expressed in Fig. 27, which indicates the chedule speed possible to make with trains having a free running speed of 0, 45, 60 and 75 miles per hr. respectively.

Thus with a train geared for a free running speed of 60 miles per hr. t is possible to make a schedule of 45.5 miles per hr. with one stop in four niles, 37.5 miles per hr. with one stop in 2 miles, etc.

For frequent-stop service, a low free-running speed is desirable as it is asier on the equipment, calls for less motor capacity and less energy consumed in performing the service. Hence, it is advisable to use the lowest maximum speed that will give the schedule desired.

68. Effect of acceleration on frequent-stop service. When using Fig. 27, it should be recognized that where stops are more frequent than one per mile, the rate of acceleration becomes a controlling factor, and as shown in the curve, when the frequency of stops approaches three or more per mile,

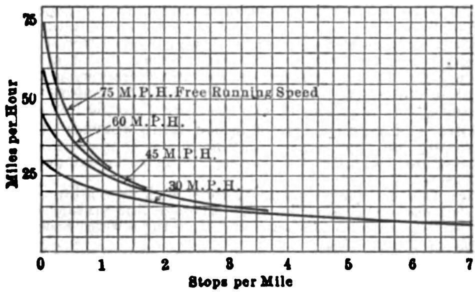


FIG. 27.—Relation between maximum and schedule speed and stops per mile.

the maximum free-running speed of the equipment does not have any appreciable effect upon the possible schedule speed. Hence, for frequent stop service where it is of great importance to attain the highest possible schedule speed, recourse should be had to Fig. 22, in order to determine the advantages of higher rates of acceleration than the 120 lb. gross which forms the basis of Fig. 29.

69. Effect of track curves on rapid service. In all classes of service, due recognition should be paid to the effect of curves of such short radii as to demand slowing down while rounding them. The safe speed at which a curve may be taken will depend upon the elevation of the outer rail, but a greater elevation than 8 in. is not common. Also curves having a spiral approach will ride much easier than those in which the tangent leads directly into the curve.

70. Safe maximum speed on track curves

Radius of curve, ft.......	10,000	5,000	2,000	1,000	500	200	100	50
Speed, miles per hr.......	100	75	50	35	25	15	10	6

The above values apply only when full elevation may be given outer rail. Speeds will be less when operating in city streets where such elevation is not possible, and where wheel flanges of three-quarters of an inch or less are the rule.

71. Limitations of theoretical schedules. On any road abounding in curves of short radius, it will not be possible to reach the schedules given in Fig. 27. No general rule can be given to fit all cases, as each problem must be treated according to local conditions. There is sufficient leeway in the schedules given in Fig. 27 to allow for irregularities of stops, as there is included a period of 10 sec. coasting that may be cut out when a stop has

Acceleration, expressed in miles per hr. per sec. = [(32.2 × 0.682)/2,000] × lb. per ton = (lb. per ton)/91.2. The above value of (lb. per ton)/91.2 applies only to the net lb. per ton available for car acceleration only. In this particular problem assume 7 per cent. of the accelerating tractive force as being required to overcome the inertia of the rotating parts, then the factor of acceleration expressed in miles per hr. per sec. = (net lb. per ton)/(91.2 × 1.07) = (lb. per ton)/97.5. Hence—acceleration = 122/97.5 = 1.25 miles per hr. per sec.

Assume that car resistance remains constant at all speeds up to 27 miles per hr., as error introduced thereby is so small as to make it unnecessary to plot the curve step by step until motor-curve running is reached at 27 miles per hr.

The several relations may be calculated as given in Par. 76.

76. Relation of speed, distance, amperes and time (Par. 74); example of detailed calculations

1	2	3	4	5	6	7	8	9	10	11
	27	1,090	116	974	1.25	21.6	21.6	428	428	140
2	29	980	119	861	1.10	1.82	23.4	75	503	130
2	31	790	126	664	0.85	2.25	25.6	99	602	112
2	33	640	133	507	0.65	3.08	28.7	145	747	97
2	35	540	140	400	0.51	3.92	32.6	196	943	86
2	37	440	147	293	0.37	5.40	38.0	286	1,229	76
2	39	370	155	215	0.28	7.15	45.2	410	1,639	68
2	41	310	163	147	0.19	10.5	55.7	633	2,272	61
2	43	270	172	98	0.13	15.4	71.1	952	3,234	57
2	45	230	180	50	0.06	34.4	105.0	2,230	5,464	52

NOTE.—1. Speed increment of 2 miles per hr. 2. Sum of speed increments. 3. Gross tractive effort as obtained from motor characteristics (Fig. 22). 4. Car friction per motor (Fig. 9). 5. Net tractive effort available for gross acceleration after deducting car friction. 6. Acceleration as obtained by dividing net accelerating force (column 5 reduced to lb. per ton) by acceleration factor as determined (97.5). 7. Time increment as determined from 1 and 6. 8. Total elapsed time summation of 7. 9. Distance increment as determined from 2 and 7. 10. Total distance traveled, summation of 9. 11. Amperes as determined from motor characteristics. Values in 3, 5, 6 are average values obtaining during increase of speed increment in 1.

77. Example of calculation of speed-time curves; effects of track curves, grades and coasting. The above example is worked out on basis of level tangent track. The calculation of speed-time curves is generally based upon this assumption. Where it is necessary to predetermine the performance of a motor operating over grades and around curves, add or deduct tractive force so consumed from gross tractive effort and proceed as in Par. 76. Also see Par. 22 and 23.

Completing the speed-time cycle by introducing coasting and braking requires the same treatment as in Par. 76 except that both coasting and braking are equivalent to negative acceleration. Another method of plotting speed-time curves is given by Mailloux in Proceedings American Institute of Electrical Engineers, June, 1902.

ENERGY AND POWER CONSUMPTION

78. The energy consumed in moving a train at constant speed is expended in overcoming train resistance (Figs. 9 to 14 inclusive) and internal motor losses. It is customary for manufacturers to give the net efficiency of railway motors after having carefully determined their internal losses from stand tests, and hence, the railway operator is concerned only with the

85. Train input for constant-speed running on level tangent track, motor-car service

(*Input values expressed in kilowatts*)

Train weight	Speed (miles per hr.)									
	10	20	30	40	50	60	70	80	90	100
2–20 ton cars.....	9.3	22.4	42.5	72.5	116.0	...	...	...	......	......
2–30 ton cars.....	11.5	27.4	51.4	87.0	137.0	206	...	...	......	......
2–40 ton cars.....	13.2	31.6	59.0	99.3	156.0	234	336	...	......	......
2–50 ton cars.....	14.8	35.5	66.3	111.0	175.0	261	374	520	699	......
2–60 ton cars.....	16.3	38.8	71.7	119.0	185.0	274	390	540	720	945
20 ton car........	6.5	16.2	32.0	56.7	93.5	...	...	...	......	......
30 ton car........	8.0	19.5	38.4	67.3	109.0	167	...	...	......	......
40 ton car........	9.4	23.1	44.1	76.2	124.0	188	276	...	......	......
50 ton car........	10.4	25.6	49.2	84.8	137.0	210	305	430	584	......
60 ton car........	11.5	27.9	52.8	90.2	144.0	218	316	442	599	792
3–20 ton cars.....	11.4	27.2	50.9	84.1	136.0	...	...	...	......	......
3–30 ton cars.....	14.0	33.3	61.8	103.0	162.0	240	...	...	......	......
3–40 ton cars.....	16.3	38.7	71.5	119.0	185.0	271	391	...	......	......
3–50 ton cars.....	18.4	43.7	80.6	134.0	206.0	308	437	602	805	......
3–60 ton cars.....	20.1	48.0	87.4	144.0	222.0	326	460	635	925	1,092
5–20 ton cars.....	14.8	35.3	65.4	109.0	171.0	...	...	...	......	......
5–30 ton cars.....	18.3	43.5	80.0	133.0	205.0	303	...	...	......	......
5–40 ton cars.....	21.3	50.8	93.2	154.0	237.0	348	493	...	......	......
5–50 ton cars.....	26.2	61.9	112.0	183.0	279.0	406	568	773	1,026	......
5–60 ton cars.....	31.3	72.8	130.0	208.0	312.0	448	622	835	1,100	1,415

86. Train input for constant-speed running on level tangent track, locomotive passenger service

(*Input values expressed in kilowatts*)

Gross train weight	Speed (miles per hr.)									
	10	20	30	40	50	60	70	80	90	100
200 tons.	17.5	41.2	75.8	124	196	277	398	530	710	920
300 tons.	26.1	60.5	108.0	172	258	369	511	689	905	1,160
400 tons.	32.0	79.0	139.0	219	330	462	635	840	1,100	1,405
500 tons.	41.0	99.0	170.0	268	395	563	755	995	1,295	1,645
600 tons.	50.0	118.0	203.0	315	464	645	875	1,150	1,489	1,890
700 tons.	59.0	135.0	235.0	363	530	735	996	1,305	1,682	2,132
800 tons.	69.0	154.0	267.0	410	596	828	1,117	1,460	1,878	2,375
900 tons.	77.0	173.0	300.0	459	663	920	1,238	1,615	2,070	2,620
1,000 tons.	85.0	193.0	330.0	507	730	1,011	1,358	1,771	2,261	2,860

87. Power required on grades. The values of power required to drive a car at any speed, apply only for constant speed on tangent level tracks. On up grades there is required an additional tractive effort of 20 lb. per ton for each 1 per cent. grade. Hence, to calculate power required on grades, proceed as follows:

The total train resistance is $F_0 = F + F_g$, in lb. per ton; wherein F is the train resistance in lb. per ton found from the curves, and F_g the tractive effort due to the grade (F_g = per cent. grade × 20). Then the power input is

$$P = \frac{2WF_0V}{1{,}000\eta} \qquad (16)$$

tion curves, as it eliminates the question of motive power with its internal losses, and considers only the moving train itself.

90. The energy required to move a train from rest to a given velocity is represented by

$$W = \frac{ms^2}{2} + F_0 L \qquad \text{(ft-lb.)} \qquad (18)$$

wherein m is the mass; s the velocity in ft. per sec.; F_0 the total train resistance in lb., and L the distance in ft. covered.

The most convenient form of expressing energy values is in watt-hours per ton-mile. Fig. 29 has been constructed from the speed-time data in Fig. 22, giving the energy consumption for any rate of acceleration and elapsed time for a distance of 5,280 ft. or 1 mile run. This set of curves is plotted with train resistance = 0, and hence represents the value of the energy of acceleration only.

91. Energy dissipated in braking. In bringing a train to rest by means of brakes, the energy stored in the train during acceleration and represented by $ms^2/2$ is all wasted in heating the wheels and brake shoes, and the values in Fig. 29 therefore represent the energy thus dissipated as heat. The curves have no value as applying directly to service conditions as all moving trains have more or less running resistance, but they are useful as indicating the energy required to accelerate the mass, all of which reappears as heat in the brake shoes and car wheels, unless some method of regenerative braking be used (Par. **115**). At best, however, such regenerative methods are vastly inefficient and the energy values given in Fig. 29 represent the price paid for a high schedule speed coupled with frequent stops.

92. Curves of energy consumption. Unless the train reaches a speed of more than 40 miles per hr. it is a sufficiently close approximation for preliminary calculations to assume a constant rate of train resistance of from 10 to 15 lb. per ton, the latter figure being the more conservative value. Hence, Figs. 30 and 31 are plotted with a constant value of train resistance at all speeds of 10 and 15 lb. per ton respectively. These curves used in conjunction with the speed-time curves of Fig. 22 permit of the complete solution of any acceleration problem so far as relates to performance of the train and its net energy consumption. For convenience, both speed-time and energy curves are made up with the same elapsed time for a mile run as abscissa, this distance run being chosen as being a convenient basis for comparison.

Having determined the watt-hours per ton-mile for a mile run, the same value holds true for any other distance run as long as the speed-time curve is entirely similar in every respect and the areas are proportional to the respective distances run. Thus, a mile performance in 120 sec. with a tractive effort of 90 lb. per ton (including 15 lb. per ton train resistance) will require an output rate of 73 watt-hr. per ton-mile, and the same energy, 73 watt-hr. per ton-mile, would be required to perform a run of half the distance in $1/\sqrt{2}$ times 120 sec., or 84.8 sec.

Thus while the speed-time curves must be changed in area proportional to the distance travelled, the value of energy consumption found for one distance holds equally true for any other distance made with a similar speed-time curve.

93. Example of calculation of energy consumption. Given a run of 1,760 ft. to be made in 75 sec., train weight 100 tons, 33.5 per cent. on drivers, coefficient of adhesion 12 per cent., train resistance 15 lb. per ton. Find energy consumption.

Available tractive effort $= 200{,}000 \times 0.335 \times 0.12 = 8{,}000$ lb. $= 8{,}000/100 =$ 80 lb. per ton.

To reduce to mile basis $\sqrt{5{,}280/1{,}760} \times 75 = 130$ seconds. (See Par. **43**.)

From Fig. 31, 1 mile in 130 sec. with 80 lb. tractive effort gives 60 watt-hr. per ton-mile.

The same value, 60, is true for 1,760 ft. made by similarly shaped speed-time curve in 75 sec.

94. Motor-curve acceleration. Instead of being able to accelerate a train at a uniform rate until maximum speed is reached, all types of electric motors operate best with a certain amount of motor-curve acceleration at a rate constantly falling off from the initial or straight-line acceleration which is only carried part way to full speed. Also, the electric motor has internal losses, electrical and mechanical, which together with certain losses inherent to its system of control make it necessary to add a greater or less percentage to the net energy-consumption curves given in order to obtain the *input* to the train. The different types of motors have their distinctive internal losses and type of control, and the performance relation of the several motor equipments to the net energy-consumption curves is best expressed by the efficiency of acceleration of the several systems.

95. The efficiency of acceleration is the percentage of the net energy consumption of motor output, to the gross input of the train. The values given in Figs. 30 and 31 hold true as the net output of any type of motor and control system, hence, given the efficiency of acceleration of any system, the net energy values form the basis of calculating train inputs for any operating conditions. See Par. **98, 108** and **113.**

The losses in the motor equipment during acceleration are divided into: internal motor losses including loss in gears, and losses incident to method of control.

96. Internal motor losses consist of copper I^2R in armature and field, hysteresis and eddy-current losses in the iron circuit, brush-friction and I^2R loss, bearing friction and gear losses. All these losses are included in the curves furnished by the manufacturers for normal 500 volts constant potential at the brushes, but no such values are readily available for fractional-voltage operation during the accelerating period.

97. Starting resistance losses. It is customary to assume full-load current of a railway motor during the straight-line acceleration period, and at standstill the IR drop in the motor copper will approximate 50 volts. It is necessary, therefore, to provide sufficient starting resistance in series with the motor to take up the remaining 450 volts or the difference between the line potential and the motor copper drop. This starting resistanc is cut out in successive steps as the motor armature gains speed and establishes its own counter-electromotive force, until a period is reached, when the starting

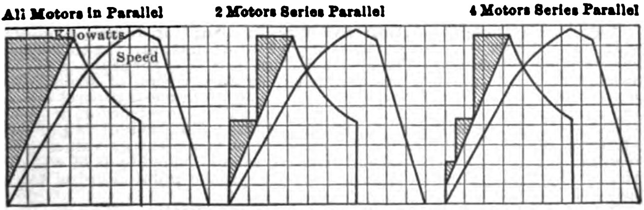


FIG. 32.—Direct-current control of series-wound motors (shading shows loss in starting rheostat).

resistance is entirely short-circuited and the full line e.m.f. is just sufficient to maintain full-load current through the motor. This period completes the straight-line acceleration, as after this point the series-wound motor will still accelerate the train, but at a constantly decreased rate, until full constant speed is attained. It is evident then, that a large amount of power is consumed in the starting resistance and to reduce this excessive loss at starting, the method was introduced of connecting two motors in series during half the period of straight-line acceleration, thus reducing the amount of starting resistance required (Par. 50).

A current-input curve is plotted for the three methods of control of direct-current railway motors in Fig. 32 the shaded portion indicating the energy lost in heating the starting resistances, and showing the economy gained by starting with motors in series. This economy is expressed numerically in Par. 98.

er hr. per sec. assumed. As a high rate of acceleration is undesirable with igh-speed equipments, the rates given in the table should not be greatly ex- ›eded unless there are strong local reasons making such high rates necessary.

102. Interruptions to service treated as "equivalent stops." The ıble of schedule speed includes little or no leeway to make up for lost time, nd where such interruptions of service are liable to occur they should be reated as additional stops per mile, and the proper schedule speed, maxi- ıum free-running speed, etc., should be taken for the *equivalent* number of tops per mile, including actual stops, slow-downs for curves, crossings, etc., nd a margin for unexpected delays. Thus, with one actual stop of 15 sec. uration occurring every 2 miles, there may be slow-downs for curves, etc., ıaking the equivalent number of stops approximate one per mile, in which ase a 24-mile per hr. schedule with 40 miles per hr. maximum speed of quipment would be a safer estimate of speed possible than the 32 and 45 niles per hr. respectively given for one stop in 2 miles. In other words, ‹eep the maximum speed of the equipment at the lowest value that will ıdmit of maintaining the schedule desired with the frequency of stops given. Not only is there a saving in energy consumption resulting from the use of owest possible maximum speed, but, as will be shown later, there is also a arge saving in the capacity of motor required to perform the service.

103. Train input in kw., frequent-stop service, tangent level track

Stops per mile	⅛	¼	½	1	2	3	4	5	6	7
Schedule speed, miles per hr.	50.0	40.0	32.0	24.0	18.5	15.5	13.7	12.5	11.7	11.0
Maximum speed, miles per hr.	65.0	55.0	45.0	40.0	30.0	25.0	23.0	21.0	20.0	19.0
Stops, seconds.......	30.0	20.0	15.0	12.0	10.0	9.0	8.0	7.0	6.0	5.0
Eff. of accel., per cent.	75.0	75.0	75.0	74.0	72.0	70.0	69.0	68.0	67.0	65.0
Accel., miles per hr. per sec.	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7

The above data are common to all trains.

Stops per mile	⅛	¼	½	1	2	3	4	5	6	7
20 ton car.....			51	36	29	26	24	23	22	22
30 ton car.....		96	69	51	40	36	33	32	31	31
40 ton car.....	176	119	85	63	51	45	43	41	40	40
50 ton car.....	195	130	94	73	61	55	52	50	49	49
60 ton car.....	200	140	106	82	70	64	62	60	59	58
2–20 ton cars..			78	60	50	45	43	41	40	40
2–30 ton cars..		137	104	80	69	64	62	60	59	58
2–40 ton cars..	228	160	124	103	89	82	79	77	76	75
2–50 ton cars..	255	183	147	125	111	103	99	97	95	94
2–60 ton cars..	282	202	165	144	127	117	115	113	111	110
3–20 ton cars..			102	76	67	63	61	60	59	58
3–30 ton cars..		173	135	112	97	90	88	86	84	83
3–40 ton cars..	280	200	164	140	127	117	115	113	111	110
3–50 ton cars..	300	236	198	172	155	145	142	139	137	136
3–60 ton cars..	342	263	219	191	175	167	163	160	158	157
5–20 ton cars..			144	124	110	102	98	97	95	94
5–30 ton cars..		238	196	171	154	145	142	139	137	136
5–40 ton cars..	370	292	246	216	197	188	183	180	178	176
5–50 ton cars..	438	350	302	270	250	236	228	225	222	220
5–60 ton cars..	495	400	352	314	290	280	275	271	266	263

These train resistances corresponding to the different train weights agree with Figs. 9 to 14.

poor power-factor during the starting or fractional speed period, and also entails a prohibitive I_2R loss in the secondary, if this be of the short-circuited (squirrel-cage) type. Voltage variation is only used in special cases where the excessive size of the required motor is no handicap.

Secondary-resistance control of three-phase slip-ring motors is the method ordinarily employed. The rotor winding is terminated in three rings, which allow the insertion of non-inductive resistance in the rotor circuit. This resistance is decreased as the motor comes up to speed, and the rings short-circuited at approximately 10 per cent. below synchronous speed. This method of starting results in a poor efficiency of acceleration (Par. 112).

112. Concatenation control may be employed to increase the efficiency of acceleration of three-phase slip-ring motors. As the speed of the induction motor is fixed by its frequency of supply and not by its impressed e.m.f. it is not possible to connect two such motors in series. It is possible, however, to connect the stator winding of motor No. 1 to the line, the rotor winding of motor No. 1 to the rotor winding of motor No. 2 short-circuiting the stator winding of motor No. 2; this constitutes the concatenated method of connecting induction motors and corresponds in results to the series connection of direct-current series-wound motors. With induction motors so connected, stability is obtained with half-speed of the rotors and a concatenated set can be treated in all respects as a single induction motor having double the number of poles in its field.

Concatenation is feasible only with motors of low frequency, 25 cycles or less, owing to the low power-factor incidental to such a combination. In general, however, concatenation is used with railway induction motors, not to effect a possible increase in the efficiency of acceleration, but to provide a second efficient running speed for the low-speed requirements in terminal yards.

113. Efficiency of acceleration; three-phase induction motors

Per cent. straight-line acceleration	100	90	80	70	60	50	40	30	20	10	0
Efficiency per cent	40	43	46	49	52	55	58	61	64	72	75

The accelerating efficiency of an induction-motor railway equipment is indicated for parallel operation only, concatenation not being considered. As straight-line acceleration will constitute fully 50 per cent. of the total period during which power is supplied in a typical rapid-transit run, an induction-motor equipment will have an efficiency of acceleration not to exceed 55 per cent. This represents the power efficiency and does not include the power-factor which will approximate 80 per cent. during acceleration with non-inductive resistance inserted in the secondary circuit, thus making the *apparent* efficiency of acceleration approximately 44 per cent.

Hence, for acceleration problems involving a consideration of railway induction motors of the polyphase type, divide energy values given in Figs. 30 and 31 by 0.44 to obtain the volt-amp. input at the train and *not including* any trolley or distribution losses. The proper field of the induction motor is the haulage of trains at constant speed behind locomotives and the use of this motor will be further discussed under Locomotion.

114. Regenerative (dynamic) braking. In service calling for frequent starting and stopping of trains, it is evident that the $mS^2/2$ constituting the energy loss in heating brake-shoes and wheels, forms a considerable percentage of the total energy input to the train. As the electric motor is reversible, that is, can absorb power and give out mechanical energy, or can give out electric power when mechanically driven as a generator, it seems feasible to expect that some means of control can be designed which will enable a train to be braked electrically with reduced wear and expense of brake-shoe maintenance, besides returning to the line a considerable percentage of the energy delivered to the train during acceleration. Also on roads having excessive continuous grades, it is desirable to return energy to the line partly for the economy thus effected, but largely in order to reduce the danger that goes with braking long heavy trains by means of brake-shoes.

115. Motor capacity for regenerative braking. The standard direct-current motor, being of the series-wound type, cannot be used directly as a stricted space thus available makes it imperative that the weight and outside dimensions of railway motors shall be scaled to the lowest possible limit consistent with the average and momentary output demanded by service requirements. It is customary, therefore, in railway-motor design, to force the density of the magnetic circuit far in excess of what is considered good practice in the design of stationary motors. The effect of this high saturation of the iron circuit is to entail an iron hysteretic and eddy-current loss of such a high value as to preclude the possibility, in many cases, of running the motor continuously at full voltage without overheating it due to the iron loss alone. It is evident, therefore, that recourse must be had to methods of comparative rating of railway motors other than the usual continuous running at full voltage, obtaining in the case of stationary motors. On locomotives these space restrictions have been largely overcome by use of the side-rod drive with the motor mounted above the wheels.

120. The nominal rating of a railway motor shall be the mechanical output at the car axle, measured in kilowatts, which causes a rise of temperature above the surrounding air not exceeding 90 deg. cent. (162 deg. fahr.) at the commutator, and 75 deg. cent. (135 deg. fahr.) by the thermometer, at any other normally accessible part after 1 hr.'s continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature, as measured by resistance, shall not exceed 100 deg. cent. (180 deg. fahr.) during the test.

The statement of the nominal rating shall include the power, voltage and armature speed at rated volts and kilowatts.

121. The continuous-rating input of a railway motor shall be defined by the current in amperes at which it may be operated continuously at half, three-quarters and full voltages respectively, without exceeding the specified temperatures, when operated on test stand with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the volume of air on which the rating is based shall be given.

122. The maximum load on railway motors does not usually exceed 150 per cent. of the nominal rating.

123. Two factors determine the capacity of railway motors, namely: commutation and heating. During the accelerating period the current input demanded by a railway motor is always considerably in excess of the current afterward required to run the car at full speed on level tangent track. The value of this current will depend upon the several conditions entering into the problem, weight of train, schedule speed, and frequency of stops, these factors determining the rate of acceleration and maximum speed required as previously outlined. A motor must be selected which can commutate the abnormal current required during the accelerating period without excessive sparking at the brushes.

124. Division of load between motors. For close calculations it is necessary to plot the actual speed-time curves obtaining with any individual motor. In dividing the total current input to the train by the number of motors, in order to obtain the current per motor, it can be assumed that each motor will take its equal share of current at all speeds, provided the motors are of the same type and capacity, and have the same gear ratio.

125. Effect of acceleration rate and maximum speed on capacity. It is evident from working out a few examples, that high rates of acceleration can be used only when low maximum speeds are possible, and that an abnormally large motor capacity will be essential if high rates of acceleration are demanded in connection with high maximum speeds. Thus, although motor equipments of the direct-current series-wound type can always furnish enough current to slip the driving wheels, such high current inputs will be demanded as will considerably exceed the safe rated commutating capacity of motors operating cars at the 50 miles per hr. or more, common to interurban high-speed service. Various devices have been brought out for the purpose of limiting starting currents to safe predetermined values, and the current-limiting device now forms a component part of certain types of control equipment.

rating is given in amperes at half, three-fourths and full voltages. To determine the sufficiency of the motor for a given service, a typical speed-time run should be plotted and from that the square-root-of-the-mean-square (r.m.s.) current should be obtained. This should correspond to the rated continuous current. With the modern self-ventilated motors, this practically controls the temperature, since the increased speed that goes with higher core losses, also causes a better circulation of air through the motor and carries off more heat. It is found that ventilated railway motors carry practically the same current at all voltages. Enclosed motors carry 5 to 10 per cent. more current at the lower speeds corresponding to low voltages and frequent stopping service than at higher speeds and voltages corresponding to interurban service.

130. Application of thermal-capacity curves. Any given service operation, although made up of short and long runs, can be resolved into a single typical speed-time curve which will call for the same internal losses and the same distribution of motor losses as would obtain under service conditions. By utilizing data as given in the thermal capacity curve, Fig. 35, for a given motor, it is possible to predict, with reasonable accuracy, the temperature rise of a motor for any operating conditions coming within the limits of the motor capacity. As such calculations demand a vast number of experimental runs, the expense of which can only be borne by railway-motor manufacturers, some better form of expressing the relation of railway motor capacity and service performance is necessary for approximation work. Owing to the fact that railway motors of the direct-current series-wound type have become standardized along certain lines, it is possible to establish a working relation between the commercial 1-hr. rating of a motor and its ability to do work under service conditions.

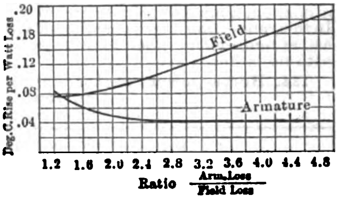


FIG. 35.—Thermal characteristics.

131. Service capacity curves. Applying results similar to Fig. 35, to a series of speed-time curves for different distances run, a curve similar to Fig. 36 is obtained for an equipment having a fixed gear ratio, in this case proportioned for a maximum speed of 45 miles per hr. on tangent level track. This curve, called a service capacity curve, gives directly the temperature rise for a given equipment, in this case a 125-h.p. motor, for any schedule speed that can be performed with a varying number of stops per mile, the equipment being geared for 45 miles per hr. maximum speed when running free.

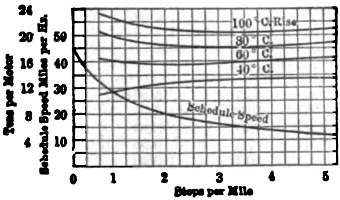


FIG. 36.—Motor service capacity.

132. Application of service capacity curves. It will be noted that the tons train weight per motor for a given temperature rise do not vary greatly over the whole range from five stops per mile down to less than one stop per mile. In other words, a railway motor equipment of fixed gear ratio when mounted on a car of fixed weight, will attain approximately the same temperature rise above the surrounding air, irrespective of the number of stops per mile demanded by service conditions. Thus from Fig. 36 16 tons per motor gives temperature rise of 60 deg. cent. for the motor under consideration, and this temperature rise holds good whether the car is making a schedule speed of 11.5 miles per hr. with five stops per mile, or 29 miles per hr. with one stop per mile.

This fact furnishes a means of simplifying the expression giving the relation between the 1-hr. commercial capacity test and service capacity of the railway motor. It is sufficient for purposes of approximation to rate a

These tables are based upon the temperature rise of 60 deg. cent. above surrounding air, assumed to be 25 deg. cent. The horse-power capacity required conforms to the commercial rating of railway motors, that is, the 1-hr. horse-power rating which will occasion a temperature rise of 75 deg. cent. above surrounding air, taken at 25 deg. cent

The capacities given are approximate only, and are intended as a guide in preliminary calculations. Where accuracy is demanded, or where operating conditions are abnormal, it is necessary to plot speed-time and distance-time curves for the particular motor characteristics nd conditions obtaining, from which the motor temperature should be calculated from a detail knowledge of the motor thermal constants. The method is indicated previously in this description.

135. Division of train horse-power capacity. The horse-power capacity given for any train weight may be split up into the required number of units. Thus, a train composed of five 40-ton cars running at 45 miles per hr. requires 1,180 h.p. motor capacity. This may be divided into six units of 200 h.p. each, that is, three motor cars equipped with double 200 h.p. motors hauling two trailers, or each car of the train may be a motor car and be equipped with a pair of 120-h.p. motors. Approximately the same temperature rise will obtain in either case.

Certain motors of modern construction provide for longitudinal ventilation either with blower on armature or with external blower. In either case, the armature and field losses are carried off independently of each other by the introduction of external air, hence the ratio of losses in such motors becomes of secondary importance.

136. Division of capacity for single cars and trains. For single-car operation a four-motor equipment is preferred for double-truck cars, this being especially true where snow or heavy grades are characteristic of the service. For train operation, two-motor equipments are used, as the disabling of a single unit will not incapacitate the train.

The horse-power capacity specified in Par. **134** for train operation should be made use of only when cars are always operated in trains and never singly. For example, five 40-ton cars operating in a train at 60 miles per hr. require a motor capacity of 1,770 h.p., or 354 h.p. per car, a motor capacity too low for single car operation, which demands 525 h.p. Hence, where cars are run indiscriminately, singly and in trains, the full motor capacity per car should be taken as given in the table of single-car operation.

137. Power requirements with single-phase equipment. Owing to the short period during which single-phase motors have been operated, their design has not yet become standardized, nor is there sufficient operating data upon which to base anything more than general conclusions of the horse-power required for a given service. The single-phase motor is essentially a high-speed motor, having a high copper loss and low core loss, hence, is more particularly adapted to constant-speed running, and suffers in comparison with the direct-current series wound motor when used for acceleration work. There is no lack of starting torque with the alternating-current motor, but a large tractive effort is obtained only at the expense of a large copper loss, so that alternating-current motors are unsuitable for rapid transit service demanding repeated high rate of acceleration, not because such motors cannot furnish the tractive effort required, but because the copper loss incident to such high tractive efforts will heat the motors unduly if used exclusively for acceleration service. Thus the alternating-current motor becomes much heavier than the direct-current motor on the basis of service performed with frequent stops.

138. Single-phase equipment for a service embracing infrequent stops. In interurban or express service with infrequent stops, the smaller core loss of the alternating-current motor brings it more nearly on a par with the direct-current series wound motor as regards output per pound weight of motor. It is possible therefore to use the figures of Par. **134** as applying to alternating-current motor capacity, where stops are not greater than one in 2 miles. However, the table should not be used in connection with higher frequency of stops given, as then the resulting motor capacity indicated in the table must be largely increased when applied to alternating-current motors.

Owing to the fact that the chief advantage of the single-phase motor lies in its ability to utilize the benefits of trolley potentials of 11,000 to 15,000 volts as compared with the 600 to 3,000 volts used with direct-current

141. *Continued.* **600-volt direct-current commutating-pole type**

Type	H.P.		No. motors	Type control	Weight motor (lb.)	Weight total equipment (lb.)
	500 volt	600 volt				
200	33	40	2	K-36	2,120	5,490
			4	K-35		9,880
			4	Mult. Unit		10,410
216	40	50	2	K-36	2,900	7,000
			4	K-35		13,200
			4	Mult. Unit		13,450
203	40	50	2	K-36	2,665	6,450
			4	K-35		12,100
			4	Mult. Unit		12,350
219	40	50	2	K-36	2,890	6,833
			4	K-35		13,140
			4	Mult. Unit		13,390
201	55	65	2	K-36	2,885	7,000
			4	K-35		13,180
			2	Mult. Unit		7,690
			4	Mult. Unit		13,280
210	60	70	2	K-36	3,370	7,750
				K-34		15,710
				Mult. Unit		8,690
				Mult. Unit		15,680
218	60	70	2	K-36	3,200	8,100
			4	K-34		15,000
			2	Mult. Unit		8,330
			4	Mult. Unit		14,960
214	65	75	2	K-35	3,805	9,282
			4	K-34		17,414
			2	Mult. Unit		9,430
			4	Mult. Unit		17,240
233	65	80	2	K-35	3,350	8,370
			4	K-34		15,700
				Mult Unit.		15,940
205	90	110	2	K-35	3,865	9,200
			4	K-44		18,330
			2	Mult. Unit		9,800
			4	Mult. Unit		18,300
225	95	115	2	Mult. Unit	3,860	10,200
			4	Mult. Unit		18,769
222	115	140	2	Mult. Unit	4,100	10,710
			4	Mult. Unit		19,900
207	135	165	2	Mult. Unit	5,160	13,050
			4	Mult. Unit		25,950
212	195	225	2	Mult. Unit	6,200	14,800
			4	Mult. Unit		29,780

149. The distinctive feature of cylinder (drum) control is that the various electrical connections are made and broken manually, by means of a hand controller. This consists of an upright cylinder upon which are mounted the contacts and against which stationary fingers press. When the cylinder is rotated (by means of a handle) the contacts connect the proper fingers to form the required electrical connections.

150. Cylinder (drum) controllers are classified as follows: Type "*K*" Controllers are of the series-parallel type and include the feature of shunting and short-circuiting one motor or group of motors, when changing from series to parallel connection.

Type "*L*" controllers are of the series-parallel type, but completely open the power circuit during transition from series to parallel connection.

Type "*R*" Controllers are of the rheostatic type and are designed to control one or more motors by means of resistance only. Certain of these controllers are arranged so that the motors may be grouped either in series or in parallel at the option of the operator, but as this must be accomplished by throwing a separate lever, these controllers are not used as series-parallel controllers and their field is limited.

Type "*B*" controllers may be either of the rheostatic or the series-parallel types, but they differ from the ordinary rheostatic or series-parallel controllers by having the contacts arranged so that if desired, the power may be cut off, the motors reversed and then short-circuited through a variable resistance, the motors thus acting as series generators. Beside the braking effect of the motors acting as generators, use is sometimes made of magnetic rail brakes or axle brakes, the coils of these magnetic brakes being in series with the short-circuited generators.

151. The rated capacity of drum controllers is based upon the maximum horse-power of the motors with which they can be used, the motors being rated in accordance with standard practice, that is, the 1-hr. or nominal rating as defined in the standardization rules of the American Institute of Electrical Engineers. This rating is usually based upon a pressure of 500 volts, so that controller ratings are based upon a nominal potential of 500 volts. If the controllers are used with motors wound for lower voltages, the horse-power ratings will, in general, be proportionately less.

152. Standard series-parallel controllers

Title	Capacity at 500 volts	Controlling points	Maximum potential
K-10	2-40 h.p.	5 series 4 parallel	600 volts
K-11	2-60 h.p.	5 series 4 parallel	600 volts
K-12	4-30 h.p.	5 series 4 parallel	600 volts
K-28	4-40 h.p.	5 series 5 parallel	600 volts
K-34	4-75 h.p.	6 series 4 parallel	750 volts
K-35	4-55 h.p.	5 series 3 parallel	750 volts
K-36	2-60 h.p.	4 series 4 parallel	750 volts
K-51	2-60 h.p. (Field control motors)	5 series (1 with short field) 4 parallel (1 with short field)	750 volts

153. Auxiliary contactor control. In order to increase the reliability and efficiency of drum types of controllers there has been developed a system whereby the main power circuit is broken by means of remote-control switches mounted under the car, when the controller is moved to the "off" position. The use of these additional power-operated switches relieves the main controller fingers of the serious arcing and burning, especially when opening the circuit under overload conditions.

156. Multiple-unit control. The distinctive features of multiple unit ontrol are: the various main circuit connections are made and commutated y means of individual power-operated switches (either electrically operated r electropneumatically operated); the various switches are controlled by neans of secondary or control circuits. The multiple-unit type of control vas brought out primarily for the control of motors in a service requiring hat cars be operated singly or severally coupled together in a train and oper-ated simultaneously. This control is also used very extensively at present n car equipments where the motors have a capacity of 60 h.p. or more at 600 volts. When several cars are coupled together in a train, the control 'train lines" of the cars are connected together by means of jumpers between cars so that if the train-line wires are energized from any master controller on any car, similar control circuits in each car are energized, thus causing the simultaneous operation of all motor cars. The control circuits of each car are arranged so that when operating in trains, the movement of all cars will be in the same direction regardless of whether any of the cars are turned end for end. See Fig. 38.

The principal pieces of apparatus which, in general, make up a multiple unit control equipment are as follows:

Main circuit apparatus	Control circuit apparatus
Current collectors	Control switches
Switches and fuses	Master controllers
A number of remotely controlled switches mounted in groups	Junction boxes
Resistors	Receptacles
Reverser	Jumpers
	Relays (if necessary)

Two general types of multiple unit control are used in this country, these two types differing chiefly in the method of operating the individual switches. The control system manufactured by the Westinghouse Elec. & Mfg. Co. operates the main switches pneumatically, whereas that manufactured by the General Electric Co. closes the main switches by means of solenoids. Both companies manufacture automatic as well as manually operated control for multiple-unit acceleration.

157. General Electric multiple-unit control is described in detail in Par. **158** to **167**. In the automatic system the acceleration is effected by current-limiting relays and interlocking switches on the contactors. The multiple-unit system of control with hand-operated or manually controlled acceleration is in general use both for train and single-car operation. It is, in effect, identical with the hand-operated cylinder type of control except that instead of combining all the various circuit-breaking contacts upon a single cylinder operated by hand, it divides each contact into a separate circuit-breaker or contactor, and actuates these electrically through train wires by means of a small master controller. The motor control therefore comprises those parts which handle motor current, all of these parts being electrically operated and located underneath the car.

158. The master controller (Par. **157**) Fig. 39 comprises those parts which switch the control current operating the motor-control apparatus. The master controller (Par. **159**) is operated by hand, and is located in the vestibule at either end of the car. The motor control is local to each car, and current for this circuit is taken directly from the trolley or third-rail through the contactors, starting resistance and reverser to the motors, thence to the ground. Where it is necessary to operate with a gap in the third-rail system, it is sometimes customary to install such a train line that any car may supply the motor current for the other cars of the train.

The master control includes train wires (Par. **167**) made continuous throughout the train by means of couplers between the cars. On each car the operating coils of the motor control are connected to this train line through a cut-out switch, these train wires being energized in proper sequence by the hand-operated master controller on the platform. Current for the master control is taken directly from the trolley or third-rail through the master controller, which is being operated by the motorman, to the train-line, and wires of the train line, for energising the operating coils of the motor control. The value of the current required is very small, not exceeding 2.5 amp. for each car in the train. The master controller is provided with two handles, one for operating and one for reversing the train movement.

The operating handle is provided with a button which must be kept down except when the handle of the controller is in the off position, as releasing this button permits an auxiliary circuit to open, cutting off the supply of current to the master controller, and thus de-energising the train-line and opening up the motor-control apparatus. This button is intended to serve as a safety appliance in case of physical failure of the motorman.

The reverser handle is connected to a separate cylinder which establishes control connections for throwing the electrically operated reverser either forward or reverse position when the master-controller handle is on the off point. The operating circuit for the reverser is so interlocked that unless the reverser itself corresponds to the direction of the movement indicated by the reverser handle of the master controller, the line contactors on that car cannot be energized.

160. The contactor (Par. 157) is a switch operated by solenoid coils, and each contactor may be considered as the equivalent of a finger and its corresponding cylinder segment in the hand-operated "*K*"-type controller. It consists of an iron magnet frame with an operating coil and two main contacts, one fixed and the other directly connected to the movable finger. These main contacts open and close in a moulded-insulation arc chute provided with a powerful magnetic blowout. Interlocks are provided for making the necessary connections in control circuits to ensure proper sequence in operating the different contactors.

All of the contactors are mounted in a box placed beneath the car, this box being provided with a sheet-iron cover lined with insulating material.

161. The reverser (Par. 157) is a switch, the movable part of which is a rocker arm operated by two electromagnets working in opposition. The coils receive their energy from the master controller through the train-line, and the connections are such that only one coil can be operated at a time. Leads from the motors are connected to the main reverser fingers, and by means of copper bars on the rocker arm, the proper relations of armature and field windings are established for obtaining forward or backward motion of the car. Also see Par. 173.

162. Circuit couplers between cars (Par. 157) are so designed as to give a corresponding connection of train wires, this being secured by means of proper mechanical design of plug and sockets, it being rendered impossible to insert the plug in the socket improperly.

163. Automatic multiple-unit control. Sprague General Electric (Par. 157) provides for the acceleration of the train at a predetermined value of current in the motor, this feature being provided without preventing the manual operation of the master controller at less than the predetermined current if desired.

The operation of the contactors is controlled from the master controller, but is governed by a notching or current-limit relay in the motor circuit, so that the accelerating current of the motors is substantially constant.

This is accomplished by having small auxiliary interlocking switches on certain of the contactors, the movement of each connecting the operating coil of the succeeding contactor to the control circuit. The contactors are energised under all conditions in a definite succession, starting with the motors in series and all resistance in circuit; the resistance is subsequently cut out step by step; the motors are then connected in parallel with all resistance in circuit, and the resistance again cut out step by step. The progression can be arrested at any point, however, by the master controller, and is never carried beyond the point indicated by the position of the master controller. The rate of the progression is governed by the current-limit relay, so that the advance cannot be made at a rate so rapid that the current in the motors will exceed the prescribed limit. One of these relays is provided with each car equipment, so that while the contactors on each car of a train are controlled from the master controller in use for the application and removal of power, the rate of progression through the successive steps is limited by the relay on each car independently, according to the adjustment and current requirements of that particular car.

169. The HL system of control (Westinghouse) is widely used for the control of direct-current motors on city and interurban cars and is described in detail in Par. 170 to 179. A standard car equipment for the control of 4-40-h.p., 500-volt motors arranged for double end operation in trains includes the following part:

Main circuit apparatus	Control apparatus
2 Trolleys	2 Master controllers
1 Lightning arrester	2 Control and reset switches
1 Main knife switch	1 Control resistor
1 Main fuse box	3 Train line junction boxes
1 Switch group	2 Train line receptacles
1 Reverser	1 Train line jumpers
1 Main grid resistor	1 Set of pneumatic details

In Fig. 41 is shown the control connections of the above apparatus. This system of control uses the shunting method of transition from series to parallel for the smaller sizes of motor equipments, but for the larger equipments, the bridging method is used Par. 148.

170. The main knife switch (Par. 169) is arranged for mounting underneath the car and is enclosed in a box, which protects it from the weather, and insures against accidental contact.

The **main fuse box** (Par. 169) is of the magnetic-blowout, copper-ribbon type, arranged for mounting under the car. The connection of this fuse box in the main circuit is shown clearly in Fig. 41.

171. Switch group. The various main-circuit connections are made by means of a number of independent switches known as unit switches, each provided with a strong magnetic blowout, and normally held open by a powerful spring. Each switch is closed, when desired, by compressed air acting on a piston. This action forces the switch jaws together against the spring pressure, the force being sufficient not only to compress the spring, but also to apply a heavy pressure at the switch jaws. The air is admitted to or exhausted from the cylinder through a valve which is operated by means of a solenoid in the control circuit. The switch group consists of a number of these unit switches mounted with blowout coils, in a common frame, and completely enclosed by removable sheet-iron covers lined with asbestos. Switches for cutting out damaged motors are mounted on one end of the group, and the overload trip relay is mounted on the other end.

172. Line switch. In larger equipments, where it is necessary to have a larger number of switches, two of the switches are mounted in a separate frame with the overload trip. This assembly constitutes what is termed a line switch.

The **overload trip** mechanism (Par. 169) consists of a core, which is drawn into the end blowout coil of the switch group or line switch, when an excessive current passes through this coil. The core is normally held out by means of a spring, but when drawn into the blowout coil, is latched and must be released either manually or by energising a reset coil. When actuated, the trip opens the control circuits of certain switches which cut off the power. Calibration for various currents is accomplished by an adjustment of the air gap.

When the position (whether closed or open) of a switch necessitates a change in the control circuits, an interlock must be employed to effect this change. This **interlock** consists of a block carrying contacts so mounted on the switch that it will be moved from one position to another according to the position of the switch. Pressing against this block are stationary fingers to which the control wires are attached.

173. Reverser (Par. 169). The direction of rotation of the motors is changed by reversing the main fields. The reverser consists of the necessary number of main circuit fingers mounted on a stationary base, and arranged to press against contacts carried on a movable drum. The drum with its contacts is moved to the forward or to the reverse position by one or the other of two pneumatic cylinders closely resembling those in the switch

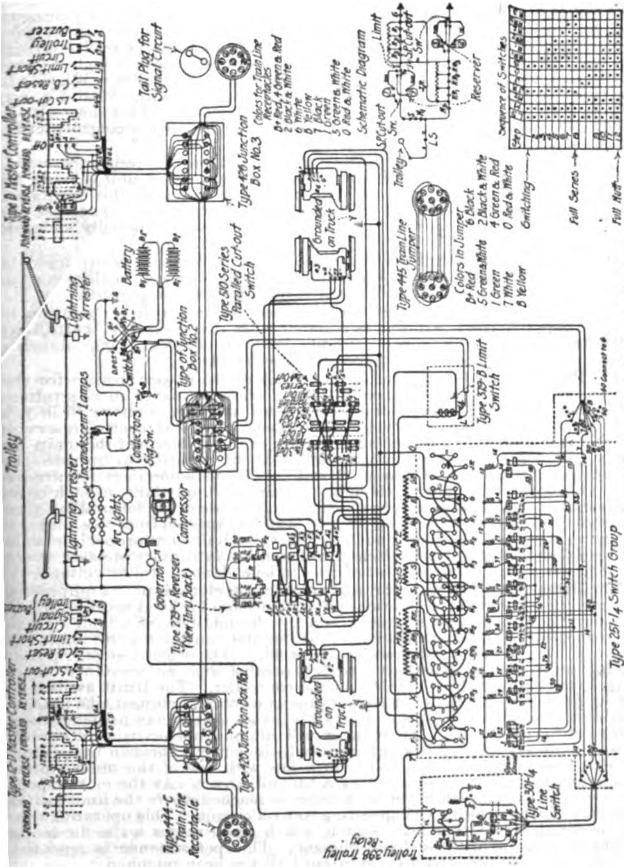


FIG. 42.—Westinghouse main and control wiring.

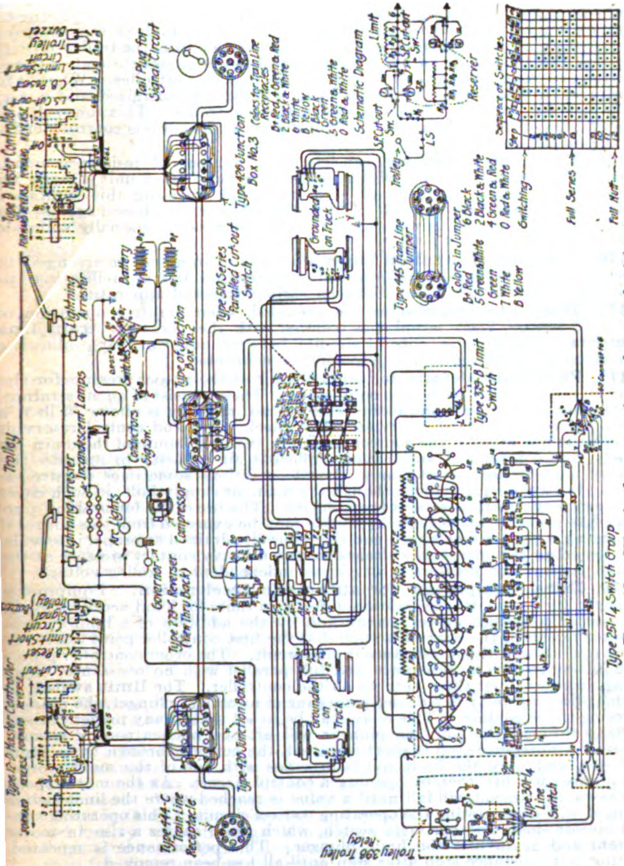


FIG. 42.—Westinghouse main and control wiring.

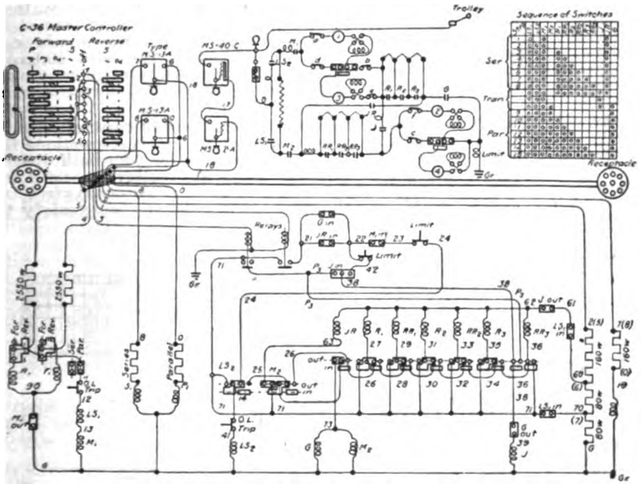


FIG. 43.—Westinghouse 600-volt direct-current motor-car main and control schematic.

180. Tap-potential control of single-phase motors. The single-phase motor is essentially the same in its characteristics as the direct-current series-wound motor, and can be started at low voltage by means of inserting series resistance according to the direct-current standard method. With alternating-current supply, however, it is possible to obtain fractional voltage without sacrificing efficiency, as the step-down transformer forming part of the alternating-current car equipment can be constructed with taps so that it will furnish fractional voltage without the necessity of introducing starting resistance. The universal method of starting single-phase motors is, therefore, by the so-called tap-potential control, and the function of the control, whether it be hand-operated "*K*" type or multiple unit, is to connect the motor terminals successively to transformer taps of increasing potential while starting.

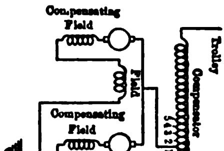


FIG. 44.—Tap control.

181. The hand-operated control of single-phase motors is identical with the type "*K*" controller used with direct-current motors, except that advantage is taken of the fact that alternating-current arcs of considerable size can be broken in the air without the aid of the magnetic blowout. Where the cars are to be operated from both alternating-current and direct-current trolley with the same equipment, the hand-operated control is provided with magnetic blowout for direct-current operation, using the same controller without the magnetic blowout for alternating-current operation, unless the motor equipment be of large capacity.

182. Control of single-phase motors for combined alternating-current and direct-current service. The control of single-phase motor is effected by connecting the motor terminals to transformer taps of increasing potential in order to vary the speed, while reversal is effected by reversing the series field-winding connections, thus calling for practically the

185. Number of starting points. Owing to the fact that the alternat-ng-current motor characteristic is more drooping than even that of the direct-urrent series-wound motor, fewer starting points ire required for alternating-current control. The General Electric Company uses five steps, and the Westinghouse uses six steps when the speed does not exceed 40 to 45 miles per hr. maximum. As each point on the controller, with potential-tap control, constitutes a running point at full efficiency, it is not necessary to use series-parallel connection of motors as is done with direct-current motors.

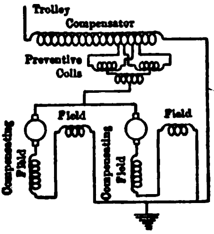


FIG. 46.—Westinghouse tap control.

186. Multiple-unit control equipments for single-phase motors differ somewhat from direct-current equipments in the general plan of operation. This difference is confined chiefly to the main circuits and main-circuit apparatus. The high-tension current passes from the overhead collector through an oil circuit-breaker, to a transformer. Low voltage currents are fed to the main motors through a group of unit switches, which can be arranged for automatic or non-automatic acceleration. Fig. 45 shows the connections for a typical type "*AB*," 11,000-volt single-phase equipment.

TYPES OF RAILWAY MOTORS

187. Direct-current series-wound motor. Wound for potentials of from 500 to 1,200 volts is the standard railway motor. Motors of from 500 to 600 volts are used in and around large cities, 1,200-volt motors being adopted on interurban electrified lines. Armature and field windings are connected in series and the use of motors of the commutating pole type is increasing. All motors designed for street, interurban and rapid transit car or train service have four field poles, the structure being entirely enclosed with hand hole covers making it waterproof. Such motors transmit power by single-reduction gear, motors being suspended at one end upon the car axle and spring suspended at the other end.

For locomotive work, the General Electric Company has brought out a two-pole gearless motor, which design is also adapted for high-speed single-car service calling for large motor outputs. The two-pole series motor is especially adapted to very high speed service; it minimizes cost of repairs and operates with decreased noise and greatly increased efficiency for express service. For further description of gearless motors see locomotives (Par. 260).

188. The single-phase series motor has been developed along several lines of which the series-wound compensated motor is the one most generally used in the United States. The single-phase motor differs from the direct-current series-wound motor in having two fields, the series or energizing field and the **compensating field.** The office of the latter is to compensate for or neutralize the inductance of the armature produced by the alternating current therein. Compensation may be the means of raising the power-factor of a single-phase motor to values closely approximating 100 per cent., and having an operating value above 95 per cent.

This compensating field may be either conductively or inductively produced, depending upon whether the winding is traversed by the main motor current, or by the current produced in its own short-circuited winding by the alternating armature flux. So far as concerns operation from alternating-current supply, one form is about as efficient as another, but the conductive compensation is an aid when the alternating-current motor is called upon to operate as a direct-current motor.

The series-field winding of the single-phase compensated motor is connected in series with the armature, and the direction of rotation can be reversed by reversing the field-winding connections similar to direct-current operation. The series-field winding may be distributed in a number of slots in the field-magnet structure similar to the compensating-field winding, or it may take the form of a concentrated winding, in which case it is similar to the winding of a direct-current series motor embracing inwardly projecting poles. The concentrated field winding is largely used in alternating-over a regular profile, either level or up a uniform gradient, in other words, where there is no combination of slow-speed grade haulage and high-speed level service.

192. The single-phase induction motor has been used for railway purposes on experimental roads, but owing to the zero starting torque of this motor it is necessary to operate it in conjunction with an auxiliary starting device and throw the motive power into action by mechanical clutches or other means after full motor speed has been obtained. This type of motive power is very limited in its field of application.

193. The split-phase converter system comprises a method of obtaining polyphase current from a single-phase trolley, for the operation of polyphase motors. It consists of a phase converter which is essentially a polyphase induction motor the capacity of which is approximately 75 per cent. of the capacity of the motors it supplies. As the phase converter is operated from one phase only, it requires a starting motor to bring it up to near synchronous speed. In all applications of this principle, the single-phase current has been converted into two-phase current. In the Norfolk & Western locomotives, these two phases are changed to three-phase by a connection similar to the well-known Scott system. The advantage claimed for the three-phase is that the motor has a better performance and is also better for pole changing while it entails no more regulating switches and has fewer leads.

BRAKING

194. Retarding factors. In order to bring a moving train to a stop, it is evident that some external force opposed to the motion of the train must be applied. The ideal force would be applied at the centre of gravity of the car (producing no tendency for the car to rotate) and would be sufficient to stop the train in case of emergency in the shortest possible time, without undue shock to passengers or equipment. With the exception of a few instances, such as short cable roads up a mountain side, the only available force which may be utilized in stopping a train is the friction which exists between the wheels and the rails. This force, besides being applied at the lower rim of the wheel and consequently not at the centre of gravity of the car, is also a variable quantity of uncertain magnitude, and therefore not an ideal retarding force. For instance the adhesion between a dry rail and wheel may be equal to about 30 per cent. of the pressure between wheel and rail, whereas with a wet rail it may be only half that amount. The addition of sand to a slippery rail will increase the adhesion from 15 per cent. to about 25 per cent. of the weight on the rails, and this amount can usually be relied upon in making emergency stops. This force of 25 per cent. of the weight on the rails applied to a car will produce a retardation equal to one-quarter the acceleration due to gravity, or 8.04 ft. per sec. per sec., or nearly 5.5 miles per hr. per sec. If it were possible to apply this force instantly and uniformly throughout the stops, a stop from an initial speed of 60 miles per hr. could be made in about 11 sec., or in a distance of 480 ft. This force, however, is only available when the wheels are rolling on the rails, for as soon as slipping occurs the adhesion rapidly decreases. Therefore the force which opposes the revolution of the wheels, namely the brake-shoe friction, must never exceed that which is keeping the wheels turning, namely the adhesion between the wheels and rails. This opposing force is obtained in several different ways, the most familiar being by applying brake-shoes to the rim of the wheels with considerable force by means of hand or power brakes. Another method, which is applicable in electric traction, is known as electric braking, as distinguished from mechanical braking, and consists in opposing the revolution of the wheels with the counter-torque of the motors or by the friction of electrically operated brake discs.

195. Tests to determine friction coefficients. About the first systematic tests to determine the value of the **coefficient of friction between brake shoes and wheel**, and between wheel and rail were conducted by Sir Douglass Galton and Mr. George Westinghouse in 1878 and 1879 on the London, Brighton & South Coast Railway, England. A report of these tests appears in the proceedings of the Institute of Mechanical Engineers of London, for April, 1879. The table in Par. **196** gives the results of these tests:

wherein f is the coefficient of friction at beginning of application: f' the coefficient of friction after brake application of T sec.

200. General laws affecting friction coefficient. The absence of more extended observations and the complex nature of fluctuations of the coefficient of friction make it impossible to formulate a practical mathematical equation which will determine the rate of retardation under varying conditions. However, the results of the tests shown in the tables above indicate a law of variations which may be briefly stated as follows, regardless of the materials used.

(a) The coefficient of friction increases with the decrease in speed;

(b) Decreases with the increased distance through which brakes are applied, and

(c) Decreases with the increase of pressure.

201. To obtain a uniform braking effort throughout the stop, the brake-shoe pressure must be varied to compensate for the fluctuations in the coefficient of friction, that is, the brake-shoe pressure must be decreased as the diminution in speed increases the coefficient of friction, and increased as the distance of brake application decreases the coefficient of friction, and further increased to compensate for the decrease of the latter with increased pressure.

For certain speeds the increase in coefficient of friction with decrease in speed is practically neutralized by a decrease due to increased distance of frictional contact. For lower speeds, however, the increase from the former cause is more rapid than the decrease from the latter, necessitating an almost abrupt decrease in brake-shoe pressure near the end of a stop, in order to avoid slipping the wheels on the rails and discomfort to passengers.

202. Efficient emergency braking. For the same pressure, the coefficient of brake-shoe friction at 60 miles per hr. is only about half that at 20 miles per hr. It is therefore evident that an emergency stop for high speed is less efficient than for a low speed, since an emergency application implies that the maximum pressure which will not slip the wheels near the end of the stop, is instantly applied at the very outset. A considerably shorter stop may be made if the pressure applied during the earlier periods of the stop is greatly in excess of that which will slip the wheels at low speed, but in the absence of the motorman's skill, some means must be provided to decrease the pressure near the end of the stop, in order that the limits of rail friction will not be exceeded, and the efficiency of the stop thereby decreased. This provision, however, requires additional apparatus, which on general principles is objectionable unless the showing is so favorable as to warrant further complications.

203. Application of the retarding force. Thus far, attention has been devoted to outlining methods for overcoming the obstacles presented by the complex nature of the fluctuations of the coefficient of brake-shoe friction which prevent the utilization of the theoretically possible retarding forces, The nature of the application of these forces imposes difficulties which prevent the full utilization of the weight on the trucks and wheels, thereby directly affecting the braking force.

At the present time it is customary to equip double-truck cars with either two motors or four motors, depending upon the nature of the service. In the former case both motors are usually placed on one truck thus permitting the use of a lighter truck for a trailer. The pressure which may be safely applied to the wheels of the motor truck without causing the wheels to slip, cannot be applied to the wheels of the trailer truck. Hence the brake rigging must be so proportioned that the greatest portion of the braking is done upon the wheels of the motor truck. Considering, however, the case where the normal distribution of weight is equal for all wheels, it is found that, during braking, a greater pressure may be applied to the wheels of the forward truck without causing them to slide than may be applied to the wheels of the rear truck. The explanation is somewhat simplified when considering single-car operation, since draw-bar forces may be eliminated.

204. Vertical thrust on forward truck. The resultant of all the parallel forces, which act on the elementary masses of the car tending to keep it in motion, is equal to the sum of all these forces acting through the center of gravity of the car and in the direction of motion. Directly opposed to the motion of the car is the wind pressure, which is exerted normal to the eleof the centre of the shoe, in order to compensate exactly for the rotating influence of the car body, is too involved for presentation here. For this reason reference is made to Mr. R. A. Parke's excellent paper in the Proceedings of the American Institute of Electrical Engineers, Vol. XXII, Dec., 1902.

207. A common form of hand brake consists of a vertical shaft at each end of the car fitted at the top with a ratchet handle or crank, or geared to a hand wheel. By means of this mechanism, the motorman can wind up a chain, one end of which is fastened to the lower end of the vertical shaft and the other end to a rod which connects with a system of brake levers. By means of a pawl (or dog) which engages in a ratchet wheel on the vertical shaft near the floor of the car, the motorman is enabled to maintain a pressure on the brake-shoe while he gains a more favorable purchase for applying more pressure, or until such times as he desires to release the brakes. This

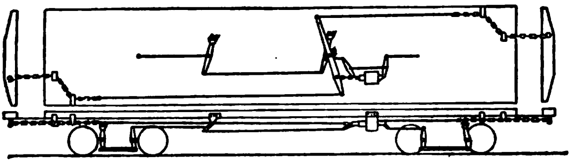


Fig. 54.—Diagram of brake rigging.

brake has been found capable of supplying sufficient braking power for the safe control of light cars running at moderate speed, but for heavy cars and high speeds the physical effort and time required to properly apply the brakes render it necessary to provide other means of supplying the proper force in a minimum length of time. Hand brakes, nevertheless, are always provided as an additional safeguard, even though the cars may be equipped with power brakes, as it is always customary to set up the hand brakes on all cars when they are left standing.

208. Air-brakes (Par. **209** to **229**) in some form, have been universally adopted on all steam roads for braking both passenger and freight trains, and the results have been attended with such success that modifications and improvements of the old steam-railroad air-brake system have been developed and adopted by a vast majority of electric lines operating heavy high-speed interurban cars, either singly or in trains. On account of the varying character of the service on different electric roads, it has been found necessary to develop several systems, or modifications of the same system which will be best adapted for the service in hand.

The most familiar types at present are known as the following: *the straight air-brake system* (Par. **209**), recommended for single-car operation only; *the emergency straight-air system* (Par. **215**), suitable for two-car operation, particularly when one is operated single most of the time and with a trailer added during rush hours; *the automatic air-brake* (Par. **218**), suitable for electric trains of three cars or more; *the combined straight and automatic air-brake* (Par. **227**), designed for locomotive operation, no matter whether steam or electric; *the electropneumatic air-brake* (Par. **228**), at present in an experimental state, but particularly adapted to train operation, inasmuch as the time element in the application and release of the brakes on the rear end of a long train is practically eliminated.

209. The straight air-brake system described in detail in Par. **210** to **214**, consists essentially of a source of compressed air (either a tank filled at intervals from a compressor at charging stations, or an air compressor, motor or axle driven, located upon the car); a reservoir which receives the air from the charging tanks or from the compressor and in which the pressure is maintained practically constant by means of a reducing valve, or by a governor which automatically controls the operation of the compressor; a brake cylinder, the piston of which is connected to a system of brake levers in such a manner that when the piston is forced outward by air pressure the brakes are applied; an operating valve mounted in each vestibule by means of which the compressed air is either admitted or released from the brake cylinders; a pipe system connecting the above parts, including cut-out valves, extra hose, to insure that air will apply throughout the entire train. All the cut-out cocks must be open except those on the rear of the last car, and the front of the first car.

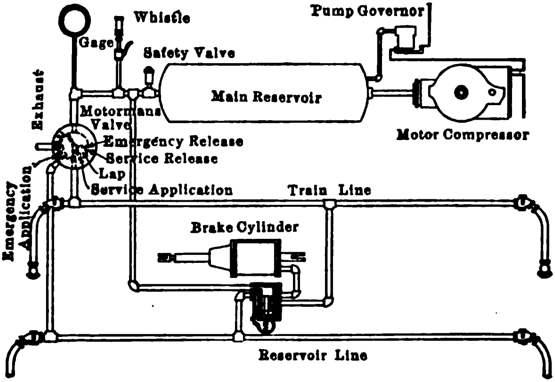


Fig. 56.—General Electric emergency straight-air brake system.

214. Field of application (Par. 209). So far as single-car operation is concerned, the straight air-brake system is very satisfactory, as the desired flexibility in the matter of graduations of applications and release of the brakes with due regard to the passengers standing can readily be secured, and this apparatus is usually so simple in construction that the motorman may become familiar with its operation to such an extent that accurate stops may be secured with a minimum amount of instruction. In trains of considerable length, however, the response of the brakes on the rear cars is too slow, since all the air must pass from the main reservoir on the front car through the opening in the motorman's valve to the brake cylinders of each car. As the addition of each car adds to the volume of the brake system, the main reservoir on the first car must be considerably increased. The reservoir capacity must be so proportioned that the pressure will not be reduced to such an extent that the brake application will be insufficient and result in overrunning the desired stopping place. These latter objections would not necessarily prevent the use of this type of air-brakes on short trains of two or three cars, but add to the objection that a broken hose connection or leaky train pipe renders the brakes on the whole train inoperative.

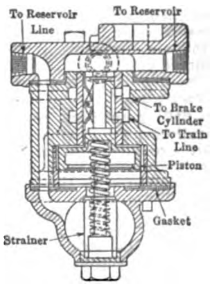


Fig. 57.—Emergency valve.

215. The emergency straight air-brake, described in detail in Par. 216 and 217, differs from the straight air-brake in the details of the motorman's valve and in the addition of an emergency valve and reservoir line which connects the motorman's valve with the emergency valves (Figs. 56 and 57). In the case of a trail car, an auxiliary reservoir (Par. 217) is also added, as shown in Fig. 58.

In the ordinary operation of single cars or short trains, the emergency valve is seldom brought into play. It is necessary, however, to provide a short direct passage from the reservoir to the brake cylinder in order to ensure the quickest possible action in time of emergency and to provide some means of automatically braking the rear cars should a break occur in the train line. At other release them, whereas in the latter, air is admitted to the train pipe to apply the brakes and exhausted to release them.

219. The apparatus required (Par. 218) for this system in addition to that already mentioned for the straight air-brakes is as follows: a set of duplex pressure gages, which indicate simultaneously the pressure in the main reservoir and in the train pipe; an auxiliary reservoir, for storing the air used by each car in braking; a triple valve, the function of which is to admit air from the auxiliary reservoir into the brake cylinder and to release it therefrom (in release position, the auxiliary reservoir is recharged), and an air-whistle reservoir, with suitable check valve for supplying air to the air whistle.

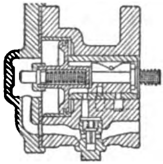


FIG. 59.—S. I. triple valve.

This system is capable of a great many refinements which may be added or omitted as requirements of a particular service may prescribe. The main points of difference between particular automatic air-brake equipments will generally be found in the details of the triple valves, and the addition of pressure maintaining and reducing valves. These features are essential in certain classes of grade work in order to prevent brakes "leaking off." These particulars have been intentionally omitted from this consideration in order to avoid undue complexity. Two forms of triple valves, however, need to be considered here inasmuch as the plain triple valve, Fig. 59, is only used on comparatively short trains, about five cars in length, whereas the quick-action triple valve, Fig. 60, is designed to be used on much longer trains.

220. Emergency application (Par. 218). For the emergency position shown in diagram, Fig. 60, the train line is open to the atmosphere, allowing auxiliary reservoir pressure on the right of the slide-valve piston forcing it to the left against the graduating spring, compressing it and uncovering the brake cylinder port. Air is thus permitted to flow from the auxiliary reservoir directly into the brake cylinder; at the same time the ports leading to the atmosphere and to the train pipe are closed.

221. To release the brakes (Par. 218), the main reservoir air is admitted through the train to the chamber at the left of the slide-valve piston, forcing it to the right, and connecting the brake-cylinder port to the exhaust pipe. At the same time, air at the main reservoir pressure raises the check valve and recharges the auxiliary reservoir to main reservoir pressure.

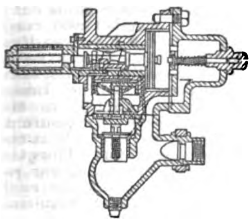


FIG. 60.—K triple valve.

A **graduated release** of the brakes may be obtained with this type of valve, by piping the exhaust from the triple valve to the motorman's valve where a movement of the valve handle will release the air the same as in the straight air-brake.

222. Necessary train-line reduction (Par. 218). A service application requires only a slight reduction in train-line pressure (from 5 to 7 lb.) which is sufficient to permit the slide-valve piston to slightly compress the graduating spring and partially open the brake-cylinder port. When the auxiliary reservoir pressure has been reduced to about the same value as the train-line pressure, the graduating spring will return the slide valve to lap position, closing all the ports before the brakes are fully applied. The auxiliary reservoir and brake cylinder are usually so proportioned that the brakes are fully applied when the brake piston displacement is sufficient to reduce the auxiliary reservoir pressure about 15 lb. Therefore, a train pipe reduction greater than 15 lb. fully applies the brakes and is wasteful of air, because the train pipe and the auxiliary reservoir must be fully charged after each application.

223. The quick-action triple valve (Par. 218), shown in Fig. 60, is designed to be used on freight trains of considerable length, its function is to apply and release the brakes on the rear cars so quickly that the running in and out of the slack is avoided. Fig. 62 is a diagrammatical section of the through the charging grooves before opening a small port in the slide valve, would permit the train line pressure to raise the check valve and slowly re-charge the auxiliary reservoir. The function of the charging device (shown on the outside of the valve in Fig. 60) is to prevent the inertia of the slide valve from forcing it to the extreme right of its travel when the valve piston is brought up against its stop. The restricted area at the left end of the exhaust cavity of the slide valve partly closes the exhaust port, and allows the brake-cylinder air to flow slowly into the atmosphere. On account of the friction in the train pipe, it is impossible to re-charge the train line at the rear of the train faster than the air will flow through the charging grooves of the triple valves. As a result, only the triple valves of the foremost cars move to retarded release, the others remaining in full release, which releases the brakes on the rear cars quickly.

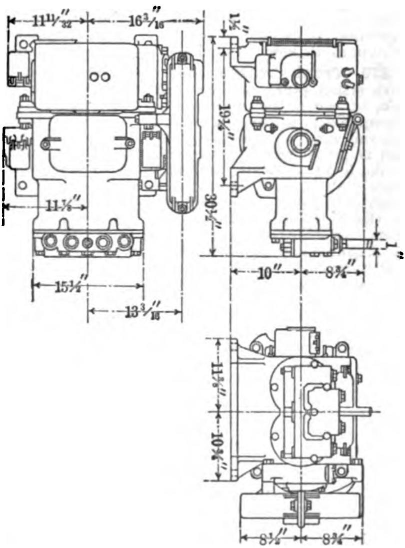


FIG. 63.—Air compressor.

226. Emergency application with quick-action triple valve (Par. **218** and **222**). The sudden reduction of train pipe pressure in the emergency position of the engineer's valve, moves the slide-valve piston to the left, compressing the graduating spring and opening a port directly to the brake cylinder, and also opening another port to the emergency chamber which unseats the emergency valve. At the same time the train-line pressure opens the check valve and air flows from the train line directly into the brake cylinder, applying the brakes with maximum pressure. The quick venting of the train line insures the rapid serial action of the brakes on the rear cars.

227. The combined straight and automatic air-brake, as the name implies, consists of two sets of motorman's valves for the control of each system. The straight air-brake, operating with pressure between 55 and 70 lb. per sq. in., applies and releases the brakes on the front car independently of the brakes on the other cars. The automatic brakes operate with air pressure from 100 to 110 lb. per sq. in., and apply the brakes on the remainder of the train independently of the brakes on the front car. The chief advantage of such an arrangement is the possibility of holding the brakes on the locomotive applied while the train brakes are released for the purpose of re-charging the auxiliary reservoirs.

228. The electropneumatic system is practically the same as the present automatic system, except that the valves are operated by solenoids in much the same way as the contactors in the multiple-unit train control. At the present time air control is retained as a safeguard in case of failure of the electric control. With electric traction, the possibilities of this system seem to be unlimited and automatic retardation as well as acceleration is quite feasible.

229. The air reservoirs should have a capacity sufficient to supply air for three or four applications without reducing the pressure more than from 12 to 15 lb. Otherwise every ordinary application of the brake will throw ported upon **elliptic and coil springs** designed to take up the shock resulting from riding over uneven track. Single-truck cars are limited to a maximum length of about 30 ft. over all and a maximum weight including car body and trucks, but exclusive of electrical equipment of approximately 15,000 lb.

233. The double-truck car is equipped with two distinct trucks joined together through the medium of the car-body framing. The swivel or **bogie truck** consists essentially of two or more axles centred in common side frames which are joined by a cross piece or bolster carrying a centre plate and also side-bearing plates upon which the car body rests.

The bogie truck may comprise two or more axles mounted in a single structure. the prevalent type, however, is composed of two axles for cars weighing up to 50 tons total weight. For very high-speed service or for heavy cars, three-axle trucks are to be recommended.

234. Classification of bogie trucks. The standard four-wheel bogie truck is built along different lines depending upon the service which it is to perform. As the weight of the car body is carried upon the cross piece or **bolster** connecting the side frames, it is evident that the construction of this bolster and its support offers a means of cushioning the effect of shocks given the car wheels when riding over uneven track. There are three general types of bogie trucks, namely: the rigid-bolster type (Par. **235**), the floating-bolster type, (Par. **236**); and the swinging-bolster type (Par. **237**).

235. The rigid-bolster type (Par. **234**) is suitable for locomotive work only, as the cushioning effect of the car body by means of springs is not carried to sufficient length for easy riding qualities. The bolster is solidly fastened to the side frames and forms an integral part therewith. The spring-suspended car superstructure is sustained by means of box springs

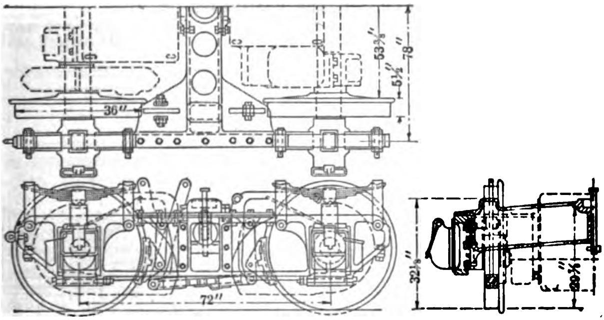


FIG. 65.—Motor, locomotive-frame, rigid bolster.

placed between the side frames and the journal boxes. These springs may be of semi-elliptic (Fig. 65) or spiral type (Fig. 68). This type of construction offers no compensation for the swaying of the superstructure, and is therefore not adapted for high-speed or passenger service.

236. The floating-bolster construction (Par. **234**), comprises in part a bolster mounted upon elliptic springs which rest upon the side frames. The bolster thus has an independent vertical movement, and travels in ways in the side frame. This type of construction is best adapted to locomotive trucks designed for slow-speed service, as the superstructure is not sufficiently cushioned to provide easy riding for high-speed passenger service.

237. The swinging-bolster construction (Par. **234**) comprises a movable bolster traveling in a guide or transom and mounted upon elliptic springs, a construction very similar to the floating-bolster type. In the former, however, the elliptic springs do not rest directly upon the side frames, but rest in a saddle hung from the transom or side-frame construction in such a manner that opportunity is provided for a transverse swing of the super-

238. Construction of bolster and side frames. The truck bolster may be made of wood or metal, and both the centre plate and side-bearing plates which it carries, may be ball or roller bearings, in order to reduce the friction and permit the truck to respond readily to the demands of track curvature. The side frames may be built up of steel plates riveted together, or forged or cast in a single piece. The construction is rigid and provides for good alignment of the axles.

239. Maximum traction trucks are designed for city service at speeds not much exceeding 30 miles per hr., and are useful where it is desired to mount a single motor on a truck providing for four wheels, having a short wheel base, and carrying 70 per cent. of the total car weight upon the driving wheel, which is larger in diameter than the trailing wheel. Maximum traction trucks are not suitable for high-speed service.

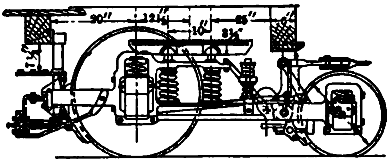


Fig. 69.—Maximum-traction truck (Brill Co.).

240. Classification of car bodies. Car bodies differ in construction according to local requirements. They may be divided into two general types, namely: open cars, and closed cars. The dividing line between these two types is not sharply defined owing to the introduction during the past few years of the convertible and semi-convertible type of car body, which permits the complete closing in of the car body sides, or partial removal thereof according to climatic conditions. The true type of open-car body is arranged with cross seats which will seat five passengers per seat and in the larger cars seating 75 passengers per car.

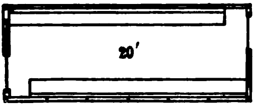


Fig. 70.—Seat capacity 24.

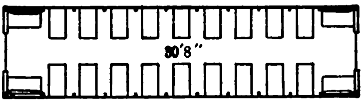


Fig. 71.—Seat capacity 44.

Besides the convertible and semi-convertible type of closed cars, a combination open and closed car is used for warm climates, as it offers the greatest advantages for all-the-year operation.

241. Arrangement of seats. The closed-body car may be provided with either longitudinal or cross seats, the former being used in the shorter cars of 30 ft. overall and under, and the latter in the larger city and suburban cars. In general it may be stated that longitudinal-seat cars are suitable only for short runs and medium rates of acceleration, and transverse seats should be used in order to provide comfort for the passenger where the accelerating rates are high or the run extended.

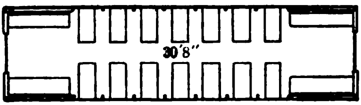


Fig. 72.—Seat capacity 44.

The prevalent type of transverse-seat car is indicated in Fig. 71, and usually contains short longitudinal end seats in addition. Owing to the possibility of crowding at the car entrance, it has been found advisable to provide more standing room at these points. This leads to a composite type of car having longer longitudinal end seats and providing transverse seats in the centre portion of the car only.

In some instances it is necessary to provide narrow city cars, and insufficient space is allowed for transverse seats capable of seating to people on the side. A modification of transverse-seat car is constructed for such cases having the longitudinal aisle and providing a two-passenger seat on one side and a one-passenger seat on the other.

249. The gas-electric car (Fig. 76) claims as its advantage the elimination of all mechanical troubles by substituting electric drive through generator and motors. Such cars are in service to a limited extent where operating conditions are favorable. Gas-electric locomotives are possible only when the service demand can be taken care of by the maximum output of the gas motor, not much exceeding 250 h.p. The possibilities of the gas-electric drive are not yet fully worked out or appreciated by operating men, and the use of such equipment is influenced largely by the possibility of using a cheap fuel. Cars are now in interurban service that consume approximately $\frac{4}{10}$ gal. of gasoline per car-mile.

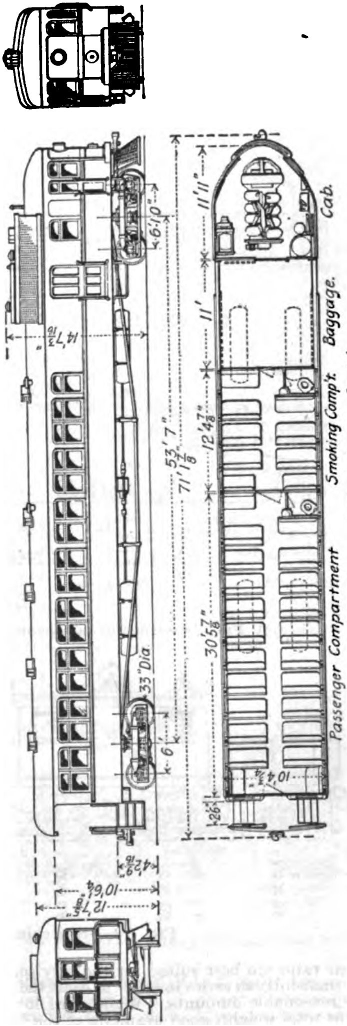


FIG. 76.—General Electric gas-electric car.

ELECTRIC LOCOMOTIVES

250. Classification. Electric locomotives may be divided into four general classes as follows: a, miscellaneous interurban freight service; b, yard-shifting and interchange freight; c, main-line freight; d, main-line passenger.

251. Locomotives for interurban lines are all of the same general type of construction and comprise a cab carried on two four-wheel trucks upon which are mounted single-geared motors in the usual manner. The locomotive is of construction similar to interurban cars, except as to superstructure and gearing of motors. The service performed by electric locomotives on suburban and interurban lines can generally be taken care of by a locomotive weighing from 30 to 50 tons, all weight being disposed on the drivers, and equipped with four geared motors of standard types. These motors have an aggregate capacity not greatly exceeding 1,000 h.p. at a 1-hr. rating. The trains hauled may reach 15 or 20 cars, totalling 500 to 800 tons as a maximum, while the average service comprises the movement of freight trains of considerably less number of cars. The duty of interurban locomotives is very variable and is of such an intermittent character as seldom to require accurate predetermination of motor capacity.

253. Main-line freight locomotives present a great variation in design and motor equipment. Main-line service demands a locomotive equipment capable of withstanding a large sustained output, and hence calls for different motor characteristics than those which meet the requirements of city and interurban-railway service. Steam-locomotive practice provides for a locomotive rating on ruling grade, based upon a tractive effort corresponding to a coefficient of adhesion of approximately 18 per cent. of the weight upon the drivers. This is exceeded somewhat under favorable rail and climatic conditions, but a lower rating is found necessary during winter months in cold climates. Hence assumption of 18 per cent. coefficient of adhesion may be considered good practice in determining electric locomotive rating on ruling grades.

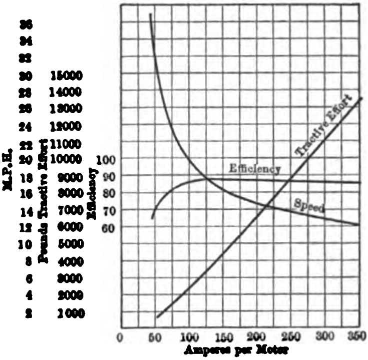


Fig. 80.—Motor characteristics Butte Anaconda & Pacific direct-current locomotive.

254. Example of calculation of permissible trailing load. An electric locomotive weighs 100 tons, all weight being disposed on drivers, what trailing load rating can it be given on 1 per cent. grade?

	Lb.
Tractive effort due to grade of 1 per cent. =	20
Tractive effort due to train resistance =	6
Total,	26
Locomotive tractive effort = 200,000 × 18 per cent. =	36,000

36,000/26 = 1,385 tons gross train weight
1,385 − 100 = 1,285 tons trailing

In Fig. 80 are presented the characteristic performance curves of the Butte, Anaconda and Pacific type of locomotive motor. This operates with direct-current supply at 1,200 volts (two in series for 2,400 volts).

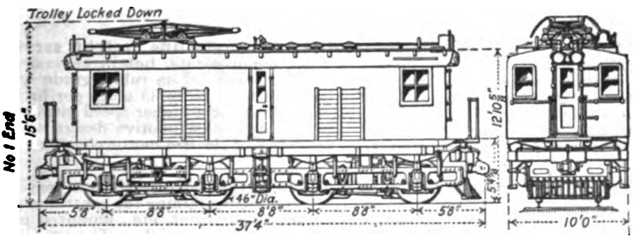


Fig. 81.—Butte Anaconda and Pacific 2,400-volt, direct-current locomotive.

255. The maximum tractive effort of a main-line freight locomotive should correspond to a coefficient of adhesion of 30 per cent., as this value is reached under good rail conditions with electric locomotives. The difference between 18 per cent. and 30 per cent. gives the range in tract-

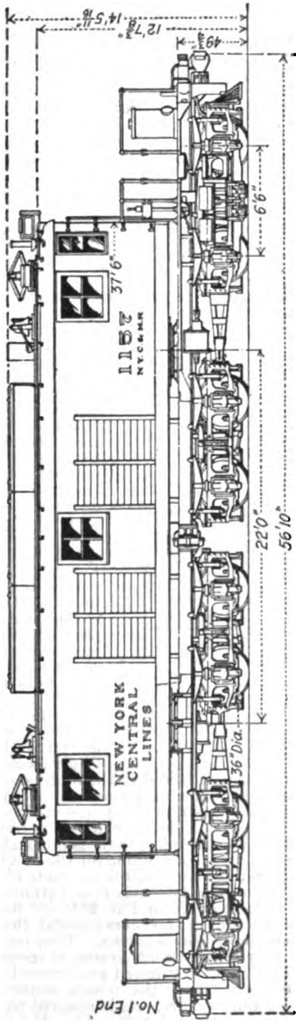


FIG. 83.—New York Central 600-volt, direct-current gearless locomotive (type of 1913, 8 motors).

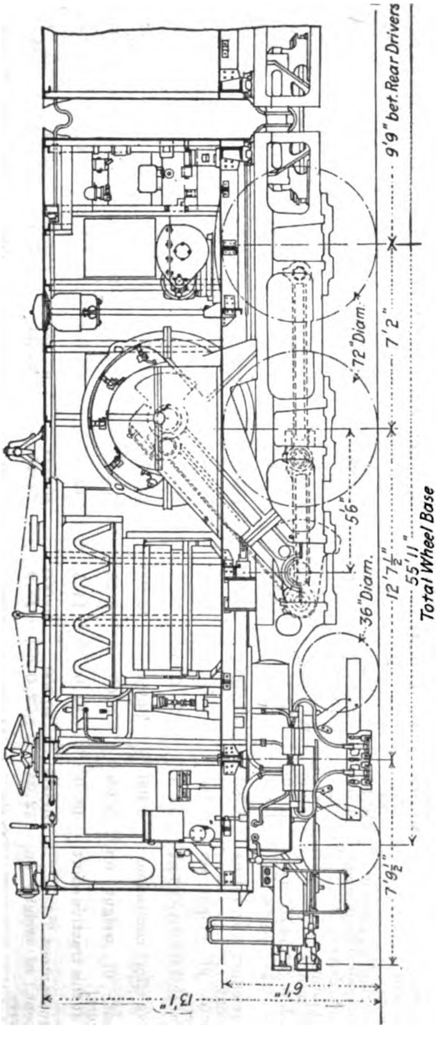


Fig. 85.—Pennsylvania locomotive (cross-section).

262. Tabulation of General Electric locomotives

Locomotives	B. A. & P.	B. A. & P.	Gt. Nor.	B. & O.	D. R. T.	D. R. T.	N. Y. C.	N. Y. C.
Service	Pass.	Frt.	Frt.	Frt. & pass.	Frt. & pass.	Frt. & pass.	Pass.	Pass.
Type	0440	0440	0440	0440	0440	0440	484	4444
Type motor	2,400 V.d.c.	2,400 V.d.c.	Three-phase	600 V.d.c.	600 V.d.c.	600 V.d.c.	600 V.d.c.	600 V.d.c.
Total weight	80	80	115	100	100	120	115	125
On drivers	80	80	115	100	100	120	71	125
Wt. electrical equipment	59,800	59,800	109,000	65,000	65,000	54,180	60,000	83,000
Wt. mechanical equipment	100,200	100,200	121,000	135,000	135,000	185,820	170,000	167,000
Diameter, drivers, in.	46	46	60	50	48	48	44	36
No. of motors	4	4	4	4	4	4	4	8
Type of motor	GE-229	GE-229	GEI-506	GE-209	GE-209	GE-209	GE-84	GE-91
One hr. h.p. rating 75 deg. cent.	1,280	1,280	1,500	1,100	1,100	1,100	2,200	2,600
Contin. h.p. rating 75 deg. cent.	1,090	1,090	1,400	660	660	660	1,050	2,000
Tractive effort 1-hr. rating 75 deg. cent.	20,200	30,600	37,200	24,500	34,400	34,400	20,600	20,400
Per cent. of weight on drivers	12.6	19.1	16.3	12.3	17.2	14.3	14.5	8.2
Tractive effort continuous	16,500	25,000	34,800	12,200	17,200	17,200	7,100	13,840
Per cent. of weight on drivers	10.3	15.6	15.1	6.1	8.6	7.2	5.0	5.5
Speed at this tractive effort	24.5	16.2	15.18	20.1	14.3	14.3	56.0	54.5
Rated voltage	2,400	2,400	6,600	600	600	600	600	600
Gear ratio	3.2	4.83	4.25	3.25	4.37	4.37	Gearless	Gearless
Quantity	2	15	4	4	6	4	47	16
Date	1913	1913	1908	1910	1909	1914	1906	1913

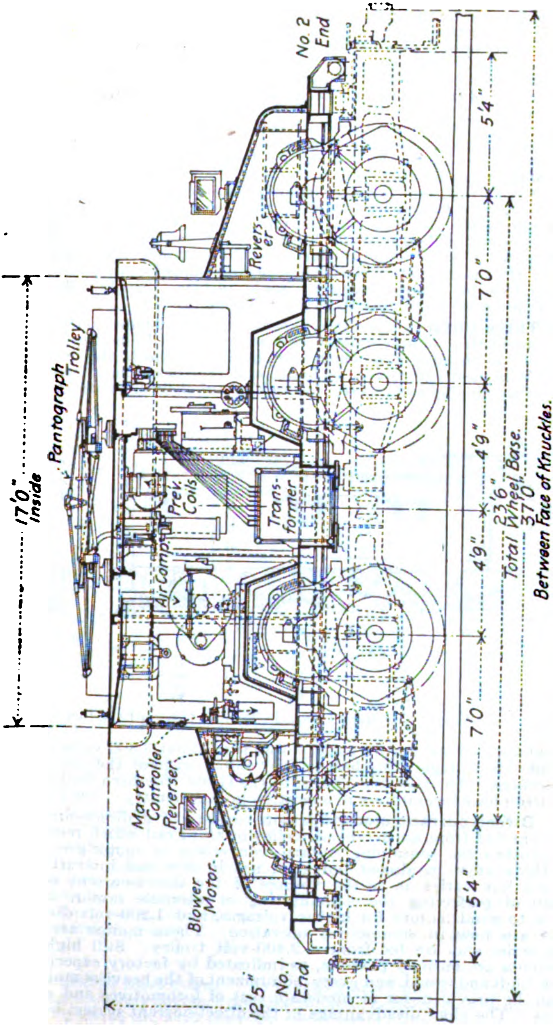


FIG. 87.—Single-phase switching locomotive.

advantages of this system include simplicity, low cost and high efficiency of the locomotives, the option of trolley or third-rail distribution, the choice of locomotive or multiple-unit trains, the benefits of bi-polar gearless-motor construction, and the use of balanced three-phase power supply of any frequency and entailing no serious telephone or telegraph interference.

Large direct-current locomotives are in service upon the following main-line electrifications.

P. R. R. New York Terminal....................	600 volts
B. & O. Tunnel Railway..........................	600 volts
New York Central Railway......................	600 volts
Detroit Tunnel Railway..........................	600 volts
Butte, Anaconda & Pacific Railway	2,400 volts
Canadian Northern Railway.....................	2,400 volts
Chicago, Milwaukee & St. Paul Railway.........	3,000 volts

DISTRIBUTING SYSTEMS

267. Train diagrams represent in graphic form the movement of all trains over a given division during the 24 hr. of operation. Such diagrams are usually plotted with distance as ordinates and elapsed time as abscissas, and they are of the greatest value in determining the average and maximum sustained demands upon the distributing and generating systems.

The average train input for a given service is determined according to methods outlined in Par. 78 to 118, so that a train diagram is useful for indicating the local demand upon any part of the distributing system during any period of 24 hr. The train diagram also furnishes means of obtaining the total average load upon the entire division covered by the diagram, by plotting in curve form the total average kilowatts demanded by the several train movements intersecting equally spaced ordinates. Thus, referring to Fig. 89, representing a typical train diagram wherein is depicted the per-

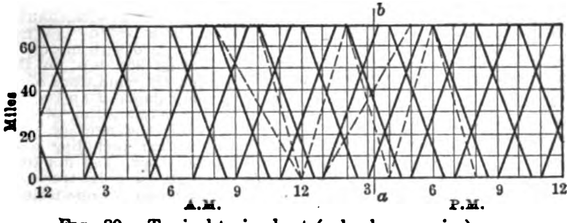


FIG. 89.—Typical train sheet (suburban service).

formance of both local and express trains, the ordinate, $a-b$, intersects the graphs of five trains. Assume that the various trains demand the following average input:

Local passenger..................................	100 kw.
Express passenger...............................	130 kw.
Freight..	210 kw.

The line, $a-b$, intersecting the various train movements, therefore, calls for a station output at 3:15 P.M. as follows:

Three local passenger trains....................	300 kw.
One express passenger train....................	130 kw.
One freight train................................	210 kw.
	640 kw.

268. Calculated load curve. By erecting other ordinates upon the 24-hr. performance sheet it becomes possible to plot a detailed generating-station load curve for the 24 hr. with the train movements as predetermined. This train load curve does not show momentary fluctuations, and these must also be considered in determining the character of the distribution system,

273. The conductance of the circuit between motors and bus bars, is seldom determined by its proper relation with interest on first cost of the conducting system and the cost of energy lost, as the first cost of the distribution conductors so determined is considerably in excess of current practice in this respect. In city systems the average and momentary maximum drop are practically the same owing to the small effect of the starting current of any one of the large number of cars controlled by one feeder. In interurban systems, where generally but two cars are controlled by one feeder, the maximum fluctuation is much in excess of the average drop.

274. Relation of trolley wire and feeders. Feeders are differently grouped according to the demands of the service and the physical arrangement of the trolley sections. The simplest conducting system to the car upon the track consists in that shown in Fig. 91, wherein the trolley is connected through circuit-breakers directly to the positive bus bar with no auxiliary

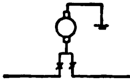


FIG. 91.—No feeders.

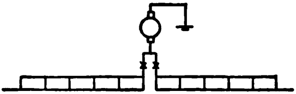


FIG. 92.—Single feeder.

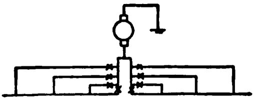


FIG. 93.—Multiple feeders.

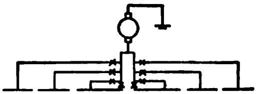


FIG. 94.—Sectionalised trolley wire.

feeders, and the negative bus is connected to the track return. The trolley is generally sectioned at the station and each section controlled by an independent feeder panel.

Where the trolley conductor itself has not a sufficiently high conductivity, it is reinforced with auxiliary feeders connected to it at frequent intervals. See Fig. 92. The result of such feeder reinforcement is simply to increase the conductivity of the trolley circuit, and corresponds to an enlargement of the cross-section of the trolley conductor itself. This grouping is best fitted for feeding a small number of units, and is more useful in the operation of suburban or interurban systems than in city work.

275. The most economical copper distribution for feeding a large number of train units would consist in a separate feeder to each train so proportioned that the drop in all feeders would be equal to the maximum drop permissible. As this would be impossible without too great a multiplicity of feeders, the arrangement in Fig. 93 is adopted. A better arrangement of the same feeder connection is shown in Fig. 94 which is identical to that in Fig. 93, except that the trolley itself is sectioned so that each feeder independently controls a single section of trolley and the cars drawing energy from that section (Par. **276** and **277**).

276. Length of trolley wire sections. Trolley sections may be from a few hundred yards to 2 miles or more in length in city service, depending upon the lay-out of the streets and the importance of sectionalizing different streets or sections of the same street in such manner as to occasion the least possible interruption to general traffic in case of failure of any one trolley section or its feeder.

277. Segregated trolley-wire sections. The trolley wire may be solid throughout as shown in Fig. 93, or preferably sectionalised as shown in Fig. 86, in which case the different sections are entirely independent and each feeder and each trolley section is calculated to give the limiting *IR* drop when feeding the maximum group of cars drawing energy from that section of the trolley. The direct-current feeder distribution shown in Fig. 94, applies more especially to city systems and may be elaborated to any extent required by the complexity of a large-city trolley system. Sectionalising the trolley is desirable from the standpoint of localising the effect of trolley breaks or

c. **Booster** in the supply station, which can be connected in series with any feeder extending to a temporarily overloaded section for the purpose of supplying the added voltage required to compensate for the excessive feeder and trolley drop.

d. **Track return**, consisting of the track rails, bonded at the joints.

e. **Track return feeders**, consisting of copper conductors reinforcing the track at points of greatest drop or at points where the track is negative to the neighboring pipes.

f. **Pressure wires** extending to important points on both trolley, track and pipes, and serving to indicate at all times the potential of the several parts of the distribution system.

Such large city systems are a matter of growth and not of calculation, as the practice giving good results in one city may not be directly applicable to the different conditions obtaining in another city.

282. Feeders for underground trolley or conduit systems. Such systems are described in Par. 324. The trolley conductors are two in number and are located underground between the two rails. These conductors are of opposite polarity, and there is no track return circuit. The arrangement, therefore, necessitates double the number of feeders required with the sectionalized overhead trolley used with track return. As both positive and negative rails are insulated from ground, the conduit systems practically eliminate any stray currents and electrolysis. Conduit systems are installed to avoid the unsightliness of the overhead trolley, and can only be considered in the largest cities owing to the enormous expense of their installation.

283. Primary distribution comprises the location of substations and the high-tension overhead transmission lines or underground cables connecting the substations to the generating-station bus bars. Primary transmission systems invariably employ alternating-current, and where synchronous converters or motor-generator sets are used, this primary current is of the three-phase type transmitted over three wires or in multiples of three if duplicate circuits are provided. Owing to the novelty of single-phase railway-motor distribution systems and the close interconnection of secondary and primary distribution systems when applied to alternating-current motor operation, this subject will be considered later (Par. 285).

284. Methods of serving direct-current substations. Substations for direct-current systems are located at strategic points along the line of travel best suited for secondary distribution. These substations may be fed from a common trunk line to which all substations are connected; this is common practice in suburban and interurban railways operated by direct-current motors. In such cases the trunk line preferably consists of two independent circuits, each of which may be used alone, providing, thereby, for continuity of service in case of the accidental grounding of one set of lines. It is also common practice to interrupt the transmission line at each substation, providing both incoming and outgoing line panels at each substation in order that the transmission-line troubles may be localized between two adjacent subs rather than that a whole trunk line be put out of commission due to the fault of any portion thereof.

In city systems or in interurban systems where the traffic is very heavy and where freedom from interruption of service that is of greatest importance, it is good practice to connect each substation to the generating-station bus bars through its own individual transmission line or underground cable. In fact, if the substation is very large, this divisibility of the transmission circuit is sometimes carried to the extreme of providing each substation with several cables connected either to individual synchronous converters or to different bus-bar sections. If this bus-bar segregation is resorted to each section is allowed to control two or more synchronous converters. It is evident that this multiplicity of high-tension transmission lines or cables can be made use of only in very large and important cities, or in interurban systems taking care of a very congested traffic.

285. Single-phase generation and transmission. Alternating-current single-phase railway-motor systems are best energized by single-phase generation and transmission, owing to the simplicity of single-phase connections throughout the system. The method of connecting the various alternating-current substations to the generating station consists usually in tying all substations to a single trunk line through circuit-breakers designed to open on short-circuit only. Individual transmission lines to

288. Three-phase, two-phase transformer connection (Sec. 6) can be used where the road is of limited extent. This method consists in employing the three-phase two-phase connection of substation transformer, feeding the two-phases to adjacent trolley sections, so that corresponding phases will be fed to a given trolley section from the transformer substation at its terminals. This system of connections will not provide perfect balance upon the three-phase side of the transformers unless the loads are balanced upon the several trolley sections. Sufficient balancing, however, may be obtained in the majority of cases, and this system of connection is in quite extended use.

289. Two-phase generation and single-phase distribution. Two-phase generators may be used to supply single-phase railway distribution systems by sending out transmission lines from the two phases in different directions, thus amounting in principle to two separate single-phase transmission systems. This method of connection is open to the objection that unless the loads are perfectly balanced upon the two phases, the voltage regulation will be very poor, and in cases of generators having poor inherent regulation, it may reach such proportions as to endanger the lamps and the general operation of the equipments.

290. General considerations in design of a new single-phase motor system. In general a new railway system, favorable for the operation of single-phase motors, operates to best advantage with the single-phase system of generation and transmission, provided the contemplated road has no future connections with neighboring systems and is free from entanglements, such as power distribution, operation of synchronous converters, etc., requiring multiphase generation and distribution. Where it is advisable to provide for the future utilisation of three-phase power, three-phase generators may be installed, operating either on one leg as single-phase generators, or using all three legs in connection with three-phase two-phase transformer connections in the substations in order to provide for reasonably good balancing of the three-phase primary distribution.

291. Three-phase, induction-motor systems may employ the same method of substation connections and primary distribution as outlined under the head of synchronous converter substations for direct-current motor systems. Owing to the fact, however, that transformer substations of all kinds may be operated without attendance, such substations are best connected to a main trunk line through circuit breakers operated by relays designed to open only on short-circuit. Where the control of the substation is extremely important, attendance should be supplied, or each individual substation should be connected to the generating station by separate transmission lines having automatic control at the generating end only. In all cases the trolley or secondary connection to the transformer substation should be safeguarded by automatic switches designed to open on short-circuit.

292. Resistance of trolley wire circuits is dependent upon the weight of trolley copper and track rail, and also upon the composition and bonding of the latter. Trolley conductors are either 000, or 0000 A.W.G., the smallest size being seldom used owing to its lack of strength and the difficulty of clamping its small diameter.

293. Trolley wire and track resistance per mile

Track rail	Ohms resistance 2 rails	000 Trolley and 2 rails	0000 Trolley and 2 rails
50 lb. per yd......	0.053	0.383	0.313
60 lb. per yd......	0.044	0.374	0.304
70 lb. per yd......	0.038	0.368	0.298
80 lb. per yd......	0.033	0.363	0.293
90 lb. per yd......	0.030	0.360	0.290
100 lb. per yd......	0.027	0.357	0.287
110 lb. per yd......	0.024	0.335	0.284

000 Trolley = 0.33 ohms. 0000 Trolley = 0.26 ohms.

porting steel towers joined by very heavy catenary construction, the whole combination being thoroughly anchored to withstand stresses, or else the

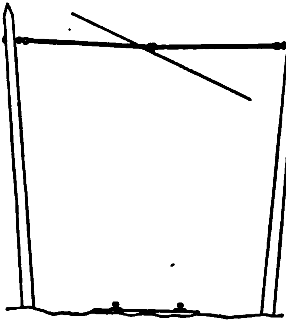


FIG. 101.—Cross suspension.

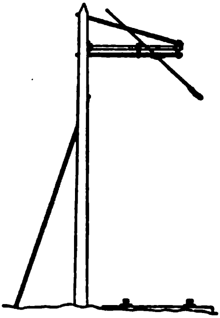


FIG. 102.—Bracket suspension.

side towers should be joined by a light steel truss, forming a bridge construction, this latter being used in steam-railroad electrification where the number of tracks exceeds two.

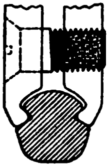


FIG. 103.—Trolley clamp.

301. Trolley wires generally have a cross-section equal to 3,000 or 4,000 cm. A.W.G., and are drawn in three sections; round, figure 8, and grooved. The use of round wire is objectionable owing to the difficulty of securely clipping it to the hangers without forming a projection on the wire itself which will tend to throw off the current collector in high-speed operation.

The use of figure 8 wire is open to the objection that owing to its unsymmetrical cross-section it is very difficult to handle during installation, although it affords a ready means of fastening and leaves a clean unbroken undersurface suitable for high-speed operation.

The grooved trolley wire (Fig. 103) is in greatest use and consists of a round wire grooved on opposite sides sufficiently deep to permit gripping by adjustable clamps or hangers. Owing to its round

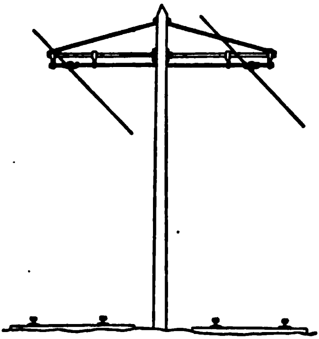


FIG. 104.—Two-track bracket construction.

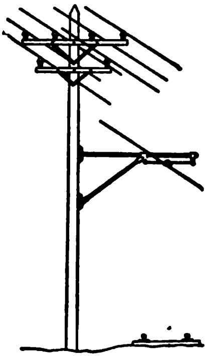


FIG. 105.—Combination pole.

between supports than is customary with the self-supporting trolley wire construction.

305. Distance between trolley-wire supports on tangents

Self-supporting trolley	110 ft.
Catenary wooden-pole bracket construction	150 ft.
Catenary steel-pole bracket construction	200 ft.
Catenary steel-bridge construction	300 ft.

The only limit placed upon the distance between supports in catenary construction on tangent track is the likelihood that long spans will have considerable lateral sway. This is corrected in part by suspending the trolley from a double catenary construction, thus forming a triangular truss of considerable rigidity. Catenary construction is only adapted to tangent track and curves of long radius, as it requires additional pull-off poles attended with considerable expense in order to be adapted to sharp curves.

306. Pole guying. With wooden-pole bracket construction it is customary to anchor the poles on curves, often on tangents.

307. Duplication of primary circuits. Primary transmission circuits may be carried upon the same poles that serve as a support for the trolley. The transmission line so supported may be supplemented by a separate transmission line hung on independent poles, in order to provide greater assurance for continuity of service.

308. Standard trolley potentials in use are as follows: 600 volts direct-current, 1,200 volts direct-current, 3,300 volts alternating-current, 6,600 volts alternating-current, 11,000 volts alternating-current.

An alternating-current trolley potential of 3,300 volts has been used in several installations but is being superseded by 6,600 volts in the smaller, and 11,000 volts in the larger installations.

309. Overhead collecting devices for use with trolley may be divided into three classes: wheel (Par. **310**), roller (Par. **314**), and sliding-bow (Par. **316**).

310. The trolley wheel consists of a grooved wheel of composition metal ranging from 3.5 in. to 6 in. in diameter, depending upon whether the service is low or high speed. Wheels are carried on a self-lubricating bearing and press against the trolley at pressures from 15 to 40 lb. depending upon the maximum speed of the equipment, this pressure being maintained throughout a wide range in height of trolley wire in order to provide for reduction in standard height of 22 ft. made necessary when going beneath bridges, culverts, etc.

311. Approximate life of trolley wheels

City service 25 miles per hr. maximum	11,000 miles
Suburban service 35 miles per hr. maximum	6,000 miles
Interurban service 50 miles per hr. maximum	3,500 miles
High-speed service 60 miles per hr. maximum	2,000 miles

312. The current capacity of the trolley wheel is determined by its speed and the pressure of contact between wheel and wire, the higher the speed the greater the pressure necessary to maintain contact without arcing. High speed also demands a very nicely balanced wheel and the maximum speed at which trolley wheels are used, corresponds to a car speed of 60 miles per hr.

Following are the current-carrying capacities of trolley wheels at various speeds.

Speed in miles per hr.	5	10	20	30	40	50	60
Current capacity in amperes	1,000	850	650	550	400	300	200

This table is compiled on the basis of maximum current-carrying capacity at the different speeds with trolley and wheel in good condition. The wheel is balanced for the higher speeds and the contact pressure varies from 20 to 40 lb. between trolley and trolley wheels.

313. Flexible trolley-wire suspension for the higher speeds. At the higher speeds it is absolutely necessary that the trolley suspension be very flexible, preferably hung from a catenary and with the clip fastening the trolley wire of as light weight as possible in order to minimize the blow of the trolley wheel striking it.

all heights by means of the so-called pantograph construction. The pantograph bow is preferable for alternating-current roads as it permits reversal of the car direction without reversing the trolley, and furthermore, by reason of the parallel motion introduced, it does not interfere with trolley construction.

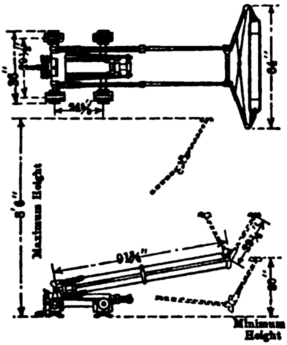


FIG. 110.—Sliding bow.

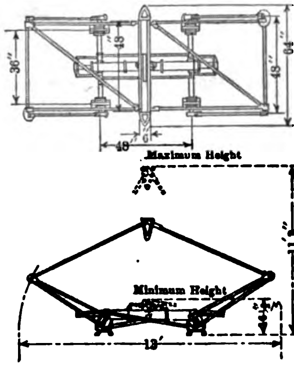


FIG. 111.—Pantograph bow.

317. Third-rail construction may be divided into two broad classes: *a*, overrunning contact (Par. **318**); *b*, underrunning contact (Par. **324**).

Third-rail voltages of 600 and 1,200 volts (Central California Traction) are in operation and still higher potentials are being proposed. The limiting third-rail voltage has not yet been reached, and it is probable that the development of improved forms of construction will result in the use of higher voltages for steam-road electrifications. Costs are given in Par. **355** and **356**. **Bonding** of the third-rail is treated in Par. **339**.

318. Overrunning-contact third rails were the first introduced and are in more general use. The construction consists essentially in supporting a steel rail, of either standard track or special composition, upon insulators placed every 10 ft. These insulators rest on supports carried upon projecting ties. Rails are joined loosely by fish plates, are bonded, and at intervals are thoroughly anchored to prevent creepage. Contact is made with the collecting surface of the rail by means of a third-rail shoe suspended from the trucks of the car or locomotive.

FIG. 112.—Unprotected third-rail.

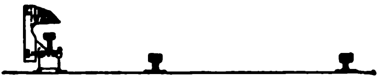


FIG. 113.—Protected third-rail.

319. Protected third-rail construction is a modification of the above, and consists in providing a wooden or metal shield over the rail in order to protect it from snow and sleet or accidental contact, the rest of the construction being identical with that outlined above. The wood or iron construction is supported by uprights placed every 10 ft. or more, and such protection is usually substantial enough to bear the weight of a man midway between supports.

o provide sufficient clearance through tunnels, etc. The distance from rack gage line to centre of third-rail varies from 20 in. to 28 in. and he height above track is from zero inches to nearly 8 in. The smaller istances apply to elevated and subway roads operating only one class of olling stock, and the greater distances apply to interurban lines or elecrified steam lines where provision must be made for the passage of all lasses of freight cars and possible steam locomotives.

322. Third-rail jumpers are used to connect the third rail severed at rossings and consist of copper cables bonded to the rail and extending hrough underground conduits. Jumper cables are heavily insulated, are ead covered, and enter the ground through solidly-constructed concrete tructures.

323. Third-rail insulators consist either of impregnated wooden blocks, 'econstructed granite or porcelain insulators designed to be held in chairs astened to elongated ties and forming a loose support for the third rail. In order to provide for elongation of third rail caused by extremes in temperature there is no solid fastening between the third rail and its insulating upport, and jumpers must be of sufficient length to allow for creepage.

FIG. 115.—Underrunning third-rail.

324. Underrunning third-rails of the protected type, first installed on the New York Central R.R., offer some advantage over the overrunning type in regard to better protection against accidental contact and against sleet and snow. The contact surface being the under side, is self cleaning, and this form of third rail has successfully operated through heavy snows completely covering the third-rail structure. The Central California Traction Co. operates an underrunning third-rail at 1,200 volts.

325. Leakage from third-rail is extremely small and may be neglected unless the road bed should be deeply impregnated with salt. Even though the third-rail be covered with snow it is found that the leakage is too small to constitute a noticeable item of expense.

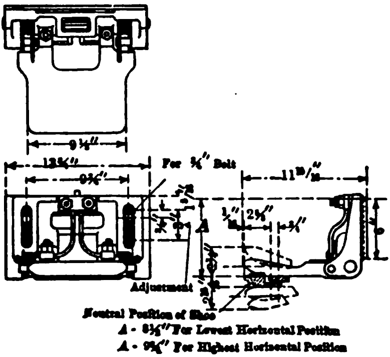


FIG. 116.—Shoe for standard and inverted rail.

326. Third-rail shoes (Par. 327) are of two general types: those acquiring their pressure by gravity and those actuated by means of springs. The unprotected overrunning third rail was first used in conjunction with gravity shoes, and in many installations this form of shoe is still in operation. Where rails are protected it is necessary to provide a form of shoe which will operate and insulators in good condition together with the upkeep of jumpers and the cables. This expense has been found in practice to be very small and the low maintenance charge of third-rails together with the possibility which such a system offers for handling unlimited current values at any speed constitute the strongest arguments in favor of its adoption.

333. Protection of third rail against sleet and snow is affected directly by the various forms of protected third rail, and it has been found that especially the underrunning type can operate in snow entirely surrounding the third rail without difficulty, owing to the fact that the under contact surface of the rail is self cleaning. With the various forms of exposed overrunning rail it has been found that the accumulation of sleet may be prevented by the use of calcium chloride mixed with water in the proportion of 1 lb. to 5 gal. and sprayed upon the rail at intervals of not more than 2 hr. during the continuance of the storm.

334. Underground trolley or conduit systems are in use only in the very largest cities owing to the enormous expense of their installation. Such systems consist in the location of two third-rails or conductors placed in a conduit located between the track rails, contact being established by means of a plough extending through a slot opening of the conduit. As the plough carries both the positive and negative contacts, there is no track return and hence the conductivity of the track as a return feeder is lost.

Underground trolley systems are installed in city streets where the congestion of travel is sufficiently heavy to warrant the large expense and where the use of overhead wires is objectionable. As conduit systems are essentially double-trolley systems, the feeder network is double that required for an overhead trolley with track return. Both conductor rails are controlled by separate feeders and are divided into sections as previously indicated for city trolley systems. Each section, with its feeders, is controlled by double-throw switches so that it may be made either positive or negative at will. With this arrangement of double-throw switches it becomes possible to throw all temporarily grounded sections on a bus of the same polarity and thus prevent possible short-circuits due to simultaneous grounding of a positive and a negative conduit conductor.

335. Double-trolley systems are installed to a very limited extent in city streets in order to prevent any liability to electrolysis possible with the single-trolley track-return system (Par. **453**). Such systems call for double collectors and double-trolley construction, which becomes complicated and expensive to maintain in city streets. One trolley is positive and the other negative, so that the track is not utilized for return and hence need not be bonded.

336. Three-phase double-trolley systems or double third-rail systems are sometimes used in conjunction with three-phase induction motor equipments requiring three conductors, in which case the track acts as the third leg of the triangle. Such systems usually carry several thousand volts upon the trolley wires, employ the catenary overhead construction, and are as yet in very limited use.

337. Three-wire systems comprise two overhead trolleys having a potential difference of 1,200 volts between them and 600 volts each to ground. In this case the car equipment consists of two separate 600-volt motor equipments including control, connection being established with the track as a neutral. Such systems can therefore operate either as 600-volt from either or both trolleys, or as a straight 1,200-volt system trolley-to-trolley with the track acting as a neutral and carrying practically no current. Where there is no restriction placed upon the voltage drop in track return, such systems suffer in comparative first cost with the single-trolley system.

338. Track return. It is almost the universal custom in electric railway systems to utilize one or both rails of the tracks as a return circuit to the generating station. It was early found that the ground itself or even adjacent bodies of water constituted a return circuit of such high resistance as to be of little practical use, hence the necessity for a carefully bonded track-return circuit, reinforced by feeders where necessary. Data on conductivity and the resistance of standard rails is given in Par. **328** and **331**.

339. Rail bonding (Par. **340** to **354**) consists in establishing contact, rail to rail, in order to utilize to the fullest extent the conductivity of the rail as a tion holds only when the bonding is installed and maintained in first class condition.

347. Double bonding is resorted to in many instances in order to insure a path of good conductivity in case of failure of a single bond. Where double bonding is not required to provide additional current capacity in order to keep temperature rise within reasonable limits, it is better engineering to install a single bond of sufficient capacity from a temperature rise standpoint and maintain this bonding in good condition. Double bonding is open to the objection that one of the two bonds may give imperfect contact and be practically useless, and such a method of installation usually results in the operation of the road with practically single bonding throughout.

348. Single bonding for suburban roads where the service is infrequent and current demands do not momentarily exceed 1,000 amp., is to be recommended provided rails are frequently cross bonded and all bonded joints are regularly inspected and maintained in their original good condition.

349. The heating of bonds will determine the size and number of bonds to be used on roads over which there is a large volume of traffic, and where the moving units demand a large kilowatt input, such as trains hauled by locomotives, etc. Following are given values of temperature rise at different current strengths:

Current amperes	500	1,000	1,500	2,000	2,500
Temperature rise deg. cent.	10	35	78	135	210

This table of heating constants applies only to bonding exposed to the air and not covered by fish plate, in the latter case the heating will be somewhat increased. The values given in the table apply only to bonds maintaining good contact with the rail. As one of the integral rails composing the track return may become useless owing to failure of a single bond, each rail must be bonded with the prospect of carrying the full return current. The heating of the bond varies approximately proportional with the square of the current value and extremes in temperature are to be avoided owing to the unequal expansion of copper and rail. It is therefore desirable that the greatest conservatism be used in selecting the bonds for a given service. This holds especially true where soldered bonds are concerned, as too high a temperature will melt the connection between rail and bond. Brazed and electrically welded bonds will, of course, withstand a larger current value and higher temperature without danger of falling off.

350. Amalgam bonds have been used with some success, the most modern comprising a spiral spring approximately 1 in. in diameter containing a soft amalgam, the whole being designed to be placed between the thoroughly cleaned fish plate and rail, and held in place by the bolts extending between them. This type of bonding is easy of application and is useful where a concealed bond is desired.

351. Welded joints in general give the greatest satisfaction where it becomes necessary to bond the rail to its full current-carrying capacity as when the bond is called upon to carry a very high value of current. Welding is obtained by three methods: Cast (Par. **352**), electric (Par. **354**), and thermit (Par. **353**).

All forms of welding are necessarily somewhat expensive, and are not well adapted to the requirements of suburban roads, using T rails laid on ties in the open, because of the inability of such joints to allow for rail expansion.

352. Cast welding is secured by pouring the metal in a mould surrounding the rail joint, thoroughly cleaned for the purpose. Such joints will have no expansion, are somewhat likely to crack, and are best suited for use in city streets where the track is held rigidly in place by the pavement.

353. Thermit welding is accomplished in very much the same manner except that a relatively small amount of metal is required. This process is not as yet in very general use.

354. Electric welding at the rail joint is perhaps best secured by welding a steel strap to each rail, the joint not being continuous between strap and rail but maintained at one or two points of contact. Electric welding has proved very satisfactory in the past, and gives good satisfaction where great current-carrying capacity is desired.

Labor

Quantity	Operation	Cost	
		Unit	Total
640	Installing ties	0.35	$224
640	Installating brackets	0.10	64
1-mile	Installating rails and protection	....	250
320	Installing bonds	0.55	176
12	Installing approach blocks	0.50	6
	Distributing ties and rails	....	50
	Distributing other material	....	50
	Total for labor	....	$920

For jumpers at cross-overs and street crossings 300 ft. of 1,000,000-cir. mil cable per mile. When this is installed in fibre conduit embedded in concrete cost will be approximately $1.80 per ft.

Total for jumpers	540
Superintendence and engineering 10 per cent	505
Total cost per mile installed	$5,535

357. Approximate cost of installation for 600-volt direct-current span construction per mile

Based on 100 ft. pole-spacing on tangents—wooden poles—standard direct-current construction—allowance made for 10 per cent. track curvature—track and road bed not included.

	Single track	Double track
Poles, 35 ft. long, 8 in. tops at $5.50	$620.00	$620.00
Line material	325.00	450.00
Wire and cable exclusive of trolley	126.00	189.00
Trolley wire 4/0 at 18 cents	656.00	1,312.00
Material	$1,727.00	$2,571.00
Labor	1,050.00	1,450.00
Labor and material	$2,777.00	$4,021.00
Engineering and superintendence	302.00	451.00
Total cost per mile	$3,079.00	$4,472.00

358. 600-volt direct-current trolley bracket construction, cost per mile

Based on 100 ft. pole-spacing on tangents—wooden poles—standard direct-current construction—allowance made for 10 per cent. curvature—track and road bed not included.

	Single track	Double track
Poles, 32 ft. long, 8 in. tops, at $4.75	$269.00	$307.00
Line material	250.00	500.00
Wire and cable exclusive of trolley	73.00	115.00
Trolley wire 4/0 at 18 cents	656.00	1,312.00
Material	$1,248.00	$2,234.00
Labor	775.00	1,290.00
Material and labor	$2,023.00	$3,524.00
Engineering and superintendence	227.00	402.00
Total cost per mile	$2,250.00	$3,926.00

Labor

40	Additional for erecting longer poles	20.00
40	Gaining roofing and setting cross arms	30.00
	Pulling and tieing in 2 trans. wire	50.00
	Pulling and tieing in 1 ground wire	35.00
	Extra guying and grounding cable	10.00
40	Distributing poles extra for long poles	10.00
	Telephone cradles, etc	20.00
	Distributing material other than poles	10.00
	Total for labor	$185.00
	Labor and material	$928.00
	Engineering and superintendence	55.25
	Total cost per mile	$983.25

363. Bill of material and cost per mile of 33,000-volt three-phase transmission line

On same poles as direct-current trolley 100 ft. spacing on tangent—40-ft. poles, $\frac{5}{16}$-in. steel cable for lightning protection—3 wires on one cross-arm—3 ft. between wires.

Quantity	Material	Cost: Unit	Cost: Total
60	Extra cost of poles	$2.00	$120.00
60	Cross arms 5 in. × 6 in. × 10 ft. 6 in.	1.00	60.00
120	Braces 2¼ in. × ¼ in. × 3 ft. 6 in.	0.22	26.40
60	Bolts for cross arms ⅝ in. × 14 in.	0.25	15.00
120	Bolts for braces ½ in. × 6 in.	0.06	7.20
60	Lags for braces and poles	0.045	2.70
60	Parts for attaching ground wire	0.04	2.40
180	Insulators and pins	0.90	164.00
40	Lb. No. 8 B. & S. insulator ties 4 ft. long	0.255	10.20
30	Lb. No. 6 B. & S. tinned copper for grooved connections	0.255	7.65
5,300	ft. $\frac{5}{16}$-in. galvanised cable for ground wire	0.01	53.00
1,000	ft. ⅜-in. galvanised cable for guy (rest included with trolley material)	0.014	14.00
8	Splicing sleeves, solder, etc		7.00
	Material for double arming at curves		50.00
	Material exclusive of wire		$539.55
	Wire 3 miles No. 2 B. & S. at 18 cents		600.00
	Total material per mile		$1,139.55
	Labor		
60	Additional for erecting longer poles	0.50	30.00
60	Gaining roofing and setting cross arms	0.75	45.00
	Pulling and tieing in 3 trans. wires	20.00	60.00
	Pulling and tieing in 1 ground cable		35.00
	Extra guying and grounding ground cable		10.00
60	Distributing poles—extra for long poles	0.25	15.00
	Distributing material other than poles		20.00
	Telephone cradles, etc		20.00
	Total for labor		$227.00
	Labor and material		$1,366.55
	Engineering and superintendence		55.45
	Total cost per mile		$1,422.00

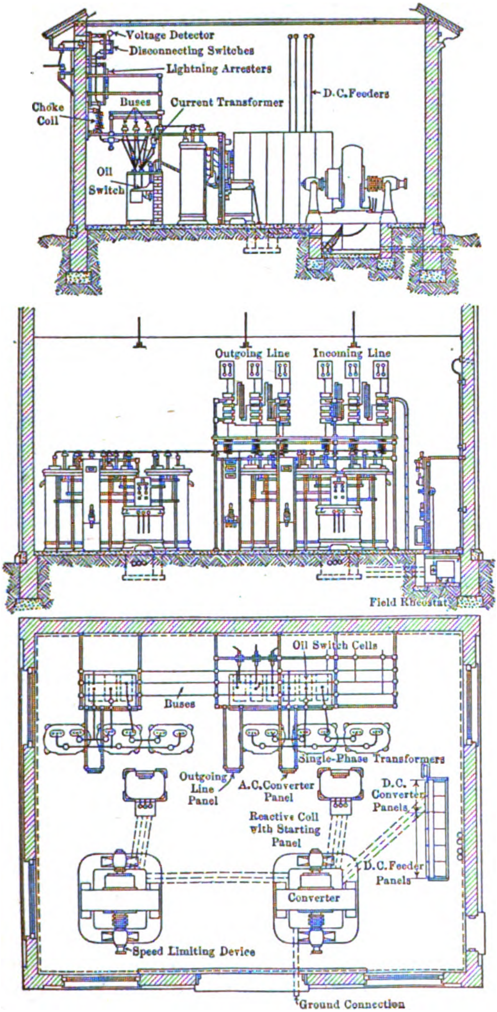


Fig. 117.—Synchronous converter substation.

current side of the converters; f, synchronous converters (see Sec. 9); g, direct-current outgoing feeders; h, switchboard panels controlling both the alternating-current and direct-current side of the converter as well as both alternating-current and direct-current incoming and outgoing feeders.

372. Ratio of conversion of synchronous converters varies somewhat with the construction of the machine, being in general as follows: three-phase converters 370 volts alternating-current to 600 volts direct-current; six-phase converters, 430 volts alternating-current to 600 volts direct-current. Machines having long pole arcs have a somewhat higher ratio of conversion than those of shorter pole arcs. In order to provide for the differences in types of machines and also for the varying drops in the primary distribution system to which rotary converter substations are connected, it is customary to provide five primary taps of 2.5 per cent. each in the step-down transformers. One of these taps is 2.5 per cent. above the receiving potential in order to take care of the high ratio of conversion of longer pole-arc converters.

373. Substation voltages. A typical step-down transformer (Par. **374**) will have primary and secondary ratios as follows: primary voltages 19,600—19,100—18,600—18,150—17,700—17,200 secondary voltage 370. Such a transformer would be adapted to operate a three-phase 25-cycle rotary converter from a "Y"-connected 33,000-volt transmission line.

Standard primary substation voltages are 11,000 volts, 19,100 volts, 33,000 volts, 66,000 volts. It is customary to use **delta transformer connections** for both 11,000 and 19,000 volts and "Y"-transformer connections with grounded neutral for 33,000 volts and higher. Many substations now operating at 19,100 volts delta are doing so temporarily pending a change to 33,000 volts "Y" for which higher potential the transformers are insulated.

374. Step-down transformers are of several types, as follows: A. B. or air-blast transformers, O. C. or oil-cooled transformers, W. C. or water-cooled transformers, oil transformers self-cooled, F. O. or forced-oil transformers.

Any or all of these several types of step-down transformers can be built three-phase or single-phase, in which latter case three transformers are required for either "Y" or delta connection with each converter.

375. Comparison of transformer cooling methods. Air-blast transformers when used call for the construction of an air chamber over which they are placed and from which they receive air at a pressure of from ½ oz. to 1 oz. Air is supplied by a duplicate motor-driven fan feeding into the air chamber. This type of transformer is very generally used up to and including potentials of 33,000 volts. For higher potentials and for small transformer units oil is resorted to for cooling by a variety of means.

The design of the small self-cooled (oil) transformer is especially adapted to the smaller sizes, owing to its cheapness. For larger sizes it becomes necessary to cool the oil either by means of a cooling coil placed in the transformer and through which water is circulated, or by providing means of circulating the oil itself through an outside pipe coil, in order to reduce its temperature. In general the air-blast type of transformer is preferred for potentials not exceeding 33,000 volts on account of its freedom from fire risk in case of a short circuit or "burn out." For very small single-converter units or those having connection to the higher primary potentials, some form of oil-cooled transformer is to be preferred.

376. The general arrangement of apparatus in substations is somewhat similar in all cases, as such buildings are usually designed for the purpose. In general the wiring scheme consists in providing the shortest and most direct path from the incoming primary lines to the outgoing direct-current feeders, and the interior-wiring scheme is carried out with the object in view of preventing any crossing of circuits or doubling back upon themselves.

377. Duplicate apparatus in a substation may or may not be installed, depending upon local requirements. The manufacture of synchronous converters, transformers, and general substation apparatus, has been so far perfected that failures in such apparatus are very infrequent. It is, therefore, quite customary to install substations containing but a single converter and set of transformers, although it is always good engineering to provide duplicate converter, transformers, switchboard, etc., throughout. This practice is

379. Alternating-current substations designed for use with alternating-current railway motor equipments are generally designed for operation without attendant (Par. 285 to 288). Such substations comprise a

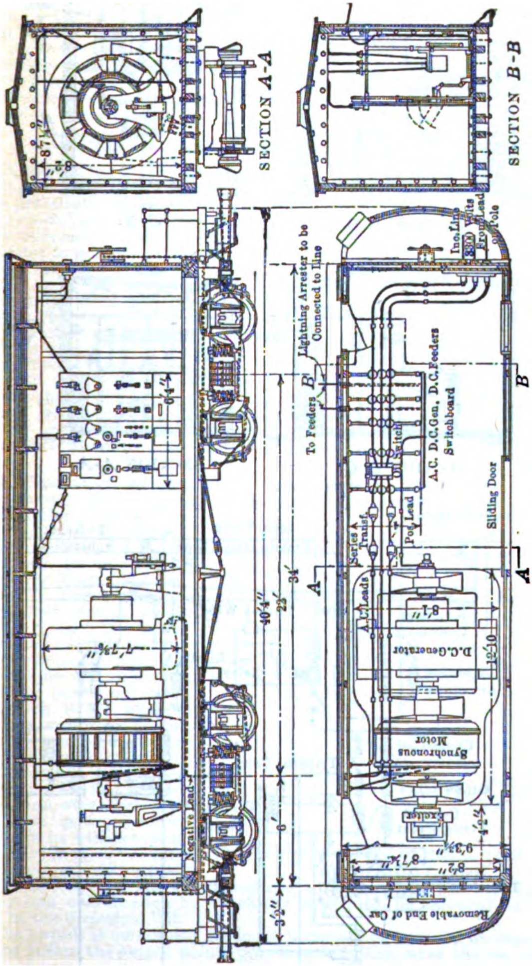


FIG. 120.—Motor-generator portable substation.

small fireproof building containing step-down transformers, generally in duplicate, together with the necessary switchboard apparatus. Both primary and secondary transformer circuits are provided with automatic

›il switches designed to open on short-circuit or extreme overload only [hese automatic switches serve merely as a safety device to protect the transormers from burn out. As such substations have no operator and are ubject to violent fluctuations in load greatly exceeding the average, it is ıecessary that all protective devices be limited in their function in order to guard against short-circuit and not overload.

In order to facilitate the location of faults, alternating-current transformer ubstations are commonly supplied with both voltmeter and ammeter ›esides being equipped with lightning arresters upon both the high-tension and ow-tension incoming and outgoing feeders. Step-down transformers are of he self-cooling oil type.

AUTOMATICALLY OPERATED TRACK SWITCHES

380. Advantages of automatic track switches. The practice of urning switches with switch bars from the front platform of cars has been nade practically impossible by the addition of the vestibule and fender, and nany roads have undertaken to install electrically operated switches. Thus he inconvenience and waste of time occasioned by requiring a motorman or onductor to get off the car and turn switches, or employing a switch tender. Jsually the hand-operated switches are held in place by a block of rubber or iece of steel to prevent splitting the switch as often happens in case of louble-truck cars, and these small blocks frequently require considerable nanipulation before they are taken out and the switch turned. An electrically operated switch is turned at will by the motorman running over an nsulated section of the trolley with power on, or left on its original position ›y coasting over this section. Perhaps the simplest manner by which utomatic track switching may be accomplished is by placing two solenoids ›etween the tracks at the switch and connecting their cores to the switchoints. By energizing either of these solenoids the switch will be turned in one way or the other, and it remains to place two insulated sections in the rolley wire whereby a car can cause current through one or the other, or ıeither.

381. Operation of automatic track switch. The following are the vays in which the switch may be operated: a, a motorman desiring to go in he direction, "A" (Fig. 122), may find the switch et for track, "A," in vhich case he may either oast over both insulated ections or traverse, under ›ower, that section which vill not disturb the switch ınd coast over the other, or f the sections are in proper equence he can run over ›oth with power on; b, if he switch is set against ıim, the motorman must elect the insulated section vhich will turn the switch, ınd traverse it with power m. If it is the last section ıe can run over both sections with power on; c, ikewise, if he wishes to run n the direction, "B," but f the sections are arranged or all the combinations mentioned above for the direction "A," there will ›e one less combination by which the switch can be operated by the cars oing in the direction, "B."

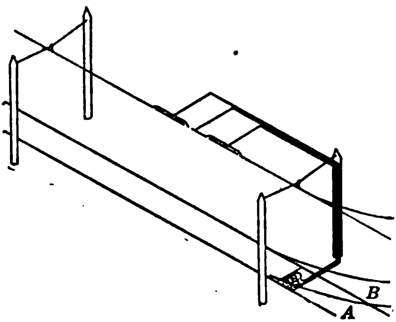


Fig. 122.—Electrically operated track switch.

If the switch is on a down grade for approaching cars the arrangement of ections before the switch points proves satisfactory, since the car can coast ›ver both sections if necessary. If, however, the approach to the switch is ›n a considerable up grade, it would be difficult to coast very far at the speed ›ermissible on the grade. Hence one insulated section is sometimes placed n the trolley beyond the switch, in which case a car will run over the first of installation, signalling naturally divides itself into two classes, namely *interlocking* (Par. 404 to 420) and *block signalling* (Par. 421 to 426).

TYPES OF FIXED SIGNALS

387. Targets and lamp signals. In American practice, targets of various forms are generally used to show the positions of switches except where the latter are operated from interlocking plants. The signals generally used in interlocking practice, as well as for train-order signals and block signals, are of the **semaphore** type, in which an arm, composed of a casting on which are mounted colored glasses called roundels and a wooden blade, is pivoted about a horizontal axis so that it may be moved either manually or by power, from a horizontal position to an inclined or vertical position in order to indicate the various conditions affecting the movement of trains. All fixed signals, in addition to their day indications, are provided at night with lights of prescribed colors. With semaphore signals, one light is provided for each signal arm and is so placed that as the arm moves to its various positions, the different colored glasses will move in front of the lamp to show red, yellow, green, white or purple light as desired. For block signaling, signals of the enclosed-disc type are used to some extent, although the semaphore affords more distinctive indications.

"Light signals," consisting of electric lamps placed behind suitably colored lenses and so shaded as to permit their colors to be distinguished by day, have been introduced to some extent on electric railways, and have been recently developed to considerable efficiency.

The American Electric Railway Association's Committee on block signals has recommended as the preferred type of signals for electric roads, a semaphore moving in the upper left-hand quadrant as viewed from an approaching train; the arm in the horizontal position indicating "Stop;" in the inclined position, 45 deg. upward, indicating "Caution;" and pointing vertically upward, indicating "Proceed." It is considered that less interference with the view of signals by pole lines adjacent to the track will thus result than if the steam railroad practice of displaying the blade to the right of the mast, as seen from an approaching train, is followed. This is based on the American practice of locating signals to the right of the track which they govern (Fig. 123).

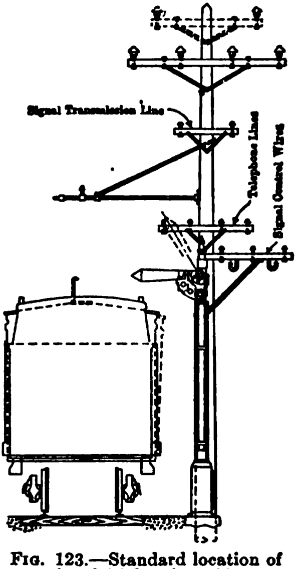


FIG. 123.—Standard location of signal (right of track).

388. The usual type of automatic signal is the electric-motor semaphore. The arm comprising the blade and the casting carrying the colored glass roundels is pivoted near the top of the post, the shaft to which it is connected carrying a crank or arm connected to the "up and down" rod placed inside of the tubular iron signal post. The lower end of this rod is connected to the mechanism proper which consists of an electric motor and gearing whereby the motor transmits motion to the up and down rod. A device called a "slot" which comprises a magnet and latch is so arranged that if the magnet is energized the motion of the motor is transmitted to the signal arm, but if the magnet is de-energized, mechanically disconnects the motor from the up and down rod allowing the signal to go to the stop position by gravity. Signal mechanisms of the "top-post" type have the motor mounted adjacent to the semaphore-arm shaft at the top of the post.

may retain continuous and direct control of a signal while occupying any portion of the track protected by the signal.

393. The function of the closed track circuit is to maintain a relay normally in an energized state; the influence of the train upon the rails is to de-energize this relay by shunting or short-circuiting the generator, a process as effectively accomplished by a single car as by a train of considerable length. On account of the low insulation resistance between the rails, due to the conductivity of the ties and ballast, track circuits are susceptible to influence from excessive leakage of current from rail to rail. This leakage may approach, in its effect, the value of current conducted by the wheels and axles of a train. Obviously a failure of the source of energy or a break in the circuit, whether in the rails themselves or in the wires connecting the battery

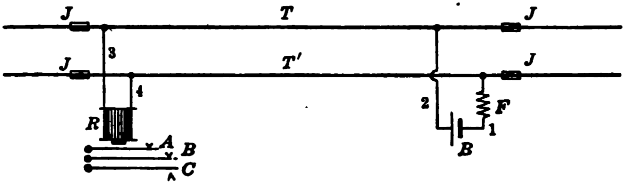


FIG. 124.—Track-circuit.

B, Source of energy, as two gravity-battery cells in multiple, or one storage-battery cell with series resistance F to limit current output when rails are short-circuited by wheels and axles of a car, or a transformer, 2 to 8 volts where alternating current is used. J, Insulated rail joint. T T′, The track rails included within the block, adjacent rails being bonded. R, Relay, normally energized by current from B. A B, Contacts carried by armature of relay R and closed when R is energized. C, Contact carried by armature of relay R and closed when armature falls by gravity upon R being de-energized. The path of current is from B through wire 1, resistance F (if used) track rail T′, wire 4, magnet coils of relay R, wire 3, track rail T, wire 2 to B. The distributed leakage of current between track rails T and T′, through the ties and ballast, is in multiple with relay R.

or the relay to the rails, produce the same effect upon the relay as if a train were running or standing on the rails. The contacts carried by the armature of the track relay (Fig. 124), which are closed only when the relay is energized, are included in the circuits which control the signals themselves. These circuits must be closed in order that the signals may indicate "proceed." Thus the track circuit conforms to the principle demanded by sound practice, namely, that the signals shall invariably display the "stop" indication when their operating or controlling energies cease to be active from any cause.

394. Requisite performance of the electrical equipment. The source of energy supplying current to a track circuit should do so at the least e.m.f. that is practicable. The current capacity should not be excessively great nor yet too limited. When a train is so far advanced within the block from the relay end as to constitute a somewhat imperfect shunt upon the relay, stray currents sometimes find a path through it from adjacent rails through damp or defective rail insulations. Relays should not be sufficiently sensitive to respond to these currents. In excessively long blocks and where the likelihood of such occurrences exist, one of the remedies is to locate a relay at each end of the section and supply current to the centre of the circuit, so that as the shunting effect of the train recedes from one relay it approaches the other. Naturally the resort to this device entails additional cost and complication, for the operating circuit of the signal is carried through the entire block for control by both relays.

395. Low e.m.f. impressed upon track circuits is advantageous for two reasons: first, to minimize the break-down effect of the e.m.f. upon rail joints of defective insulation or upon damp ties and ballast and other parts that afford a normal leakage of current from rail to rail in wet weather; second, to reduce to a minimum the energy normally discharged through

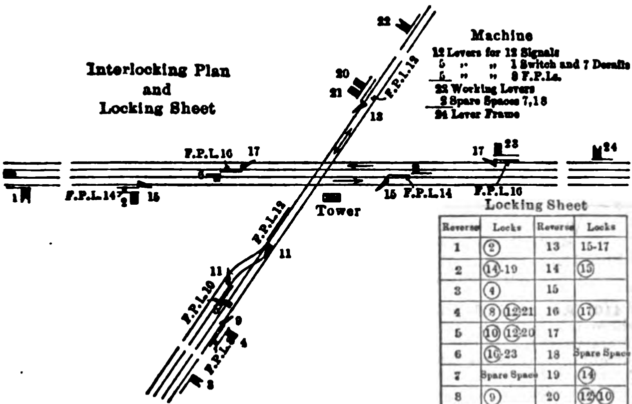
400. Impedances and power-factors per 1000 ft. of track
(Union Switch and Signal Co.)

Weight of rail	Bonding	27.5-ft. rails, 25 cycles per sec., Impedance	27.5-ft. rails, 25 cycles per sec., Power-factor	27.5-ft. rails, 60 cycles per sec., Impedance	27.5-ft. rails, 60 cycles per sec., Power-factor	30-ft. rails, 25 cycles per sec., Impedance	30-ft. rails, 25 cycles per sec., Power-factor	30-ft. rails, 60 cycles per sec., Impedance	30-ft. rails, 60 cycles per sec., Power-factor	33-ft. rails, 25 cycles per sec., Impedance	33-ft. rails, 25 cycles per sec., Power-factor	33-ft. rails, 60 cycles per sec., Impedance	33-ft. rails, 60 cycles per sec., Power-factor
100 lb.	Total capacity..	0.10	0.40	0.25	0.40	0.10	0.4	0.25	0.40	0.10	0.40	0.25	0.40
	2 No. 6 copper..	0.13	0.72	0.28	0.56	0.13	0.7	0.28	0.56	0.13	0.69	0.27	0.54
	1 No. 8 iron 1 No. 6 copper	0,17	0.83	0.30	0.65	0.16	0.82	0.30	0.63	0.15	0.79	0.29	0.62
	2 No. 6 c.c.–40 per cent.	0.19	0.87	0.30	0.69	0.19	0.86	0.32	0.69	0.17	0.84	0.31	0.68
	2 No. 6 c.c.–30 per cent.	0.25	0.91	0.36	0.75	0.22	0.91	0.35	0.74	0.20	0.88	0.34	0.73
	2 No. 8 iron....	0.40	0.97	0.50	0.88	0.36	0.96	0.47	0.87	0.34	0.96	0.44	0.85
90 lb.	Total capacity..	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43
	2 No. 6 copper..	0.14	0.73	0.29	0.58	0.13	0.72	0.28	0.58	0.13	0.70	0.27	0.54
	1 No. 8 iron 1 No. 6 copper	0.17	0.83	0.31	0.67	0.16	0.82	0.31	0.64	0.16	0.80	0.29	0.62
	2 No. 6 monnot–40 per cent.	0.19	0.87	0.33	0.71	0.19	0.87	0.33	0.70	0.17	0.84	0.31	0.68
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.36	0.76	0.26	0.91	0.36	0.76	0.20	0.89	0.34	0.73
	2 No. 8 iron....	0.40	0.97	0.51	0.89	0.37	0.97	0.48	0.88	0.35	0.96	0.45	0.86
85 lb.	Total capacity..	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46
	2 No. 6 copper..	0.14	0.74	0.29	0.60	0.13	0.73	0.29	0.59	0.13	0.71	0.28	0.58
	1 No. 8 iron 1 No. 6 copper	0.17	0.84	0.32	0.68	0.17	0.83	0.31	0.67	0.16	0.81	0.30	0.65
	2 No. 6 monnot–40 per cent.	0.19	0.88	0.33	0.72	0.19	0.87	0.33	0.69	0.18	0.85	0.32	0.70
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.37	0.77	0.23	0.91	0.36	0.77	0.21	0.89	0.35	0.76
	2 No. 8 iron....	0.41	0.97	0.52	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.46	0.84
80 lb.	Total capacity..	0.11	0.48	0.26	0.48	0.10	0.48	0.26	0.48	0.11	0.48	0.26	0.48
	2 No. 6 copper..	0.14	0.75	0.29	0.62	0.14	0.73	0.29	0.60	0.13	0.72	0.29	0.60
	1 No. 8 iron 1 No. 6 copper	0.17	0.84	0.32	0.69	0.17	0.84	0.31	0.68	0.16	0.82	0.31	0.67
	2 No. 6 monnot–40 per cent.	0.20	0.88	0.34	0.73	0.20	0.88	0.34	0.73	0.18	0.85	0.33	0.71
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.38	0.78	0.23	0.91	0.37	0.78	0.21	0.89	0.36	0.76
	2 No. 8 iron....	0.41	0.97	0.53	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.47	0.87
70 lb.	Total capacity..	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52
	2 No. 6 copper..	0.15	0.77	0.30	0.65	0.14	0.76	0.30	0.65	0.14	0.75	0.30	0.64
	1 No. 8 iron 1 No. 6 copper	0.18	0.86	0.33	0.72	0.17	0.85	0.33	0.71	0.17	0.82	0.32	0.70
	2 No. 6 monnot–40 per cent.	0.20	0.89	0.36	0.75	0.20	0.89	0.35	0.75	0.18	0.86	0.34	0.74
	2 No. 6 monnot–30 per cent.	0.24	0.92	0.39	0.80	0.24	0.92	0.38	0.81	0.22	0.90	0.37	0.78
	2 No. 8 iron....	0.42	0.97	0.54	0.90	0.38	0.97	0.51	0.89	0.36	0.96	0.48	0.87

Resistance of bond wires	27.5-ft. rails	30-ft. rails	33-ft. rails	
2 No. 6 copper..............	0.057	0.052	0.048	Bond wires 48 in. long. No allowance is made for conductance by the splices.
1 No. 6 copper and 1 No. 8 iron.	0.098	0.089	0.082	
2 No. 6 monnot–40 per cent..	0.124	0.112	0.103	
2 No. 6 monnot–30 per cent..	0.166	0.150	0.138	
2 No. 8 iron...............	0.348	0.315	0.291	

406. Mechanical processes involved in interlocking. In all interlocking machines the desired sequence of operations is secured by means of the dogs, bars, or tappets which constitute the mechanical locking. These parts are so interrelated that if any lever in the machine is reversed (that is, moved from its normal position), the act of the signalman in unlatching this lever will cause parts of the locking so to operate that no other lever in the frame can be moved which would allow a train movement conflicting with the train movement controlled by the first lever. The mechanical locking between the levers of the machine also provides for the movement of the levers in proper sequence when the route for a train is being set up, by assuring that the switches must first be properly set and must then be locked in the proper position before the signal governing the route can be cleared.

407. Prevention of switch operation while train is passing. Long bars of steel, called **detector bars,** are held by clips along the outside of the head of the rail at switches. They are of a length greater than the maximum distances between any of the adjacent wheels of a train, and are so mounted that they must move upward above the level of the top of the rail before the switch may be unlocked. They generally are mechanically connected to and operated simultaneously with the lock plungers which pass through holes or notches in the lock rods of switches to lock them in proper position. This method of protection may prove unsatisfactory owing to the increasing width of rail heads, and, especially on electric roads, the relatively narrow wheel treads of which may fail to engage the top of the detector bar while the vehicle is passing over it. Electric track circuits controlling electric locks mounted on the levers of the interlocking machine itself, are becoming quite generally used as a substitute for detector bars in the prevention of switch movement while trains are passing.



Locking Sheet

Reverse	Locks	Reverse	Locks
1	(2)	13	15-17
2	(14)-19	14	(15)
3	(4)	15	
4	(8) (12)-21	16	(17)
5	(10) (12)-20	17	
6	(16)-23	18	Spare Space
7	Spare Space	19	(14)
8	(9)	20	(12)-(10)
9	11-15-17	21	(12)-(8)
10	(11)	22	(21)
11	15-17	23	(16)
12	(13)-11-(11)	24	(23)

FIG. 125.—Typical interlocking plan and locking sheet.

408. Arrangement of mechanical interlocking plant. The plan of a single-track line crossing a double-track line is shown in Fig. 125. There is a siding switch on the single line, located so near the double-track line that it is necessary to include it in the interlocking. Derails are shown on all tracks.

the switch lever and others in the frame, allowing movement of the latter to be made in proper sequence.

411. The Electric-Pneumatic Interlocking System of the Union Switch and Signal Company. This system is so named because compressed air is employed to shift the switches and signals, while electricity is used to control or direct the admission and discharge of pressure to and from the cylinders by which the shifting is performed. The system is comprised of the following elements: an air compressor (preferably in duplicate for reserve) which, especially in terminal station plants, is often used for many other duties; a main air pipe extending throughout the interlocking system with branch pipes connecting it with each switch and signal to be operated; a double-acting cylinder at each switch which, through a motion plate, operates and mechanically locks the switch in its two positions by movement of the piston; a slide valve for each switch cylinder used to direct the pressure to either side of the piston in order to effect the movement of the latter (Par. 412); a single-acting cylinder, operating the signal (Par. 414); a source of energy (Par. 415).

412. Arrangement and operation of the switch-cylinder slide valve (Par. 411). There are two miniature cylinders employed for shifting the slide valve; two pin valves, operated by electromagnets, control the movement of the pistons in these cylinders. Mounted over the slide valve is a third small cylinder, also under the control of a magnet and pin valve. The piston of this small cylinder engages with and locks the slide-valve against movement save when the magnet is energized and the pin-valve is actuated to permit the pressure to withdraw the lock.

By energizing and de-energizing the magnets in proper sequence, the slide valve is unlocked, shifted, and again locked by the operating and indicating strokes of the lever. During this process each movement of the valve is accompanied by a corresponding unlocking, shifting, and relocking of the switch through the resulting operation of the switch enforced by the piston of its own cylinder. The three magnets are directly connected with contacts that are actuated by one of the levers in the interlocking machine, a separate wire being used for each magnet.

413. Indicating system (Par. 411). In the latest development of this system, a circuit controller is employed which is actuated by each switch movement. When the switch is in one of its extreme positions and locked there, this controller allows a current *of given polarity* to traverse two wires which connect it with a polarized relay in the tower. Conversely, when the switch is moved to and locked in its opposite position, a current of the *reverse polarity* is sent through the relay. During transit of the switch, and, in fact, when the switch is in any position and unlocked, the controller establishes a shunt or short circuit between these two wires. This short circuit renders the apparatus immune, at such times, to the effects of any stray current which might energize the relay. The circuit controller or pole changer, the relay in the tower, and the two wires joining them substitute the fundamental elements of the indication system of this type of power interlocking.

The polarized relay frees one or the other of two electric locks which, previous to this action, has been arresting the *complete* movement of the switch lever in the tower. This incomplete movement of the lever from full "normal" or full "reverse" involves about two-thirds of its total movement. After the partial movement has been made, the *complete* lever movement can be consummated only in the event of one of the two locks which previously restricted the lever's movements becoming energized. The energisation of this lock can occur only when the indicating relay has shifted its armature in response to a reversal of current in the two indicating wires. Such reversal is only possible when the switch has fully moved and become locked in response to the incomplete lever movement. After the lever has been released, its movement may be completed. Following the processes involved in a final execution of the lever stroke, the mechanical interlocking between switch and signal levers permits the shifting of the proper signal lever for train movements over the switch. The current supply to each and every signal leading over the switch is carried through other contacts of the indicating relay, so that unless the relay is energised in the proper polarity and the lever and the switch correspond precisely in position, no signal whatever can be given over that switch. Conversely, should a signal be properly switch in either direction, a circuit controller is actuated in such a manner as to cut the motor out of circuit, and partly establish connections for the operation of the switch in the opposite direction when the proper lever movement is subsequently made.

The switch-indication circuit is in all respects the same as in the electropneumatic system. A polarized relay controlled by a pole-changer at the switch is used. The pole-changer is so arranged that in any position except the extreme ends of stroke, when the switch is locked, the wires feeding the polarized indication relay are short-circuited and disconnected from the source of energy.

For the operation of the units in this system, direct current at a potential of 110 volts is used. This is supplied to the switches and signals through heavy mains running from the storage battery in the tower. Current from these mains is fed to the motors through the electrically operated circuit controllers as already explained. These controllers are energized by current from the same battery at the same potential. The resistance of the various pieces of apparatus is such, however, that the current flowing in these control circuits is very small. Consequently the wires from the interlocking-machine levers to the units need never be of larger size than is required for mechanical strength. For the indication circuits, the potential is cut down by resistances, one at each switch or in series with each signal indication circuit, therefore the indication wires may also be small. The selection of signals and their control by the various switches in a route is accomplished through the polarized indication relays and combination contacts in the same manner as in electropneumatic interlocking. The indication magnets and the general design of the interlocking machine are the same in both systems.

417. The electric-dynamic indication interlocking system of the General Railway Signal Co. (see Par. **418** to **420**) was the earliest and is the most widely used system of electric interlocking. The source of power consists of a storage battery with its charging unit, which furnishes current at 110 volts for the operation of the switch and signal motors. Power-control apparatus is introduced between the battery and the interlocking machine. The interlocking machine proper is provided with levers, built generally in units so that any lever with its safety and indication magnets, accessories and housing may be removed from the frame without disturbing adjacent levers. The levers are of the sliding type which are pulled out or pushed in to operate the various units. The mechanical locking is of the vertical type, the tappet bars being moved vertically by the horizontal motion of the levers through the medium of a cam slot in each lever. Fig. 127 shows a cross-section of a unit-lever type electric interlocking machine, and Fig. 128 shows typical circuits for this interlocking system.

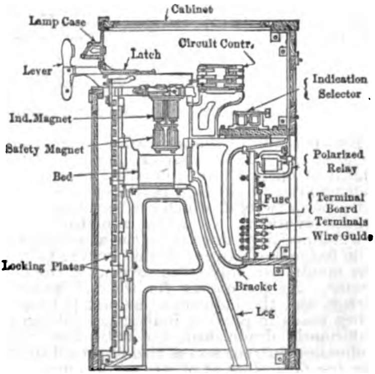


FIG. 127.—Electric interlocking machine.

Alternate levers have their handles turned upward and downward. Beside the interlocking machine, the system comprises the switch and signal mechanisms with their operating and indicating circuits and means for the prevention of unauthorized movement of any unit. Each switch or derail is thrown and locked by a switch and lock movement driven by a series-wound direct-current motor. Two wires are used for this control, one for the normal and the other for the reverse operation. These same wires are used for indicating purposes, the normal control wire being used for the reverse indication and the reverse control wire for the normal indication. The circuit is connected to the main common-return wire at each switch.

This circuit breaker controls the supply of current from the storage-battery to the interlocking machine. A check on the integrity of the cross-protection system is secured by having all necessary contacts and connections either on closed circuit or used in each process of operation and indication so that failure of any individual member would prevent operation and indication and would be promptly detected. A necessary feature in this system as in other electric interlockings, is the prevention of indication current from reaching any lever, while the unit normally under the control of that lever is being operated due to crossed wires from other units which may be indicating at the moment. This protection is secured by means of a safety magnet located below the indication magnet on each lever, Fig. 127. The windings of this safety magnet are included in the operating circuit of the lever, and its magnetic properties are so proportioned to those of the indication magnet, that if both were energised at the same instant, the safety magnet would overpower the indication magnet and prevent the latter from lifting its armature to trip the indication latch in the lever. Normally, the armature of the indication magnet rests upon the poles of the safety magnet. As a further safeguard, an indication selector is provided with its magnet coils in series with the safety magnet and in the control circuit. The function of this selector is to prevent possible receipt of an improper indication during the internal between the time that a lever is moved to the opposite position from that which it previously occupied, and the time the movement of the switch mechanism itself is complete.

420. Operation in reverse direction (Par. 417). The last portion of the stroke of the locking plunger at the switch mechanism operates the pole-changer which cuts off the operating current and puts the circuits into action for an operation in the opposite direction. The breaking of this circuit de-energizes the safety magnet, permitting the indication magnet to be energised by the current generated in the revolving motor armature. The operating circuits are so designed that the magnetic control of the pole-changer insures a correspondence in position between the lever in the machine and the operated unit outside.

THE BLOCK SYSTEM

421. Classification of block signaling systems. The block system provides for the division of the railroad into lengths of track of defined limits, over which railway traffic is controlled by block signals. Block signals and block-signaling systems may be classified as follows: a (Par. 422), manual, in which the signals are operated by hand on orders or information received by telegraph or telephone; b (Par. 423), controlled manual, in which some means (generally electrical) are employed to necessitate the cooperation of the signalmen at both ends of a block in order to clear the signal admitting a train on the block; c (Par. 424), automatic, in which the signals are power-operated and are controlled by the trains themselves through the action of their wheels upon electric circuits constituted by the rails of the track. Such signals indicate the presence of a train or single car or engine in the block and also such conditions as the presence of a broken rail, an open switch or a car standing upon a siding within fouling distance of the main track.

422. In the manual block system, when a train has passed into any block, the signalman sets his signal to the "stop" position behind it, and notifies the signalman at the entrance to the next block of the approach of the train. This second signalman in turn consults his record to see if the signalman controlling the entrance of the third block has reported the passing of all trains out of the second into the third block which previously have been admitted to the second block. If such is the case, the signalman at the entrance of the second block will set his signal to indicate "proceed" and permit the approaching train to enter the second block. Such a system necessitates the use of very carefully prepared rules and is dependent for its safe and successful performance entirely upon the watchfulness of the signalmen and the precision with which they perform the duties prescribed for them by the rules. On single-track railroads, this system necessarily involves the protection of trains against opposing movements, and is in general supplemented by the issuance of train orders from the despatcher, which provide for the meeting of trains at other times or stations than those specified in the time-table.

of the signal; and thence back over a common wire to the other side of the transformer secondary.

Fig. 129 also indicates how a portion of one of the track rails on the siding is insulated from adjacent rails and bonded to the opposite main track rail. If a train or car on the siding moves to within fouling distance of the main track, it will thus shunt the relay of the track section in which the switch is located.

426. Automatic block signaling applied to electric railways. Fig. 130 shows a simplified form of automatic block signal circuit for one track of a double-track railway using direct-current propulsion and two-rail alternating-current track circuits, the signals themselves being operated by direct current from batteries. Alternating-current track relays are generally of the vane, galvanometer or induction-motor type. In the first named, an aluminum sector revolves between the poles of a C-shaped laminated core, in which the winding is placed. This winding is connected across the rails of the track circuit and receives current through the rails from the transformer

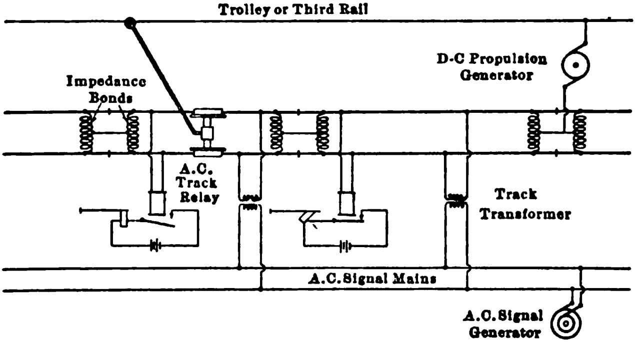


FIG. 130.—Typical circuits. Power supply for a.c. track circuits.

at the other end of the track circuit. The galvanometer type of relay has a set of fixed coils energised from a local source, and a movable coil energised from the track circuit. In the induction-motor type of relay both the track and the local windings are fixed, and the rotor is made to revolve by phase displacement in the current of the two windings. In all types the moving member carries or actuates contacts through which are controlled the circuits controlling the operation of the signals themselves.

The transformers which supply energy to the track circuit also supply energy to the local windings of motor-type track relays together with any line or secondary relays necessary in the circuits; in addition they supply energy for the operation of the signal mechanisms proper. The transformer secondary windings supplying current to the track rails are generally provided with a number of taps, so that the voltage impressed on the track may be regulated to suit the length or characteristics of the track circuit. The secondaries are naturally provided with series resistances which limit the current output when the secondary is short-circuited by the presence of a car in the block.

BIBLIOGRAPHY—RAILWAY SIGNALING

427. Association reports. Comparatively few books have been written on the subject of railway signaling, most of the available data being found in periodical technical literature, in publications of engineering societies, and in the bulletins and catalogues issued by the manufacturers of signal apparatus. The last mentioned source is voluminous, as such publications are frequently issued and contain much valuable technical information.

434. Distribution of potentials in rails and earth. For the simple arrangement illustrated in Fig. 131, the distribution of potentials is shown in Fig. 132. The following assumptions are made in the development of these curves: (a) the negative bus bar is connected to the rails at the power station by an insulated cable, with no other ground connections; (b) the line extends in one direction only; (c) the load is uniformly distributed over the line; (d) a pipe of uniform resistance lies in the earth parallel to these rails; (e) the resistance between the rails and pipe is everywhere the same. With these assumptions, the current in the rails will increase uniformly from zero at the end of the line to its greatest or total load value at the power station *O*. Taking the negative bus bar and this point *O* as the datum or zero of potential, the potential of the rails is represented by the parabola *OI*. The voltage *OD* is the total rail drop. There will be a neutral point *N* in the rails at a distance 0.42 of the total length of the line from the power station where these rails are at the ground potential. Between the power station and *N*, the rails are negative with respect to ground, and current flows from ground to the rails; while from *N* to the end of the line *E*, the rails are positive with respect to ground, and current flows from the rails to the ground.

The pipe of Fig. 131 will have a potential shown by the curve *A-H* in Fig. 132. Between *O* and *N* the pipe is positive, and this, therefore, constitutes a positive region. Conversely, between *N* and *E* the pipe is negative

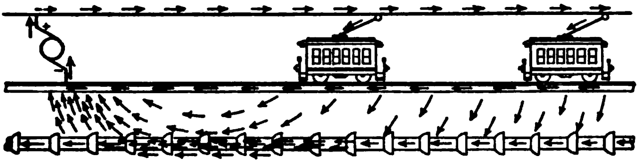


Fig. 131.—Conditions contributing to electrolysis.

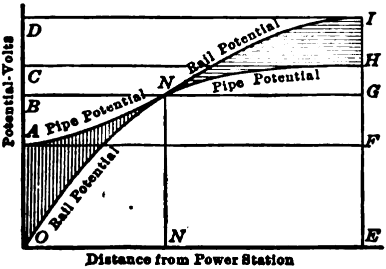


Fig. 132.—Distribution of potentials.

and this is a negative region. The current flow between pipe and rails is proportional to their potential difference. The total current flowing from rails to pipe, shown by the shaded area *N-I-H*, is equal to the total current flowing from pipe to rails, shown by the shaded area *O-A-N*. The current on the pipe will be a maximum at the neutral point *N*, and will be zero at the power station and at the end of the line. The greatest negative potential *C-D* of the pipe, with reference to the rails, will be at the end of the line; and the greatest positive potential *O-A* of the pipe will be at the power station. For the case assumed, the greatest positive potential will be twice the greatest negative potential. The total rail drop *O-D* is equal to the sum of the three voltages, the greatest positive pipe potential *O-A*, the greatest negative pipe corrosion may be considerably less than the theoretical rate. The amount of corrosion produced by electrolysis is independent of the applied voltage, except in so far as this voltage determines the amount of current flowing.

439. Corrosion of lead and tin. Where electric current leaves lead or lead alloyed with a small percentage of tin to flow to surrounding soil, the metal is oxidized by the electrolytic action, forming white or yellow salts. The rate of oxidation of lead by electrolysis under ordinary conditions is equal to approximately 74 lb. (34 kg.) for every ampere leaving the lead in one year. Where lead-sheathed cables are drawn in clay conduits, stray current may flow from the cable sheaths to water in the conduit or to the damp conduit itself. In such cases pittings are usually produced at the lower surfaces of the cable sheaths. Owing to the thin walls usual with lead cable sheaths, together with the high electrochemical equivalent of lead, such cable sheaths are damaged by electrolysis far more easily than are iron pipes.

ELECTROLYSIS SURVEYS

440. Nature of survey. The principal measurements generally made in an electrolysis survey of an underground pipe or cable system are as follows: a, voltage measurements between the pipes or cable sheaths and the rails (Par. **441**); b, voltage measurements between the pipes or cable sheaths and other underground metallic structures (Par. **441**); c, measurements of current flowing on the pipes or cable sheaths (Par. **442**). In order to be able to completely judge the electrolytic condition of an underground metallic system and to be able to decide upon remedial measures, it is necessary in addition to make measurements of rail drop and of the resistivity of the soil in various parts of the system.

441. Potential survey. To make a potential survey, potential differences between the underground structures and rails are measured at a number of points along every street where these structures and electric railway tracks are located. With lead cable sheaths contact is made directly on these sheaths in manholes. With underground pipes contact may be made by means of service pipes, hydrants or drip connections. The connections used for the potential measurements may be tested for continuity by means of an ammeter momentarily connected between the contacts with a dry cell in series if necessary. Where there are a number of underground metallic structures which may be affected by electrolysis, it is desirable to make simultaneous measurements of potential difference between the rails and each of these structures, and from these results to compute the potential differences between each pair of structures.

442. Current survey. To determine the current on a pipe or cable sheath, the drop between two points on a continuous length of pipe or sheath is measured by means of a millivoltmeter. From tables of pipe and cable sheath resistances, as given on the following pages, the strength of current may be computed by Ohm's law. For convenience the currents corresponding to one millivolt drop in a 1-ft. length of pipe or cable sheath are also given in the tables. This figure for current, divided by the distance in feet between the millivoltmeter contacts, and multiplied by the reading in millivolts, is the actual value of the current flowing. Where great accuracy is required, the resistance of a pipe or cable sheath should be measured instead of computed from its dimensions. In the case of lead cable sheaths, the drop measurements can usually be made in manholes where the cables are exposed. In the case of iron pipes, the millivoltmeter leads must be connected directly to the metal of the pipe on which current is to be measured; and no joint must be included between the two contacts. Service pipe connections cannot be used for such current determinations. Temporary contacts are conveniently made by means of a sharpened piece of steel rod, fastened in a wooden handle, with connecting leads soldered to the rod inside of the handle. For permanent connections which can be used at any time for measuring drop on the pipe without again exposing the pipe, rubber-insulated wires may be soldered to brass plugs and these screwed into the pipe; the wires are then brought to the street surface, preferably inside of the curb, and the free ends left in drip or service boxes. It should be noted that small potential differences, such as 0.1 millivolt or less, may be caused by local galvanic or thermal action, and care should therefore be taken that such observations do not lead to erroneous conclusions.

443. Table for determining current on iron pipes from voltage drop in measured length of pipe.—(*Continued*)

Cast-Iron Gas Pipe American Gas Institute Standard—Adopted 1911 Weight, 1 cu.ft. = 450 lb. Resistivity, 1 lb-ft. = 0.00144 ohm.				Standard wrought-iron and steel pipe					
						Wrought iron resistivity 1 lb-ft. = 0.000181 ohm.		Steel resistivity 1 lb-ft. = 0.00021 ohm.	
Nominal diam. of pipe (in.)	Weight per ft. exclusive of bell (lb.)	Resistance per ft. exclusive of bell (ohm)	Current for 1 millivolt drop per ft. of continuous pipe (amp.)	Nominal diam. of pipe (in.)	Weight per ft. (lb.)	Resistance per ft. (ohm)	Current for 1 millivolt drop per ft. of continuous pipe (amp.)	Resistance per ft. (ohm)	Current for 1 millivolt drop per ft. of continuous pipe (amp.)
4	17.3	0.0000833	12.0	1/8	0.24	0.000754	1.33	0.000873	1.14
6	27.3	0.0000528	19.0	1/4	0.42	0.000431	2.32	0.000500	2.00
8	38.0	0.0000379	26.4	3/8	0.56	0.000324	3.09	0.000376	2.66
10	51.1	0.0000282	35.5	1/2	0.84	0.000216	4.64	0.000250	4.00
12	67.1	0.0000215	46.6	3/4	1.12	0.000162	6.18	0.000188	5.33
16	102.	0.0000141	70.9	1	1.67	0.000108	9.23	0.000126	7.95
20	140.	0.0000103	97.1	1 1/4	2.24	0.0000808	12.4	0.0000937	10.7
24	187.	0.00000770	130.	1 1/2	2.68	0.0000676	14.8	0.0000784	12.8
30	258.	0.00000559	179.	2	3.61	0.0000501	20.0	0.0000582	17.2
36	346.	0.00000416	240.	2 1/2	5.74	0.0000316	31.7	0.0000366	27.4
42	453.	0.00000318	314.	3	7.54	0.0000240	41.7	0.0000278	35.9
48	609.	0.00000237	423.	4	10.66	0.0000170	58.8	0.0000197	50.8
...	...	...	...	6	18.76	0.00000965	104.	0.0000112	89.4
...	...	...	...	8	28.18	0.00000643	156.	0.00000745	134.
...	...	...	...	10	40.07	0.00000452	222.	0.00000524	191.
...	...	...	...	12	49.00	0.00000370	271.	0.00000428	234.

445. Table for determining current on lead cable sheaths from voltage drop in measured length of sheath

COMPUTED BY ALBERT F. GANZ

Resistivity, 1 ft. length, 1 sq. in. sectional area = 0.00010 ohm

Outside diam. of lead sheath (in.)	Thickness of lead sheath (64th in.)	Resistance of lead sheath (ohm per ft.)	Current for 1 millivolt per ft. (amp.)	Outside diam. of lead sheath (in.)	Thickness of lead sheath (64th in.)	Resistance of lead sheath (ohm per ft.)	Current for 1 millivolt per ft. (amp.)
0.50	4	0.001163	0.860	2.00	6	0.0001781	5.61
0.50	5	0.000965	1.036	2.00	7	0.0001538	6.50
0.50	6	0.000836	1.196	2.00	8	0.0001359	7.36
0.625	4	0.000906	1.104	2.125	6	0.0001672	5.98
0.625	5	0.000745	1.343	2.125	7	0.0001443	6.93
0.625	6	0.000640	1.563	2.125	8	0.0001273	7.86
0.75	4	0.000741	1.350	2.25	6	0.0001575	6.35
0.75	5	0.000606	1.650	2.25	7	0.0001359	7.36
0.75	6	0.000518	1.931	2.25	8	0.0001198	8.35
0.875	4	0.000627	1.594	2.375	6	0.0001488	6.72
0.875	5	0.000511	1.957	2.375	7	0.0001284	7.79
0.875	6	0.000435	2.300	2.375	8	0.0001132	8.83
1.00	5	0.0004419	2.263	2.50	7	0.0001217	8.22
1.00	6	0.0003750	2.668	2.50	8	0.0001073	9.32
1.00	7	0.0003268	3.061	2.50	9	0.0000959	10.43
1.00	8	0.0002913	3.437				
				2.625	7	0.0001156	8.65
1.125	5	0.0003892	2.569	2.625	8	0.0001019	9.81
1.125	6	0.0003294	3.037	2.625	9	0.0000911	10.98
1.125	7	0.0002866	3.491				
1.125	8	0.0002547	3.926	2.75	7	0.0001102	9.08
				2.75	8	0.0000971	10.30
1.25	5	0.0003476	2.876	2.75	9	0.0000868	11.53
1.25	6	0.0002939	3.404				
1.25	7	0.0002552	3.918	2.875	7	0.0001050	9.51
1.25	8	0.0002265	4.415	2.875	8	0.0000927	10.79
				2.875	9	0.0000828	12.08
1.375	5	0.0003142	3.183				
1.375	6	0.0002650	3.773	3.00	8	0.0000887	11.28
1.375	7	0.0002299	4.35	3.00	9	0.0000792	12.62
1.375	8	0.0002038	4.91	3.00	10	0.0000716	13.96
1.50	6	0.0002416	4.14	3.125	8	0.0000849	11.77
1.50	7	0.0002092	4.78	3.125	9	0.0000758	13.18
1.50	8	0.0001853	5.40	3.125	10	0.0000686	14.58
1.625	6	0.0002218	4.51	3.25	8	0.0000815	12.27
1.625	7	0.0001920	5.21	3.25	9	0.0000728	13.74
1.625	8	0.0001698	5.89	3.25	10	0.0000659	15.19
1.75	6	0.0002051	4.88	3.375	8	0.0000783	12.77
1.75	7	0.0001772	5.64	3.375	9	0.0000700	14.29
1.75	8	0.0001567	6.38	3.375	10	0.0000633	15.83
1.875	6	0.0001906	5.25	3.50	8	0.0000755	13.24
1.875	7	0.0001648	6.07	3.50	9	0.0000674	14.84
1.875	8	0.0001456	6.87	3.50	10	0.0000609	16.42

of a completely insulated return circuit, as obtained with a double-trolley system (Par. 451 and 452). The methods which have been tried for minimizing electrolysis from stray railway currents may be divided into three classes: a, the **insulation method** (Par. 453 to 455), which is intended to increase the resistance of the path of the current through earth; b, the **drainage method** (Par. 453 to 456), which essays to remove the current harmlessly from structures by metallic connections or bonds between these structures and the railway return circuit; and c, the **return-feeder method** (Par. 458 to 460) which aims to reduce the voltage drop in the grounded rails.

451. Brief description of double-trolley systems and where used (Par. 452). Double-trolley railways (Par. 335) may be provided with positive and negative overhead trolley wires insulated from ground, as used for example in Washington, D. C., Cincinnati and Havana; with positive and negative conductors in underground conduits insulated from ground, as used on the surface lines on Manhattan Island and in Washington, D. C.; or with separate insulated third and fourth rails for the positive and negative conductors, as used on the Metropolitan District Railway in London.

452. Objections to double-trolley systems (Par. 451). The principal objection to the underground double-trolley system is the very high cost of installation, which makes this method practicable only in densely populated districts. The principal objections to the double-overhead-trolley system are the high cost of installation and the complication resulting from two overhead trolley wires, especially at crossings and where several lines meet and are on common tracks.

453. Insulation of rails. Where a road operates on a private right-of-way, the rails can often be practically insulated from ground, and the escape of current from the rails substantially prevented. For surface or subway lines this can be accomplished by placing the rails on wooden ties above ground and using broken stone for ballast. For lines operating on elevated structures substantial insulation may be secured by fastening the rails on wooden ties and keeping them out of metallic contact with the structure.

454. Insulation of pipes. Attempts have been made to insulate pipes from earth by paints, dips and insulating coverings. Practical experience as well as a large number of tests have however shown that no dip or paint will permanently protect a pipe against electrolysis in wet soil. The first difficulty is so to apply the paint that an absolutely perfect coating is formed. It is also necessary to prevent mechanical damage to the coating. Where imperfections exist or develop, aggravated trouble may result. Experience further shows that even where paints or dips are apparently intact, electrolytic action is not always prevented, and, in fact, very serious electrolytic pittings have been found under apparently good coatings. It has been found that in most cases the coatings applied have either been completely destroyed by the effects of the wet soil and the electric currents, or defects in the coating have developed, causing concentrated corrosion at such defective spots. The destruction of paints in wet soil where subjected to an electric current is probably due to a trace of moisture finding its way through the coating, giving rise to the flow of a feeble current and resulting in a very slight amount of electrolysis. The gases and other products of electrolysis then form blisters and finally rupture the coating. Pipes in positive districts covered with imperfect insulating coatings are in greater danger from electrolysis than bare pipes. Coating pipes in negative districts with insulating coverings does some good in reducing the amount of stray current which reaches the pipes. Where it is attempted to apply a heated material like pitch or asphaltum to a cold pipe, it is impossible to completely cover the pipe. The only kind of insulating covering which appears to afford certain protection is a layer of at least 1 or 2 in. of a material like coal-tar pitch or asphaltum, of such a grade that it is not brittle and so will not crack, but yet is hard enough to remain in place. The best way to apply such a layer is to surround the pipe with a wooden box, to support the pipe upon creosoted blocks of wood or upon blocks of glass, and then to fill the space between the box and pipe with the molten material. The cost of carrying out such an installation is however prohibitive except in a few special cases, such as service pipes in very bad localities, or in the case of some very important individual pipe lines of small size. Embedding a pipe in cement or concrete, even if this is several inches in thickness, will not protect a pipe from electrolysis, because damp concrete is an electrolytic conductor like soil.

the cable sheaths to render them at the same potential or slightly negative with respect to neighboring structures. The effectiveness of bonding as a protective measure depends upon the uniformity of the conductor to be protected. The method is therefore not generally applicable to underground piping systems, because these do not form continuous electrical conductors, but are more or less discontinuous networks. While lead-calked joints usually have a relatively low resistance, they frequently develop such high resistances as to make them practically insulating joints, due undoubtedly to the formation of oxide coatings.

457. Possible dangers from drainage connections. Drainage connections to underground metallic structures have the objection of paralleling the trolley rails by a low-resistance grounded conductor, thereby greatly increasing the total stray current through earth and on underground structures. Such drainage connections will generally result in greatly increasing the stray current flowing on the structure, giving rise to the danger of current shunting across high-resistance joints or shunting from one section of the system to an adjoining section. Also, where such connections are applied to a gas or water piping system, large stray currents are often caused to flow through buildings by way of the service pipes. These stray currents cause a serious danger from possible fires as well as from possible gas poisoning or gas explosions. Another serious objection is that such drainage connections make the structure negative in potential to all other underground structures, thereby setting up a tendency for current to flow from such other structures to the bonded structure. A piping or cable system which is bonded to the railway return circuit, thereby becomes a source of danger to all other structures which are not so connected, and this danger increases as the negative potential is increased.

Drainage connections to underground structures should never be used until the railway return circuit has been sufficiently improved, so that only small amounts of stray current are made to flow over such connections. With the construction of electric railways common in America, drainage connections to underground cable sheaths are generally necessary to protect the thin-walled lead cable sheaths against stray-current electrolysis. In the case of piping systems such drainage connections are however not to be used except in special cases, and then only as a final measure to remove small remaining currents.

458. Reverse-current switches for drainage connections. Cases arise where the polarity of underground structures reverses at times with reference to the railway return circuit. Consequently, where these structures are provided with metallic connection to the railway return circuit, current would be made to flow to these structures when these are negative in potential. To prevent this, automatic reverse-current switches are used in series with the drainage connection. The action of these switches is to keep this circuit open while the structures are of negative potential, and closed while they are of positive potential. Such reverse-current switches are frequently used in connection with drainage connections from telephone cables.

459. Insulated return feeder system. Since the drop in potential in grounded rails is the cause of the flow of stray current through the earth, the escape of stray currents will be reduced in the proportion that the drop in the rails is reduced. It is therefore desirable to use heavy rails of high electrical conductivity, and to maintain these rails perfectly bonded, so that they form continuous low-resistance conductors. The next important consideration is to limit the distance from the supply station to which this station delivers direct-current power, so that current is not returned through an excessive length of track; this is usually accomplished by the use of a number of distributed substations. Finally, the current should be removed from the rails by means of insulated return feeders connected to the rails. These feeders draw current from the rail at such points as are necessary to avoid both an excessive potential gradient in the tracks and through earth and an excessive total voltage drop in the tracks. Where it is necessary to bring current back from a distant point in the tracks, it is sometimes more economical to employ a negative booster in series with a return feeder of small cross-section, than to make this feeder of cross-section large enough to drain the required current from the tracks at the distant point. It may also be necessary to install resistances in short feeders. With such insulated track return feeders, part of the voltage drop is removed from the rails and is transferred to the insurails at the power station, with a resistance in the connection proportioned to maintain this point in the rails at the same potential as the other return-feeder connection points. The unit of leakage current is assumed as the amount which flows when the negative bus bar is grounded through a negligible resistance, the rails being connected to the negative bus bar only at the power station. In practice each return feeder would actually be connected to a number of points in the rails in the immediate neighborhood of the connection points shown.

460. Examples of installations of insulated return feeder systems. Such systems are in almost universal use in Germany and in Great Britain, and have given most satisfactory results. In America a considerable number of such systems have also been installed, the most prominent reported example being on the subway system of the Interborough Rapid Transit Company in New York City. Description of insulated return feeder systems installed in Springfield, Ohio, and in St. Louis, Mo., are given in Bureau of Standards Technologic Papers No. 27 and No. 32.

461. Advantages of the insulated return feeder system. This system is intended to relieve the tracks of current by insulated conductors, and thus tends to prevent the escape of current into earth. With a properly laid out return feeder system and properly bonded tracks, it is possible and practicable to reduce stray currents through earth and therefore stray currents on underground piping and cable systems to any desired minimum values and such currents may be made so small as to be negligible. This system, therefore, removes the cause of the trouble in that it minimizes the escape of current into earth.

ELECTROLYSIS FROM GROUNDED ELECTRICAL DISTRIBUTION SYSTEMS

462. Grounded neutrals in three-wire direct-current systems. Direct-current electric-lighting systems in which the distribution is on the Edison three-wire plan, having the neutral conductor grounded, are, in American practice, provided with such large neutral conductors of copper that only negligible stray currents are produced from such systems. This grounding of the neutral is intended to serve only as a safety measure, and is not for the purpose of using the earth to carry current.

ELECTROLYSIS FROM ALTERNATING CURRENTS

463. Damage relative to direct-current electrolysis. A large number of laboratory tests have been made to determine whether electrolysis is produced when an alternating current flows between a metal and an electrolyte, as for example between a pipe and surrounding soil. These indicate that slight electrolytic corrosion may be produced; this effect is generally less than 1 per cent. of that which would be produced by a corresponding direct current. With alternating current, however, electrolytic corrosion is produced at both electrodes, while with direct current, electrolytic corrosion occurs only at the positive electrode.

464. Grounded transformer secondaries. The secondaries of transformers are frequently grounded, for the purpose of preventing a high and dangerous voltage from existing between the secondary circuit and ground. Such ground connections however do not produce flow of current to ground, and such grounding of transformer secondaries therefore does not cause danger from electrolysis.

ELECTROLYSIS IN CONCRETE

465. General effects. Concrete when damp is an electrolytic conductor having a resistivity of the same order as damp soil. When iron is embedded in damp concrete and an electric current flows from the iron to the concrete, the iron may be oxidized by the electrolytic action. The oxides of iron formed occupy more space than the original iron, with the result that an outward pressure is produced which in time may crack the concrete. An exhaustive investigation of the effect of electrolysis on iron embedded in concrete has been made at the Bureau of Standards in Washington, and the results of this investigation are published in Technologic Paper No. 18 of the Bureau of Standards. This investigation appears to show that when no chlorides are present, the iron is practically passive at temperatures below 45 deg. cent.

what is known as the Unification Ordinance, which also contains clauses relating to electrolysis. These divide the city into three zones, and prescribe different voltage limitations for each zone. The Board of Supervising Engineers is, however, authorized to modify these voltage requirements as may be deemed advisable. The above ordinances although not entirely in accord are both in effect in Chicago.

In a number of cities in Ohio electrolysis ordinances have been enacted in which the most important features are track voltage requirements. In these ordinances the average potential difference during any 10 consecutive minutes between any two points 1,000 ft. (0.305 km.) apart on the uninsulated return circuit must not exceed 1 volt, and the average potential difference during any 10 consecutive minutes between any two points more than 1,000 ft. (0.305 km.) apart on the uninsulated return circuit within the limits of the municipality must not exceed 7 volts.

472. Legal status of liability for electrolytic damage. There has been considerable litigation at various times with reference to damage from electrolysis. It has been held by various courts that no one utility can claim the exclusive right to use the earth as a return circuit, and that priority of such use is of no importance to either side of the controversy.

473. Peoria decision. In the celebrated Peoria case which was finally decided after having been in the courts for over 10 years, the railway company was enjoined and restrained from injuring the property of the water company by electric current escaping from the rails or structures of the railway company. No particular method for preventing escape of current is prescribed in the decree, because the court in its decision states that a court does not have the power to prescribe by injunction any specific system, and that this power resides only with legislative bodies. The decree also requires the water company to co-operate with the railway company to the extent of giving the railway company access to its piping system for the purpose of measuring flow of current upon its system and of determining whether injury from electrolysis is being continued, in order that the railway company may determine whether it is complying with the terms of the decree.

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SECTION 17

ELECTRIC COMMERCIAL VEHICLES

BY STEPHEN G. THOMPSON

Consulting Engineer

CONTENTS

(*Numbers refer to Paragraphs*)

permitting it to maintain a high average speed, and due further to its freedom from intricate mechanism for transmitting the motor energy to the wheels, and the absence of numerous reciprocating parts.

7. The gasoline motor vehicle finds its best field of application in short-haul deliveries where the mileage is beyond that safely and conveniently obtained from the electric vehicle, its economic value being governed entirely by the individual characteristics of the particular business to which it is applied.

8. Electric vehicles may again be divided into two general classes according to the character of service, viz., (1) commercial vehicles and (2) passenger vehicles. The source of energy supply permits another classification, namely, (1) storage battery vehicles and (2) the so-called "**trackless trolley**" consisting of a motor-propelled vehicle receiving its energy from an overhead double trolley system. Under the second classification, the storage battery vehicle is by far the more important at the present time. The highway trolley vehicle has not yet come into extended use in this country, although it is employed to a limited extent abroad.

9. Commercial electric vehicles at the present time form by far the more important class of electric vehicles, and receive practically exclusive consideration in this section. This is because of their economic value as a means for highway freight movement.

10. Passenger vehicles involve no engineering features which are not very well covered by the discussion of the fundamentals of vehicle engineering and their application to commercial types.

CHASSIS CONSTRUCTION

11. In design, the electric vehicle is of necessity a compromise, the selection of its component parts being governed principally by the question of economy of operation, rather than mechanical efficiency. Few standards are as yet established, machines of each make reflecting the individual ideas of the designing engineer as to what in his opinion constitutes the best practice.

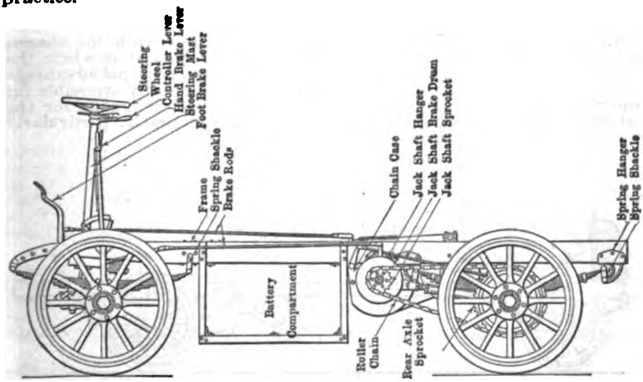

FIG. 1.—Baker chassis. Side elevation.

12. The chassis of the various makes differ only in peculiarities in design required by some special construction. The standard frame is rectangular, of structural or pressed steel, with lateral members for supporting the motor, battery compartment, and other equipment forming a part of the vehicle. Except in instances where the type of the drive employed requires that the axles themselves shall constitute a part of the mechanism, rigid axles are used. In the rear the ends of the axles terminate in spindles

17. The chassis capacity of an electric vehicle may be expressed as the sum of the body weight, plus the battery weight, plus the load weight at maximum speed. The **gross weight** is the sum of the chassis capacity plus the chassis weight. Variations in load, battery, and body weights are permissible so long as the gross weight moved at maximum speed does not exceed that prescribed by the manufacturers.

VEHICLE RESISTANCE AND ENERGY CONSUMPTION

18. The rolling resistance of a wheel is due to the yielding or indentation of the road, which causes the wheel continually to mount a slight incline. The resistance is measured by the horizontal force necessary at the axle to lift it over the obstacle, or to roll it up the inclined surface. The rolling resistance varies with (a) the diameter of the wheel; (b) the width and composition of the tire; (c) the speed; (d) the spring suspension; (e) the nature of the road surface. This resistance varies all the way from 3 lb. per ton with true steel wheels rolling on heavy clean rail, up to 200 lb. per ton in ordinary wagon wheels through sand.

19. Vehicle resistance. The best authorities* give the following values or vehicle resistance:

Steel-tired wheels on steel rail........................	3 to 5 lb. per ton.
Pneumatic-tired wheels on asphalt pavement..........	15 to 35 lb. per ton.
Solid-tired wheels......................................	20 to 40 lb. per ton.
Steel-tired wheels on average road, about..............	50 lb. per ton.

20. Truck resistance. In conducting tests on trucks with different makes of rubber tires, results have been secured where the total resistance has run as low as 25 lb. per ton and as high as 60. all other conditions re-

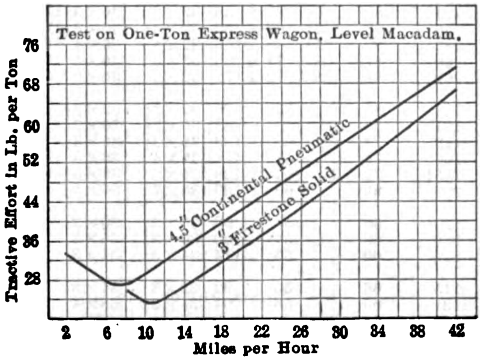

FIG. 4.—Curve showing tractive effort in pounds per ton at different speeds.

maining the same except the tire. This is due simply to a variation in the rubber compound, the low results being secured with a very high quality of rubber, whereas the high results were due to an inferior compound. (Also see Par. 24.) The loss in transmission here amounts to approximately 3 lb. per ton, friction and windage consume 5 lb. per ton, and the remainder is due to the tires.

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* Whitney, F. E. "Electric Vehicle Tires;" Electric Vehicle Association of America, October 27, 1913.

: Electric Vehicles

r the manufacturers)

	Battery			Motor		Controller		
at-ery (lb.)	Size compartment (in.)	Type and number of cells standard equipment	Kw-hr. capacity	Make	Type	Location of lever	No. f'rd speeds	Type of drive
,283	49×25½	Op. 42 L, 60 E	9.27L	Gen. Elec.	Series	Under wheel	5	Dble-reduction chain
,555	49×37	Op. 42 L, 60 E	11.58L				5	
,817	51×44½	Op. 42 L, 60 E	13.90L				5	
,414	63×55	Op. 42 L, 60 E	18.63L				5	
,350	30×43	Op. 42 L, 60 E	13.6 L	Gen. Elec.	Series		3	Worm
,700	37×46	Op. 42 L, 60 E	18.2 L				4	Two-motor concentric gear
,100	48×46	Op. 42 L, 60 E	22.7 L				4	
,650	54×48	Op. 42 L, 60 E	29.5 L				4	Four-motor, four-wheel
,080	71×46	Op. 42 L, 60 E	34.0 L				4	
900	For A- 4 E	60 E	10.8 E	Own	Series	On wheel	5	Dble-reduction chain
,260	For A- 6 E	60 E	16.2 E				5	
,820	For A- 8 E	60 E	21.6 E				5	
,250	For A-10 E	60 E	27.0 E				5	
,700	For A-12 E	60 E	32.4 E				5	
,125	36×45*	Op. 44 L, 60 E	10.8 E	Gen. Elec.	Series	On wheel	5	Flex. shaft and chain
,350	42×50*	Op. 44 L, 60 E	16.2 E				5	
,550	42×50*	Op. 44 L, 60 E	16.2 E				5	
,750	42×50*	Op. 44 L, 60 E	16.2 E				5	
,250	42×65*	Op. 44 L, 60 E	21.6 E				5	
,500	54×70*	Op. 44 L, 60 E	27.0 E				5	
,800	50×70*	Op. 44 L, 60 E	32.4 E				5	
,000	60×70*	Op. 44 L, 60 E	32.4 E				5	
875	For 48-A4, E	Op. 44 L, 48 E	9.1 L	Gen. Elec.	Series	Left of seat	4	Dble-reduction chain
,255	For 60-A5, E	Op. 44 L, 60 E	12.1 L				4	
,485	For 60-A6, E	Op. 44 L, 60 E	14.2 L				4	
,970	For 60-A8, E	Op. 44 L, 60 E	19.0 L				5	
,410	For 60-A10,E	Op. 44 L, 60 E	23.7 L				5	
,790	For 60-A12,E	Op. 44 L, 60 E	28.5 L				5	
800	30×20	30 L	8.28L	West'g-house	Series	Left of seat	4	Dble-reduction shaft and chain
,200	35×20	40 L	11.04L				4	
,500	44×20	40 L	13.20L				4	
,300	37×49	Op. 40 L, 60 E	16.2 E	Special	Series		4	Balance gear
,600	37×49	Op. 42 L, 60 E	16.2 E				4	Balance gear
,900	38×49	Op. 42 L, 60 E	21.6 E				4	Balance gear
,700	58×70	Op. 44 L, 60 E	27.0 E				6	Balance gear
,200	58×80	Op. 44 L, 60 E	32.4 E				6	Balance gear

D, dual. L, lead. E, Edison. Op., optional.

effort, owing to the superior ability of the pneumatic tire to adapt itself to surface irregularities.

23. Critical speed for minimum effort. It is noticeable that there is a critical speed at which the minimum tractive effort or draw-bar pull occurs, and that it varies with the type of tire used. The same effect has been observed and demonstrated in railway traction; this is attributed to wave motion in the rolling surface. In the case of the automobile it is caused by the kneading of the tires.

Solid tires		18 to 25 lb. per ton.
Electric special	single tube	15 to 23 lb. per ton.
	double tube	16 to 25 lb. per ton.
Standard double tube		30 to 35 lb. per ton.
Iron stud tread		31 to 36 lb. per ton.

These values apply to level running.

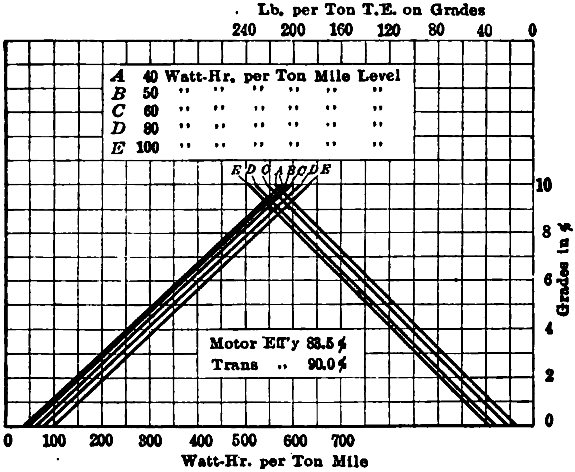


Fig. 6.—Wattage with varying grades and varying tractive effort for level running.

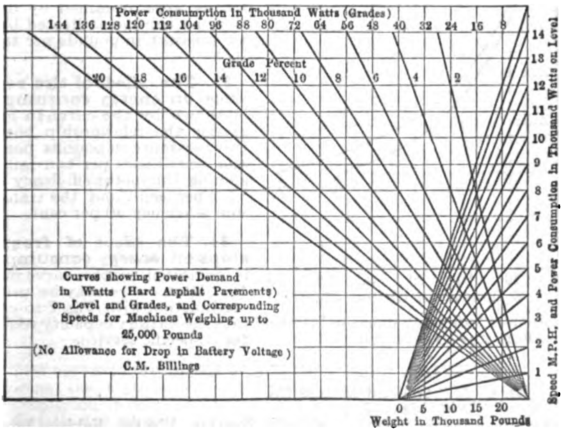


Fig. 7.—Graphs showing power demand in watts.

TRANSMISSION GEAR

35. Transmission of the motor energy to the wheels is accomplished by several methods in general use, but considerable difference of opinion exists as to what constitutes the most desirable method of motor application and the best transmission design. Without commenting upon the general

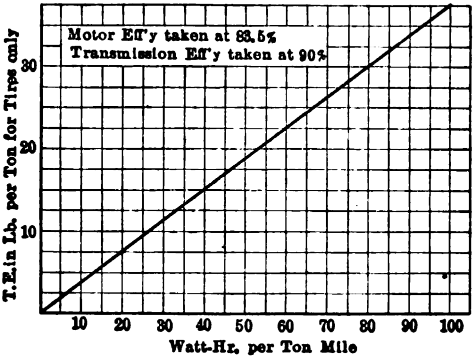


FIG. 9.—Diagram showing tractive effort in pounds per ton due to tires alone, with varying energy consumption of vehicle.

features, as illustrated in the various types hereafter described, it may be stated that simplicity of construction and design should govern the selection of transmission gear so far as is possible, without sacrificing efficiency.

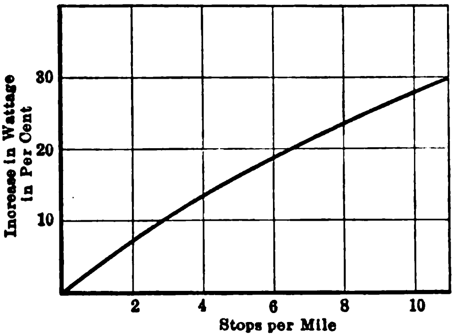


FIG. 10.—Curve showing per cent. increase of energy consumption due to stops.

36. The essential elements of a transmission gear comprise a means of reducing the high speed of the motor to the comparatively low speed of the propulsion or running wheels (reduction gear), and a **differential gear** which permits one wheel to turn faster than the other in propelling the vehicle in any curved path.

The **primary chain** *B* is enclosed in an oil-tight case, or, in some instances, protected from dust merely by an extension of the battery compartment. The former construction is preferable, as the life of the chain is increased by the better means afforded for lubrication.

The counter-shaft is usually assembled in such a manner as to permit its installation or removal as a complete unit. The differential gear is mounted on the differential housing. Adjustment of the silent chain is accomplished by a radius rod with an adjusting screw. For the roller chains, similar distance rods are employed. The armature shaft, jack shaft, and wheels are all equipped with anti-friction bearings. For counter-shaft assembly, see Fig. 12.

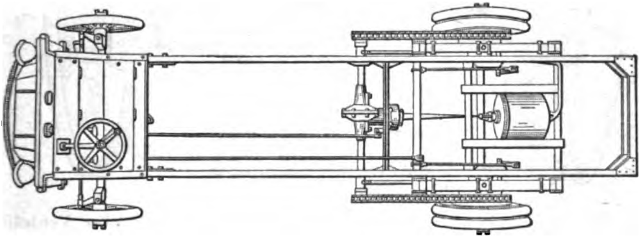


FIG. 13.—Top view of chassis showing drive assembly. (General Motors Company.)

38. The floating shaft and chain drive employs a flexible spring-steel blade for transmission from the motor to the counter-shaft. This shaft has a cross-section that permits torsional displacement or yielding under stress. The counter-shaft is of the floating type with bevel driving gear and pinion reduction. The power is transmitted from the counter-shaft sprockets by roller chains to the rear wheels. The motor is suspended in positive alignment with the chassis frame, with entire weight on frame members and supported at diametrical points. See Fig. 13.

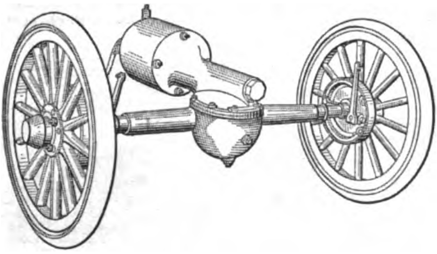


FIG. 14.—Rear axle assembly, spiral gear drive. (Commercial Truck Company.)

39. The spiral gear drive (Fig. 14) has the advantages of clean-cut appearance and compactness, few parts, good lubricating facilities, mechanical efficiency, and extremely quiet operation. Through a worm and gear drive the power is transmitted from the motor to the wheels by a single reduction, making an extremely simple mechanism.

The rear wheels are mounted on roller bearings entirely independent of the driving mechanism, and are driven by floating shafts engaging the outer ends of the wheel hubs. The inner ends of these shafts are squared into the hubs of bevel differential gears. The whole mechanism is immersed in oil, and gives noiseless operation. The rear axle unit consists of motor, gear pinions mounted on each end of the armature shaft to mesh with their respective halves of a "double" cog-rack near the periphery of the disc wheel. Thrust stresses arising from one bevel set are balanced by the other. A small number of parts make up the complete assembly. The arrangement lends itself to **four-wheel drive and steering**, features often required in special applications, where turning space is limited.

43. Other wheel systems which obviate the use of bevel gears and embody the double spur-gear reduction are shown in Fig. 17 and Fig. 18.

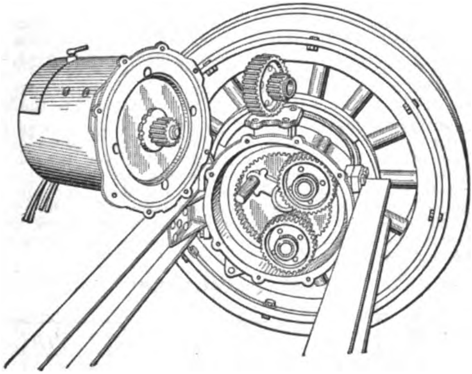


FIG. 17.—Concentric gear drive. (Commercial Truck Company.)

In the former, showing the **spur concentric form of gear**, the gear cases are mounted between two axle members, the extension of the case forming the axle spindle. The motor is bolted to the inner side of the gear case in a fixed position. The armature pinion engages spur gears which are carried

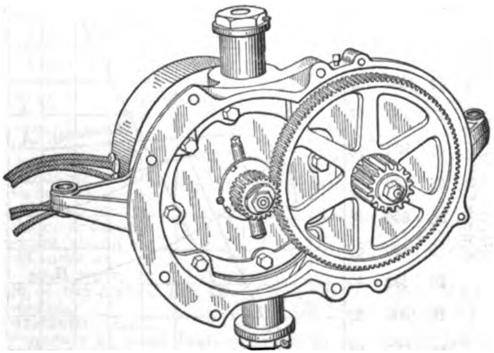


FIG. 18.—Double spur-gear reduction drive. (Commercial Truck Company.)

by studs integral with the driving shaft. The driving shaft passes through the axle spindle and connects with the outer end of the wheel hub through a square form in the hub cap.

The drive illustrated in Fig. 18 is employed with forged steel axles, which

45. Design. In order to meet the requirements of automobile manufacturers, vehicle motors are made in a number of different sizes, each of which can be supplied in several electrical ratings. The features of design follow closely after railway motor practice, since the conditions of vehicle service are very severe. Special attention is given to commutation, insulation, efficiency and reliability. These motors are all of the series-wound type.

46. Special torque characteristic. It is of paramount importance that the storage battery should be protected, and all motors are designed with this object in view. The current-torque curve has the property that doubling the current will approximately quadruple the torque, with reference to any given point on the curve.

During starting and acceleration an electric vehicle requires about five times the normal running torque. Again, the average **maximum grade** encountered in cities is about 7.6 per cent., to climb which also requires about five times normal torque.

47. General motor characteristics. The characteristic curves of torque, speed, current and output, for vehicle motors, are shown in Fig. 19 and Fig. 20, being representative of the products of two leading manufacturers.

48. Performance specification. The manufacturer (*B*) of the motor whose characteristics are shown in Fig. 20 gives the following performance specification:

Rating: The normal full-load rating of each motor is based on the specified voltage and amperes. Where series field coils are arranged for series and parallel connection, the rating is given with field coils connected in parallel.

Speed: The rated speed is based upon the speed of the motor at the end of the specified full-load temperature run. Speeds of individual motors may vary 5 per cent. above or below the speed shown on the specified curve. Approximate speeds for loads other than full or rated load are also shown on the specified curve.

Efficiency: The efficiencies shown on the specified curve are to be calculated from I^2R losses in the armature and field windings, based on the measured resistance of these windings at a temperature of 50 deg. cent. and the measured core-loss and friction-losses, including brush and bearing friction and windage. These losses are to be determined separately for each load at which efficiency is desired. The efficiencies shown on the specified curve are approximate and represent the average of the manufactured product.

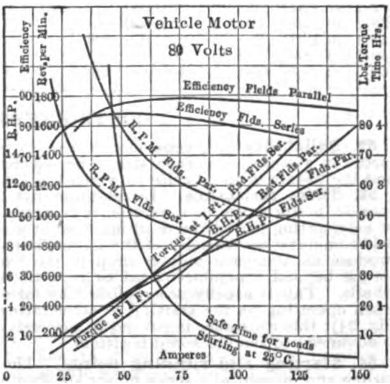


FIG. 20.—Characteristic curves of speed, torque and efficiency. (Make B.)

Commutation: Each motor will operate at rated full load with no sparking or burning of the brushes, and without blackening of the commutator. It will commutate any load encountered in normal operation without injurious sparking.

Temperature: After a continuous run (for four hours) at the specified voltage and current, no part of the windings will exceed a temperature of 50 deg. cent. above the surrounding air. Test to be made on stand with motor covers removed. Temperatures are to be measured by thermometer and rises specified are based on a room temperature of 25 deg. cent. For

55. Economical running points. Since it is apparent that the controlling factor in starting and accelerating is the torque, while for running the controlling factor is the speed, combined with torque for hill climbing, it would appear that the economical operating points on the controller are as follows: point 1 and point 2 for starting and acceleration; point 4 for running on level; point 3 for running on hills.

In pleasure vehicles the speed and the torque are similarly controlled, except that the manipulation of the fields, armature, and external resistance is planned to produce a smoother operation, which is required when personal comfort is a factor (see wiring development in Fig. 22).

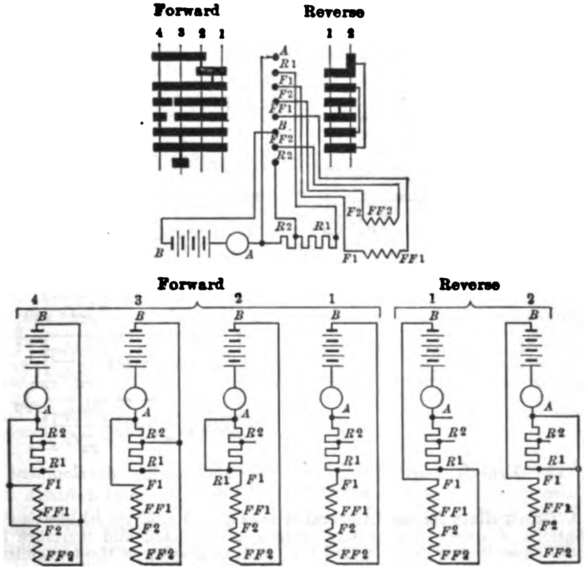


FIG. 21.—Controller connections and wiring development for commercial vehicles. (General Vehicle Company.)

56. Single-motor control is effected, in the standard arrangement, by means of series-parallel commutation of the field coils and the use of series resistance for starting and intermediate steps. At starting the fields are all in series, with all resistance in circuit.

57. Two-motor control is usually effected by series-parallel commutation of the motors, with series resistance for starting and intermediate steps. At starting the motors are in series, with all resistance in circuit.

58. The continuous-torque principle in two-motor control is an advantageous feature, because it insures smooth acceleration in changing from series to parallel connection of motors. The same principle is equally advantageous in single-motor control in passing from series to parallel connection of field coils (Fig. 21). Otherwise there is a sudden drop in torque, or jerk in acceleration, in making these changes.

64. Intermediate or "boosting" charges. Should it be desired to take advantage of any idle time of the vehicle for boosting charges, the rate for such charges may be determined by the following formulas:

(a) **Rate for lead batteries:***

$$\text{Rate} = \frac{\text{ampere-hours discharged from battery}}{1+(\text{time in hours available for boosting})} \qquad (1)$$

NOTE. See temperature limitations in Section 20.

Ninety per cent. of any total number of ampere-hours which may be charged into the battery in this manner can be added to the rated ampere-hour capacity to obtain the available ampere-hours during operation. For example: a battery of 150 amp-hr. rated capacity, if totally discharged, may be boosted for 1 hr. at 75 amp., or 75 amp-hr. returned; 90 per cent. of this added to the original capacity would give 217 amp-hr. as the total capacity during operation.

(b) **Rate for alkaline batteries:**

For 5 minutes at 5 times normal rate
For 15 minutes at 4 times normal rate — (2)
For 30 minutes at 3 times normal rate
For 60 minutes at 2 times normal rate

65. Precautions to be observed in applying boosting charges. The charging rates given in Par. 64 for alkaline batteries may be used under average conditions. However, the rate must not be such as to cause excessive heating, and its determination should be governed in each case by experience. Frothing is an indication that the charging has been carried too far (if the solution is at the proper height), and the boosting should be discontinued.

66. Battery renewals in vehicle service must be reckoned as much a part of the necessary operating expense as renewals of tires, bearings, chains or any other part of the equipment. The interval between periodic renewals is not at all a measure of the general efficiency of the battery, because the service in one case may be much more severe than in another. Economy and efficiency of vehicle operation, expressed in terms of dollars and cents, should govern the choice of a battery, assuming always that it is sufficiently standardized so that renewal parts can be obtained as desired.

INSTRUMENTS

67. Ammeters are covered, as a whole, in Sec. 3. This instrument is being largely displaced by the ampere-hour meter, for the reason that, while indicating the discharge flow from the battery, the information is of little value in operating. The switchboard meters at the garage are sufficient for determining the current-flow on charge.

68. Voltmeters are covered, as a whole, in Sec. 3. The ampere-hour meter has also displaced the voltmeter, as well as the ammeter, for the reason that the voltmeter does not indicate the condition of discharge of the battery (while running the vehicle) without the aid of a somewhat confusing mental calculation. The switchboard voltmeter, of course, is essential for determining the battery voltage while charging. **Low-reading portable voltmeters** are desirable for testing the condition of the individual cells of the battery, and are generally used in public garages and the larger private installations.

69. Ampere-hour meters are described, as a whole, in Sec. 3. This type of instrument is coming into general use in electric vehicles because it gives visual indication of the condition of charge of the battery, both while operating the vehicle and while charging. In Fig. 23 is shown a diagram of connections for the ampere-hour meter, with a differential shunt which compensates for the efficiency losses in the battery by retarding the reverse movement of the meter while charging.

* Electric Storage Battery Co., Phila., Pa.

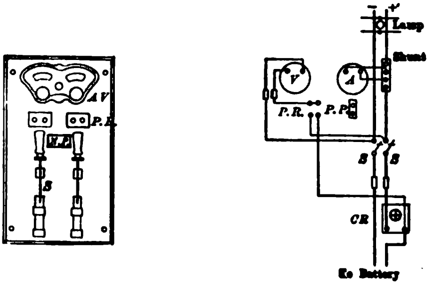
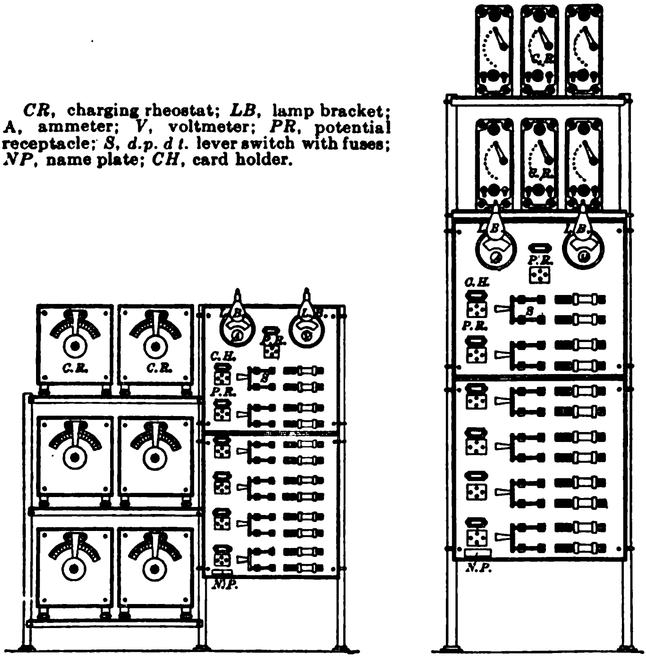


FIG. 24.—One-circuit charging panel and diagram of connections for small garage, direct-current service. (General Electric Company.)



CR, charging rheostat; *LB*, lamp bracket; A, ammeter; *V*, voltmeter; *PR*, potential receptacle; *S*, *d.p. d t.* lever switch with fuses; *NP*, name plate; *CH*, card holder.

FIG. 25.—Heavy duty charging panels for public garages, direct-current 2-wire or 3-wire systems. (General Electric Company.)

74. Table of Data on Battery Charging Rheostats for Circuits up to 115 Volts Maximum

(General Electric Company)

Charging amperes		Type of cell	No. of cells	No. of steps	Total ohms
Start	Finish				
15	5	Lead	12–18	15	17
20	6	Lead	12–18	15	17
20	5	Lead	20–28	15	13
25	8	Lead	20–28	15	9
30	10	Lead	30–36	15	4
40	10	Lead	30–36	15	4
30	10	Lead	37–40	15	2.6
40	10	Lead	37–40	15	2.6
30	10	Lead	41–44	15	1.5
40	10	Lead	41–44	15	1.5
50	12	Lead	41–44	15	1.28
60	15	Lead	41–44	14	1.0
30	30	Edison A–4	20–40	15	2.8
30	30	Edison A–4	44–60	15	1.7
45	45	Edison A–6	20–40	15	2.0
45	45	Edison A–6	44–60	15	1.2
60	60	Edison A–8	20–32	14	1.4
60	60	Edison A–8	36–44	14	1.0
60	60	Edison A–8	48–60	14	0.72
75	75	Edison A–10	20–32	10	1.17
75	75	Edison A–10	36–44	10	0.81
75	75	Edison A–10	48–60	10	0.60
90	90	Edison A–12	20–32	10	0.96
90	90	Edison A–12	36–44	10	0.68
90	90	Edison A–12	48–60	10	0.48

75. Special rheostats for use in charging alkaline batteries, either at normal or double the normal rate, have been designed and their principal characteristics are given in the table in Par. 76.

76. Table of Data on Special Battery Charging Rheostats for Edison Cells, at Normal or Double Normal Rate

	Charging amperes		Type of cell	Number of cells	Number of steps	Total ohms
	Double rate	Normal rate				
Private garage	60	30	Edison A–4	60	14	0.56
	90	45	Edison A–6	60	14	0.34
	120	60	Edison A–8	60	10	0.26
	150	75	Edison A–10	60	14	0.235
	180	90	Edison A–12	60	14	0.23
Public garage	180	30	Ed. A–4–6–8–10–12	60	14	0.565
	120	30	Ed. A–4–6–8	60	10	0.63
	180	90	Ed. A–10–12	60	14	0.23

77. Charging from alternating-current sources necessarily involves a conversion from alternating to direct current. Four types of conversion apparatus are available, according to the needs of the case, as follows: (1) Synchronous polyphase converters, requiring two-phase or three-phase supply, are not available in standard ratings except for relatively large

ections for starting, as a single-phase commutator motor, are shown in Fig. 8; the normal running connections are shown in Fig. 29.

Voltage control on the direct-current side is effected solely by changes in he value of the alternating-current voltage impressed on the slip-rings. Taps in the secondary of the transformer are provided for different numbers f cells, these taps being tagged, not for voltage, but arbitrarily, as S_1, S_2, etc. table of the proper connections for the number of cells under charge is rovided by the manufacturer.

1. Table of Standard Ratings of 60-cycle Single-phase Synchronous Converters

(Wagner Electric Mfg. Co.)

Normal charging capacity in amperes	Number of cells for which taps are provided	Possible voltage variations on d.c. side		Direct current fuse capacities	Capacities in h.p. as motor
		Min.	Max.		
16	32–44	67– 92	86–119	35	1.5–1.75
16	46–52	97–109	124–140	35	2.25
25	20–30	42– 63	54– 81	35	1.5–1.75
25	32–36	67– 75	86– 97	35	2.25
25	38–48	80–100	103–130	35	2.5–3.00
35	18–26	38– 55	49– 70	45	2.5–3.00
35	28–34	59– 72	76– 92	45	2.5–3.00
35	36–42	76– 88	97–113	45	3.0–3.50
50	18–24	38– 50	49– 65	60	2.5–3.00
50	26–30	54– 63	70– 81	60	3.50
50	32–42	67– 88	86–113	60	3.5–5.00
50	44–50	92–105	119–135	65	6.0–7.50
70	22–32	46– 67	60– 86	90	3.5–7.00

82. Protective devices form a most essential portion of the charging equipment. These consist of a reverse-current relay (controlling a main

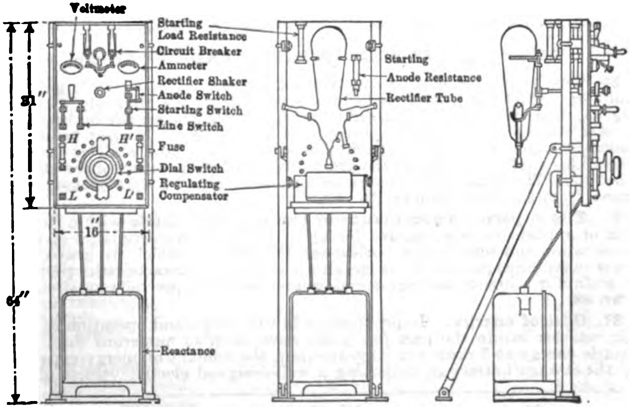


Fig. 30.—Mercury arc rectifier—front, rear and side elevations. (General Electric Company.)

tons' capacity constitutes less than 10 per cent. of the entire operating cost of the machine. Under these conditions, the path of future development lies not so much in the direction of increased efficiency, from the viewpoint of energy consumption, as through a better coordination of the parts employed.

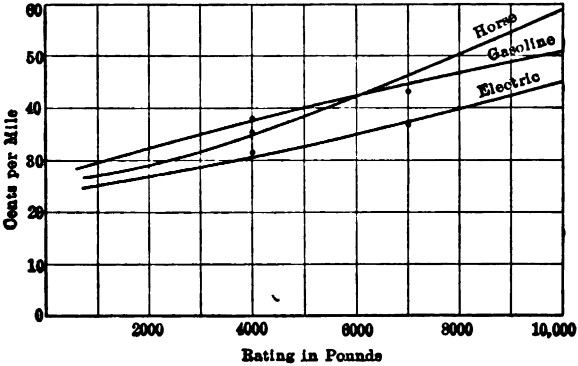


FIG. 31.—Curves of comparative cost per mile in delivery service by electric gasoline, and horse equipment.

88. Table showing Comparative Performance of Electric and Gasoline, Vehicles Operating within the Electric Zone

Conditions of test	Electric	Gasoline
Total weights (gross)	5,230 lb.	2,840 lb.
Diameter of wheels	34 in.	36 in.
Rated speed (m.p.h.)	10 to 12	15 to 18
No. of stops per mile	9.47	9.47
Power equipment	Exide storage battery and GE-1,026 motor, 85 v. 28 amp., 1,200 r.p.m. rating.	Horizontal single-cylinder gasoline engine 4½ in. bore, 6 in. stroke, rated 10 to 12 h.p.*
Test No. 1 (duration of stops, 2 min. each):		
Ton-miles per hour	25.18	11.43
Speed (m.p.h.):		
Level running	10.76	9.41
Up-grade	7.08	8.85
Down-grade	11.12	7.20
Average speed	9.65	8.48
Test No. 2 (duration of stops, 1 min. each):		
Ton-miles per hour	26.13	12.88
Speed (m.p.h.):		
Level running	11.40	10.08
Up-grade	6.90	7.83
Down-grade	11.80	10.56
Average speed	10.03	9.49
General average speed	9.84	8.98

* Engine was running continuously throughout tests.

90. Maintenance costs. In an extended investigation of the operating ›sts of gasoline and electric machines in several similar lines of business, the ıta collected showed that for the electric vehicle the average cost per car-ile for maintenance increased only 13.3 per cent. over a period of 4 years, hile that of the gasoline car increased 363 per cent. in the same time; and, ırther, at the end of the 4-year period the maintenance cost for the electric ›hicle was less than 50 per cent. of that of the gasoline machine (Par. 91).

1. Table Showing Comparative Maintenance Costs per Car-mile for Electric and Gasoline Vehicles

	Number of machines reported	Average maintenance cost per car-mile after 7 months' operation	Average maintenance cost per car-mile after 48 months' operation
Gasoline....	54	4.0 cents	18.5 cents
Electric....	69	7.5 cents	8.5 cents

These figures were obtained from the records of the operators themselves nd include all items chargeable to the replacement of mechanical parts, torage batteries and tires.

92. The greater economy of the electric vehicle is accounted for by he absence of a multiplicity of wearing parts, and the lower operating speed f the machine itself. To compete successfully with horses, a power truck ı not required to run at touring car speeds. The average speed of a 3-ton orse-drawn truck is about 2.5 miles per hour, and the average mileage not ver 12 miles to 15 miles per day. Therefore, a 3-ton motor truck operating t 7.5 miles per hour will not only compete very successfully with a horse-rawn vehicle, but its maintenance cost will be low.

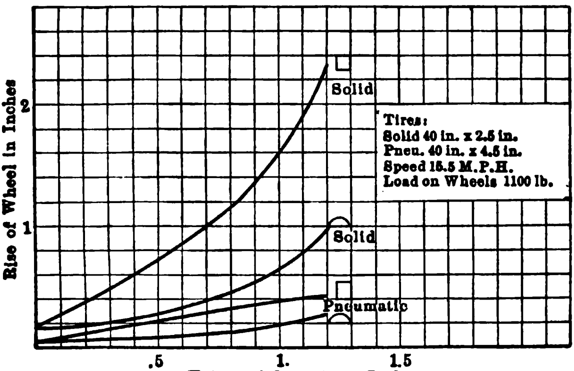


Fig. 32.—Graphs showing vertical lift of axle caused by different shaped obstacles.

93. The relation of speed to maintenance costs. As the speed of a vehicle progressively increases, the force of impact on tires, wheels, axles and springs caused by rough road surface also increases, and very rapidly. This effect is very well shown in Fig. 32 and Fig. 33, plotted from results of tests made by Welles and Michelin.* It is obvious from these results that

* Report of Standardization Committee, Electric Vehicle Association of America, October 7, 1912.

fessor Pender,* and in commercial electric vehicle applications in similar service as observed by the author. It is noticeable that the relative time values for loading and unloading do not vary in proportion to the amount of merchandise handled. This is accredited to the tendency of the machine to "speed up" the men.

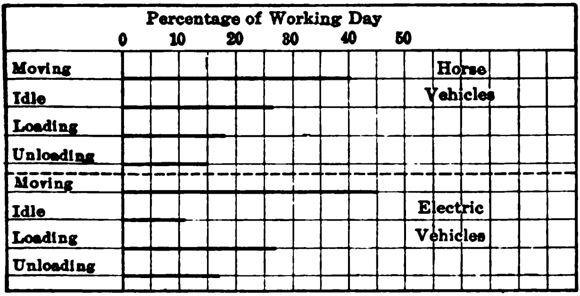


FIG. 34.—Analysis of daily performance of horse-drawn and electric vehicles.

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* Pender, H. "Notes on the Cost of Motor Trucking," Electric Vehicle Association of America; 1913.

† Obtainable from the office of the Electric Vehicle Association of America, 29 W. 39th St., New York.

SECTION 18

ELECTRIC SHIP PROPULSION

BY HENRY M. HOBART

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CONTENTS

(Numbers refer to Paragraphs)

$$\text{Frictional resistance} = 24{,}000 \times \left(\frac{14}{20}\right)^2 \times 8 = 94{,}000 \text{ lb.}$$

$$\text{Output from propeller} = \frac{94{,}000 \times 14 \times 6{,}080}{60 \times 33{,}000} = 4{,}040 \text{ thrust h.p.}$$

Of course in actual service, these values will vary tremendously with wind, wave, tide, condition of ship's bottom, disposition of cargo, arrangement of superstructure and other varying conditions. Furthermore the values given correspond with normal designs of average vessels. It is to be observed, however, that reasonable extremes in type of vessel do not occasion great departures from representative values of the frictional resistance.

5. Ship momentum. When increasing the speed of a ship, power must be expended in order to provide the greater momentum associated with the higher speed. This power is in addition to that required to overcome friction. Consider the acceleration of a 24,000-ton* ship from rest up to a speed of 14 knots. The formula for E, the energy of momentum, is:

$$E = \tfrac{1}{2}\frac{W}{g}V^2 \qquad (1)$$

where: W = weight in pounds,
g = acceleration of gravity in feet per second per second (= 32.2),
and V = speed in feet per second.

In our example we have:

$$W = 24{,}000 \times 2{,}240 = 53{,}800{,}000 \text{ lb.}$$

$$V = \frac{14 \times 6080}{3600} = 23.6 \text{ ft. per second.}$$

$$E = \frac{53800000 \times 23.6^2}{2 \times 32.2}$$

$$= 467{,}000{,}000 \text{ ft-lb.}$$

[1 h.p. = 33,000 ft-lb. per minute.
$\therefore$ 1 h.p-hr. = 33,000 × 60 = 1,980,000 ft-lb.]

$$\therefore E = \frac{467}{1.98} = 236 \text{ h.p-hr.}$$

6. Acceleration. If the acceleration is accomplished in 3 min. and at the uniform rate of $\left(\frac{23.6}{3 \times 60} =\right)$ 0.131 ft. per second per second, then the output from the propeller for providing this acceleration is:

$$(60/3) \times 236 = 4{,}720 \text{ thrust h.p.}$$

We have already seen (Par. 4) that, at a speed of 14 knots, an output of 4,040 thrust h.p. is required for overcoming the frictional resistance. Consequently when accelerating the ship from rest up to a speed of 14, knots in 3 min. the output from the propeller gradually increases from 4,720 thrust h.p., at the moment the ship starts, up to 4,720 + 4,040 = 8,760 thrust h.p., at the completion of the acceleration, and then decreases to 4,040 thrust h.p., when constant speed is attained.

In practice, the acceleration is not at a uniform rate but gradually decreases as the ship gathers speed.

7. Retardation. It is interesting to consider the conditions attending an emergency reversal when the ship (Par. 6) is proceeding at a speed of 14 knots. In order to bring the ship to rest in 3 min. (neglecting the losses in the machinery and the resistance of the ship), the propellers must, after reversal, *impart to the water* 236 h.p-hr. of energy. It may be assumed that 30 sec. is occupied in bringing the propellers up to speed in the reverse direction and that, during this time, the ship travels: (30/3,600) × 14 × 6,080 = 710 ft.

For the remaining 2.5 min. (150 sec.) the propellers must impart to the water nearly 236 h.p-hr. (say 200 h.p-hr.) of energy. The average output from the propellers is: (60/2.5) × 200 = 4,800 thrust h.p. If the retardation is uniform, the average speed during these 150 sec. is: 23.6/2 = 11.8 ft. per second and the distance traversed is: 150 × 11.8 = 1,770 ft., the total dis-

* Throughout this section the 2,240-lb. ton will be employed.

through locks, and in general conform to the requirements of such service. The "**beam draught**" ratio (B/H), and the "**displacement length**" ratio $D \div (L/100)^3$, are also amongst the criteria employed in this connection.

12. The admiralty formula. Naval designers and marine engineers (especially in Great Britain), have made considerable use of the "admiralty formula," and although it dates from the period before the advent of the marine steam turbine, it is still widely used. The "admiralty formula" expresses the indicated horse-power (i.h.p), in terms of the two-thirds power of the displacement, the cube of the speed, and a factor, C, known as the "**admiralty displacement coefficient.**" The formula is:

$$\text{indicated horse-power} = \frac{D^{\frac{2}{3}} \times V^3}{C} \tag{3}$$

It will be seen that the length (L) of the ship does not enter directly into this formula but is embodied in C, the "admiralty displacement coefficient."

Other formulæ and data relating to ship resistance, and to the power required for propulsion, are given in Taylor's "Speed and Power of Ships;" John Wiley & Sons, New York, 1910, and in Chapters II and IV of Hobart's "Electric Propulsion of Ships;" D. Van Nostrand Co., New York, 1911.

PROPELLER CHARACTERISTICS

13. General. The screw propeller was first employed for ship propulsion thousands of years ago by the Chinese. The steam-driven screw propeller came into wide use during the last half of the nineteenth century. The first quarter of the twentieth century will witness the extensive adoption of electrical transmission from the steam engine or oil engine to the propeller. This will permit various advantages which will be set forth in later paragraphs. At present it is desired to dwell on the very important advantage that the method will permit greater freedom in the choice of propeller speed.

14. Propeller thrust, diameter and speed. It will be impossible to touch upon more than the mere elements of the characteristics of propellers. In Par. 4, we briefly discussed a 24,000-ton ship for operation at a speed of 14 knots. At this speed the output required from the propeller for overcoming frictional resistance was estimated to be 4,040 thrust h.p.; now assume that 5,000 thrust h.p. will be provided. At a speed of 14 knots the corresponding thrust will be:

$$\frac{5{,}000 \times 33{,}000 \times 60}{14 \times 6{,}080} = 116{,}000 \text{ lb.}$$

It is usual in large ships to design the propellers for a **pressure** of not over **12 lb. per square inch of projected surface.** The projected surface of a propeller is the component of the area of the blades corresponding to a surface normal to the axis of the shaft. Therefore the projected area should be 116,000/12 = 9,700 sq. in.

The surface ratio is the ratio of the projected area to the area of a circle whose diameter is equal to that of the tips of the propellers blades. We may assume that we shall employ a design having a surface ratio of 0.35. Consequently in the present instance we must provide a gross area of $9{,}700/(0.35 \times 144) = 192$ sq. ft. If we employ a **single propeller,** its diameter should be: $\sqrt{(4 \times 192)/\pi} = 15.6$ ft. For a peripheral speed of 6,000 ft. per minute we arrive at a rotational speed of $6{,}000/(15.6 \times \pi) = 122$ r.p.m.

For the alternative of employing **two propellers,** and again assuming a surface ratio of 0.35, a pressure of 12 lb.per square inch of projected area and a peripheral speed of 6,000 ft. per minute, we arrive at a diameter of $(0.707 \times 15.6 =)$ 11.0 ft. and a speed of $(1.414 \times 122 =)$ 173 r.p.m.

Many other considerations enter into the determination of the preferable design. The number of blades, and their shape, size and pitch, have a far-reaching influence on the result, as have also the peripheral speed and the pressure per square inch of projected area. The determination of the most favorable disposition of the propellers with reference to the hull and to one another, is another matter of much importance. The range of practicable diameters is also affected by the size of the ship and by its lines. If the propellers are to be well immersed in all weathers the permissible diameter is quite limited in ships with shallow draught.

18. Limits of propeller size and power. It is well to call attention to the enormous power which can be delivered by a single propeller. In driving the "Mauretania" at 26 knots, an average speed at which she has made complete journeys across the Atlantic, the total thrust horse-power amounts to fully 36,000 h.p., or if equally distributed among the four propellers 9,000 h.p. per propeller. This corresponds, with her present equipment of four-bladed screws, to an output of 2,250 h.p. per blade. The propeller diameter is 15 ft., corresponding to a gross area of 176 sq. ft. The output may thus be reduced to: 9,000/176 = 51 thrust h.p. per square foot of gross area. Taking the projected area, in the case of the Mauretania's latest propellers, as probably being some 40 per cent. of the gross area at the pitch circle, we have also: 51/0.40 = 127 thrust h.p. per square foot of projected area. No significance is to be attached to these large values, as they result from the employment of propellers of a speed distinctly too high to be compatible with good efficiency, and which have, furthermore, too small an area for effective manœuvring.

The turbines of the British battle cruiser "Tiger" will deliver 100,000 shaft h.p. at the vessel's maximum speed of 31 knots. Her four high-speed propellers will hardly have an efficiency of over 50 per cent., giving a thrust horse-power of some 50,000 h.p. or 12,500 h.p. per propeller.

19. Multiple propellers. In the early stages of the development of the marine steam turbine, engineers failed to realize that its natural speed was far in excess of speeds consistent with good propeller characteristics. Consequently vessels were equipped with propellers of such small diameters as to embody merely the necessary mechanical strength at high speeds, and the necessary area was obtained by resorting to the use of several (multiple) small propellers. In certain instances this was carried to the extreme of installing more than one propeller on a single shaft.

In 1894 on the occasion of the first trial of the historical "Turbinia" (of 45 tons displacement), she was fitted with only one shaft and a single two-bladed propeller of 30 in. diameter and 27 in. pitch. As thus fitted, the "Turbinia" was quite inoperative owing to intense cavitation. The slip was 49 per cent. She was then re-fitted with three propellers on the same or single shaft; these propellers were spaced from each other by three diameters and yielded a vessel speed of 20 knots, the propeller slip being 38 per cent. In 1896 the "Turbinia" was again re-fitted, three turbines being installed. Each of the three shafts carried three 18-in. diameter screws with a pitch of 24 in. She attained a speed of 34 knots with a turbine speed of 2,200 r.p.m. and slips of 17 per cent. on the middle shaft and 25 per cent. on the side shafts. In 1903, the "Turbinia," after having her *nine* 18-in. propellers replaced by *three* propellers of 28 in. diameter with a 28-in. pitch (there being one propeller on each shaft), was again tested, and showed about the same economy up to a speed of 17 knots, and a quite considerable increase in speed for a given steam consumption, for all speeds between 18 knots and 28 knots. Further particulars of the "Turbinia" tests may be found in a paper by Parsons, read before the Institution of Naval Architects on June 26, 1903.*

SYSTEMS OF PROPELLER DRIVE

20. Reciprocating steam engines. There are three leading advantages possessed by the reciprocating engine for marine propulsion. These are:

(a) The natural speed of the marine type of reciprocating steam engine is of the same order as the natural (most efficient) speed of the screw propeller.

(b) The reciprocating steam engine may be designed for good economy over a wide range of speeds and loads, and for best economy at some intermediate speed and load.

(c) The reciprocating steam engine may readily be reversed and may exert great power during astern running. It is susceptible of ready control at all speeds including "dead-slow" speeds, and consequently endows the ship with excellent manœuvring ability.

The case for the reciprocating engine for marine propulsion, with special reference to the requirements of the United States Navy, has been very ably presented by Capt. C. W. Dyson, U. S. N., in a paper entitled "Engineering

* Stevens and Hobart. "Steam Turbine Engineering," Chap. XXIII, Whittaker & Co., London, 1906.

While the reciprocating engine has a decided advantage in the features of weight and space required, under present conditions these advantages would disappear should the necessary power to be developed be increased considerably above what is now asked for, and the advantage would rest with the turbine." . . . . . "Basing the choice between reciprocating engines and turbines for battleship propulsion under existing conditions of speed and power upon the above comparison of relative advantages of the two types, the advantage appears to rest most decidedly with the reciprocating engines."

22. Relative economy of steam engines. In the case of large, compound, triple-expansion and quadruple-expansion marine engines the economy falls but little behind that obtained in modern, high-speed land steam turbines for the same power, and is much better than that of steam turbines designed to operate at *speeds so low* as to permit direct connection to the propellers.

23. Examples of steam-engine economy. In a paper by C. Waldie Cairns* the result of 1.70 lb. of coal per indicated horse-power-hour with triple-expansion engines was given for a 36-hour trial of the 10-knot "Cairngowan" on Feb. 6, 1913. The corresponding water consumption was 15.2 lb. per indicated horse-power-hour; steam pressure, 175 lb. per square inch; vacuum, 26.8 in.; propeller speed, 61.7 r.p.m.; displacement, 9,950 tons, draft, 23 ft. 10 in.; length, 371 ft.; beam, 51 ft. See Par. **34** and **35**.

Elsewhere it has been stated on excellent authority that there are many ships which, even without superheaters, are working at 1.3 lb. and 1.4 lb. per indicated horse-power-hour (triple expansion) for all purposes.† In an editorial on p. 349 of *Shipbuilding and Shipping Record* for March 19, 1914, allusion is made to the estimate that with the combination of a reciprocating unit exhausting into a low-pressure turbine geared to a propeller shaft the water rate for large ships could be cut down to 8.5 lb. per horsepower per hour.

24. Internal-combustion engines. The only types of internal-combustion engine as yet developed which can come in for reasonable consideration for marine propulsion are those employing oil as fuel. The impracticability of providing space on board ship for gas producers and auxiliary plant precludes gas engines from consideration, so far as can be foreseen at present. Indeed it is the elimination of any equivalent to the steam-raising plant which is chiefly instrumental in giving the oil engine any standing as a prime-mover for ship propulsion.

Space and weight are factors of supreme importance on board ship, and it is the consideration that four-tenths of a ton of crude petroleum (or probably even of residue), will suffice for supplying the same number of shaft horse-power-hours to the propellers as would be supplied by burning 1 ton of coal‡ under boilers in a steam plant, that is proving so attractive to marine engineers and shipowners, even though the outlay for 0.4 ton (120 gal.)§ of crude petroleum will be much greater than for 1 ton of good coal. The advantage of the space and weight saved is of no small account, and for medium-sized and small-sized ships it should often outweigh the accompanying handicap of the increased outlay for fuel and the very great initial outlay for engines requiring the finest of workmanship in their manufacture and skilled attendance and adjustments during service. It is characteristic of oil engines as at present developed, that the weight of an engine of twice the capacity of a reference engine is, for the same speed, usually

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* Cairns, C. W. "A Comparative Trial between the Triple-expansion Engine and Geared Turbine in Cargo Steamers." Also see *Shipbuilding and Shipping Record*, Apr. 3, 1913; p. 6.

† *Engineering*, London, July 19, 1912; p. 91.

‡ Crude petroleum is taken as having 19,000 B.t.u. per pound and coal as having 15,000 B.t.u. per pound. $0.4 \times 19{,}000/15{,}000 = 0.51$. Thus the statement in the text is based on obtaining with the oil engine only twice the efficiency from fuel to shaft, as in the steam plant. While better results are guaranteed and obtained, it is desirable at so early a stage in the development of the internal combustion engine to be conservative in estimating its performance.

§ The U. S. gallon, equal to the volume of 8.35 lb. of water or about 7.5 lb. of crude petroleum, is taken here.

(double-acting, two-stroke-cycle) weigh only some 110 lb. per horse-power. Mr. Dugald Clerk in the discussion of Dr. Diesel's paper gave the table of weights in Par. 28 and also the curves which appear in Fig. 1 and Fig. 2.

It is the order of magnitude of these weights, relating to four-stroke-cycle engines, which has occasioned the strong tendency to develop the larger capacities in two-stroke-cycle engines.

A single acting, four-stroke-cycle, low-speed, 800 b.h.p. Diesel engine is considerably heavier than any of the engines shown in Fig. 2, as it has a weight of some 600 lb. per brake horse-power. Retaining the same low speed,

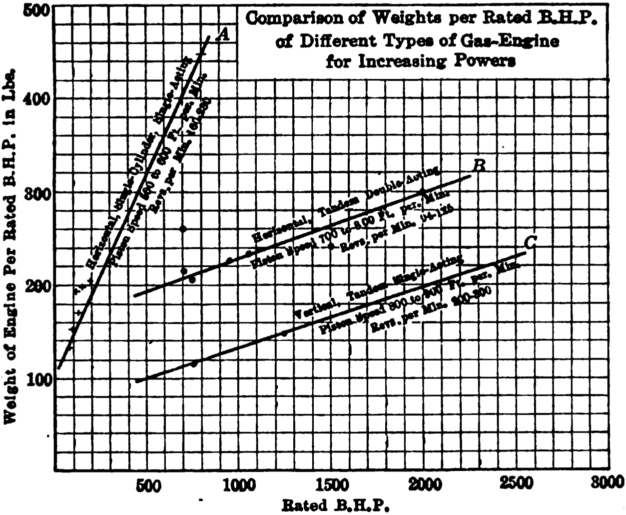

FIG. 2.—Comparison of weights per rated brake h.p. of different types of gas-engine for increasing powers.

but resorting to a double-acting two-stroke-cycle, the weight comes down to 238 lb. per brake horse-power; and in recent high-speed Diesel engines of the double-acting two-stroke-cycle type, the weight is brought down to 116 lb. per brake horse-power. The above data of weights of Diesel engines present a striking contrast to the low weights per brake horse-power which are being obtained in large steam turbines.

27. Diesel marine engines. The "Selandia," "Fionia" and "Jutlandia" are sister ships; each is 370 ft. long and 53 ft. beam. Each ship is fitted with two four-stroke-cycle vertical, single-acting Diesel engines and each of the two engines comprises eight cylinders and has a rated capacity of 1,250 i.h.p., or a total of 2,500 i.h.p. per ship. The speed at sea is 130 r.p.m. In a paper by Mr. I. Knudsen entitled "Results of Trials of the Diesel-engined Sea-going Vessel 'Selandia,' read on March 28, 1912, before the Institution of Naval Architects, the results of the trial trips are given. It is stated that reversal of the engines from full speed ahead to full speed astern can be carried out in 20 sec. The fuel oil is stored in the double bottom of the vessel, and sufficient storage capacity is provided for a continuous journey of about 30,000 miles. After three short trial trips the "Selandia" made a journey across the North Sea from Copenhagen to Aalborg with a cargo consisting of about 2,000 tons of cement. The fuel consumption (including all oil used for auxiliaries, but excluding that used for heating the vessel), was finally have the result of high efficiency and cheap fuel. When supplied in the form of coal dust, 3 cents per million B.t.u. is a fair relative figure for the fuel cost. Assuming as the sea efficiency from fuel to shaft:

(a) 14 per cent. for boiler plant and steam engine or turbine,
(b) 28 per cent. for oil engine,
(c) 21 per cent. for producer plant and gas engine,
(d) 28 per cent. for coal-dust engine,

and assuming for the price of fuel per million B.t.u.:

(a) 9.4 cents for coal for the steam-engine equipment,
(b) 28.2 cents for oil for the oil-engine equipment,
(c) 9.4 cents for coal for the gas-engine equipment,
(d) 3.0 cents for coal for the coal-dust engine equipment,

then the costs per million B.t.u. given out at the shaft and per brake horse-power-hour given out at the shaft, work out as shown in Par. 30.

30. Summary of Comparative Fuel Costs for Marine Prime Movers

	Fuel cost per million B.t.u. at shaft, cents	B.t.u. per h.p-hr.	Fuel cost per brake h.p-hr., cents
I. Steam plant................	67	2,545	0.171
II. Oil-engine plant............	101	2,545	0.257
III. Gas-engine plant..........	45	2,545	0.115
IV. Coal-dust engine plant....	11	2,545	0.028

The attractively low fuel cost in the case of the coal-dust engine would be futile in marine propulsion unless attained with an engine of small weight and of low cost and upkeep.

31. Low-speed, direct-connected turbines. Ever since the advent of the steam turbine into engineering work on land, there has been gradual but uninterrupted progress toward the employment of ever higher speeds. This progress has been accompanied by a great decrease in weight per horse-power and a very satisfactory decrease in steam consumption per brake horse-power-hour. In marine applications the difficulties encountered at an early date with respect to propeller efficiency, and the attainment of satisfactory operating characteristics of the propeller, imposed restrictions on the speeds employed. Consequently marine steam turbines have been much more heavy and less economical than land turbines for equivalent outputs.

The steam turbines of the "Mauretania" run at a speed of 188 r.p.m. and (exclusive of condensing plant) represent a weight of about 40 lb. per shaft horse-power. The steam consumption per shaft horse-power-hour during the full-speed trials was just over 12 lb.* Each of the four main turbines delivers about 17,000 s.h.p. Land turbines for twice this output can now be built with speeds of 1,800 r.p.m. and there is thus obtained, not only an enormous reduction in the weight per horse-power, but also a very satisfactory improvement in the steam consumption per shaft horse-power-hour.

32. Improved economy of high-speed turbines. By using 250 deg. fahr. of superheat, the firm of Messrs. Parsons will obtain on a 750-r.p.m., 25-cycle, 25,000-kw. set which they have constructed, a steam consumption (guaranteed) of only 11 lb. per kilowatt-hour, which (allowing for an efficiency of 97 per cent. for the electric generator) is equivalent to 8.0 lb. per brake horse-power-hour from the steam turbine. High superheats can be used much more successfully in high-speed turbines, since with their relatively small diameters they are more rigid and more free from the difficulties consequent upon expansion than is the case with large, slow-speed, steam turbines. When tested with 220 deg. fahr. superheat, a pressure of 184 lb. per square inch at the boiler side of the pressure stop valve, a condenser pressure of 0.72 in., and a load of 9,000 brake-horse-power, a 40-

* See p. 463 of *Engineering* for April 4, 1913.

51 ft. On the trial run, the displacement was 9,950 tons; block coefficient, 0.779. The steamer fitted with triple-expansion engines, the "Cairngowan," is a sister ship to the "Cairnross," has practically the same dimensions, the same propeller speed, and was loaded to the same displacement as the "Cairnross" during the 36-hr. trial. The results of the trials appear in Par. 34.

36. Alquist mechanical gearing. A very recent development in speed-reduction gearing is the Alquist mechanical gear for large powers, incorporating the feature of flexibility to the extent necessary to overcome the grave difficulties associated with rigid mechanical gears operating at high tooth speeds.

37. Electrical transmission for marine propulsion. Although mechanical speed-reduction gearing is quite appropriate for ships of low power, making long journeys at a fairly constant speed, it is inferior in a number of respects to the plan of interposing electric transmission between the prime-mover and the propeller. The electrical plan provides effectively for: (1) obtaining the desired speed reduction for operating a low-speed propeller from a high-speed steam turbine; (2) dispensing with any additional turbines for astern running, since the electric motor provides the reversible attribute. As to the first feature, the electrical method greatly excels the mechanical method in the respect that ratio of reduction can be varied to any extent desired, thus permitting the operation of the ship economically at various speeds, while the prime-mover is preferably operated at substantially constant speed. Moreover, a greater ratio of speed-reduction is practicable with the electrical system than with mechanical gearing, and more favorable speeds can be adopted both for the steam turbine and for the propeller.

The second feature, the ability to reverse the ship by reversing the electric motors which drive the propellers, has not only the advantage of eliminating the additional turbines for astern running and thus lightening and cheapening the equipment, but there is the further advantage that in all manœuvring operations the full power of the main turbines is available, instead of the limited power of the astern turbines. Thus electrically-driven ships will be characterized by their prompt and decisive manœuvring abilities.

38. Relative weight and efficiency of electrical gearing. For a given speed-ratio, the interposed electrical machinery will usually be heavier and more expensive than mechanical reduction gearing, but electrical gearing permits employing a *greater* speed reduction than is practicable with mechanical gearing. Consequently, with the electric drive, the prime-mover is lighter and more efficient than when the mechanical gearing is employed, and this greater saving as regards the main prime-movers is increased by the complete elimination of the astern turbines. It must be admitted, however, that the overall efficiency of the electrical machinery is rarely above 90 per cent. to 92 per cent. as compared with 98 per cent. efficiency of the mechanical gearing. But here again it will be found that the inferiority of some 6 per cent. to 8 per cent. efficiency is fully made up by the increased economy in the steam consumption of the prime-mover, because of its higher speed, and the improved efficiency of the propeller, because of its lower speed.

39. General conditions under which electric propulsion is best adapted. The general tendency is in favor of mechanical gearing for small ships, of low power, making long journeys at full speed, and electrical gear for large ships, and for ships requiring different speeds on different occasions, including those ships which frequently navigate inland waterways and crowded harbors and consequently require excellent manœuvring ability.

40. Special advantages of electrical gearing for ships operating at variable speeds. The most important reasons for operating ships electrically relate to the introduction of certain principles which, in land central stations for the generation of electrical energy, are recognized as having fundamental commercial importance. These principles can be well illustrated by considering the case of a battleship. Such a ship must be equipped with enough propulsive machinery to provide some stipulated maximum speed. This may require an aggregate capacity, say, of 32,000 h.p. If the ship is equipped with steam turbines direct-connected to the propellers, probably there would be four turbines, each of 8,000 h.p., connected to each individual propeller. But the ship will be driven at its full speed only a small portion of the time. Its cruising speed is only some six-tenths of the

44. Ocean liners. Although each year witnesses increases in the size of ocean liners, the most recent vessels are equipped for slightly lower speeds than the 26-knot "Mauretania" and "Lusitania" of the Cunard Line. These two ships have an overall length of 790 ft., a breadth of 88 ft., a draught of 33 ft. 6 in., and a displacement of 38,000 tons. At full speed their turbines, of which there are four, develop some 68,000 shaft h.p.

The new Hamburg-American liner "Imperator" has an overall length of 920 ft. and an extreme breadth of 98 ft.; height, 100 ft. from keel to boat-deck and 246 ft. from keel to masthead; displacement, about 57,000 tons; propelled by four Parsons turbines, driving four screws of 16.5 ft. diameter, and four blades each. The total shaft output is about 62,000 h.p., corresponding to a draught of 35 ft. 6 in. and to a sea speed of some 22.5 knots; the corresponding propeller speed is 175 r.p.m. The coal bunkers have a capacity for over 8,500 tons. Full complement of passengers, 4,000; total ship's company, 1,180.

The Hamburg-American turbine liner "Vaterland" has an overall length of 905 ft. and a breadth of 100 ft.; the turbines develop 61,000 h.p. at about 180 r.p.m., corresponding to a sea speed of about 22 knots; accommodates 5,700 persons including the crew.

The Cunard liner "Aquitania" has an overall length of 901 ft.; breadth, 97 ft.; and draught, 34 ft.; depth from keel to boat-deck is 92 ft.; propelled by steam turbines driving four screws; speed, 23.5 knots—corresponding to 60,000 h.p.; displacement, 50,000 tons.

45. Oil boats. The largest oil-carrying vessels have capacity for 15,000 tons of oil. The "San Fraterno,"* when fully loaded with 15,700 tons of oil, has a draught of 28 ft.; length, 542 ft.; breadth, 66 ft. 6 in.; contract speed, 11½ knots (exceeded in trials); propelled by a quadruple-expansion engine; equipped for oil burning.

46. Ore and Grain Boats. Similar in general shape and capacity (Par. 45) are the ore carriers which transport cargoes of ore or grain between the Great Lake ports. The limitations of the depth of waterways through which they pass sometimes require a draught of less than 20 ft. On routes where such limitations do not hold, these vessels are often loaded to a draught of 24 ft. Their length is of the order of 600 ft.; beam, 58 ft; and moulded depth, 32 ft. They can accommodate a cargo of some 20,000 tons of ore or coal, or nearly half-a-million bushels of wheat, and can be loaded at the rate of 8,000 tons per hour. They are propelled at a speed of some 10.5 knots by a single screw, usually driven at about 120 r.p.m. by a triple-expansion engine of some 2,200 h.p.

47. Tug-boats are of course designed for towing service, mainly in sheltered waters. The three essential requirements are: (a) high speed when running free; (b) fair speed when towing; (c) high thrust or pulling effort at practically zero speed. If attention is paid first to the second requirement, the others will usually take care of themselves.

48. Battleships. The modern battleship has a length of from 550 to 600 ft., a breadth of some 90 ft. and a displacement of the order of 25,000 tons. A battleship is usually equipped for a maximum speed of about 21 knots; the cruising speed is about 12 to 14 knots. At maximum speed the engines are required to develop some 30,000 shaft h.p. Effectiveness in a battleship outweighs all questions of cost. Consequently a general movement is taking place toward the practice of burning oil fuel. By this plan, not only can a greater weight of fuel be stored in a given volume than with coal, but a ton of oil has a calorific value some 33 per cent. greater than a ton of coal. Consequently, with oil fuel, the radius of action is greatly increased. Furthermore, the use of oil fuel ameliorates the almost intolerable conditions in the stokehold. Every gain in economy is important, not from the standpoint of money actually to be saved, but on account of the increased radius of action on a single supply of fuel.

49. Battle-cruisers. Ships of this class constitute a modern development. They differ from battleships in the respect of being equipped for much higher speeds. This entails a certain sacrifice in armament and in armouring. The United States Navy has no battle-cruisers. As examples of battle-cruisers may be mentioned the following:

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* *Shipbuilding and Shipping Record*, April 24, 1913, p. 149.

be capable, their horse-power per ton of displacement is usually much higher than for vessels of any other class. Take for instance the British torpedo-boat destroyer "Velox"; the displacement is only 440 tons, but at maximum speed of 36.6 knots (see page 70 of Hobart's "Electric Propulsion of Ships"), the vessel requires some 12,000 shaft h.p. This small boat has four propellers, and an engine capacity of about (12,000/440 =) 27 h.p. per ton of displacement, whereas scout cruisers have only some 4 h.p. per ton of displacement. Battleships are provided with only 1.0 h.p. to 1.3 h.p. of engine capacity per ton of displacement. The *cruising* speed of the "Velox" is only 11.3 knots, which requires merely some 300 h.p.

Thus a noteworthy characteristic of this class of ship is the great ratio of the power required at maximum speed to that required at cruising speed. In the case of the "Velox" this ratio is 12,000 : 300 = 40 : 1.

ELECTRIC PROPULSION

55. Consequences of the self-contained feature in a ship-propulsion installation. There is one very important aspect of the proposition of driving a ship electrically, which should facilitate its introduction in marine practice. Each ship represents an independent, self-contained proposition. There is no particular need for, or advantage in, a rigid adherence to some one particular system. There are usually several alternative methods of dealing with any engineering problem and it is often difficult to determine which is the best. Generally, one can definitely discard several methods as less suitable for some particular case, but there will usually remain two or three methods between which it is difficult to choose.

In undertaking the electrification of a railway, this may well constitute a great embarrassment, since it is important to have standardisation and interchangeability of rolling stock over extensive systems. But in the case of ship propulsion, comparisons of various types of engine equipment, of propeller designs and speeds, of locations of propellers, of number of propellers, of kinds of fuel, etc., are continually being made on ships of otherwise identical characteristics. The rapid progress which is continually in evidence in marine engineering is largely a consequence of this established policy. It is easy to foresee that the application of electrical methods to ship propulsion will be more readily accomplished (so far as it is demonstrated to realize the economic advantages that are claimed for it), than has been the case with railway electrification.

The engineer's task will include determining upon a thoroughly appropriate installation in each case. It will be entirely unnecessary for him to adopt any other than the economically appropriate solution in any case, out of consideration for uniformity with the machinery employed in some other case.

Various combinations of machinery for the electric propulsion of ships have been worked out, and some of them have crystallized into "systems." But there are many sound plans and principles of proved appropriateness which have been employed in electric-power applications on land which are equally entitled to be designated as "systems" appropriate for ship propulsion. It is therefore not considered desirable to devote any space to detailed descriptions of "systems." The reader may care to refer to Chapters XIII to XVI, inclusive, of Hobart's "Electric Propulsion of Ships" for descriptions of various systems which have been proposed by Mavor, Emmet, Durtnall, Day, Hobart, and others.

56. Turbines versus internal-combustion engines in electric propulsion. For anything over 4,000 h.p. it would appear that for electrically-driven ships the economic advantage will be greater when the steam turbine is employed as prime-mover than when the oil engine is employed. In the first place, the cost of steam turbines is only a matter of some 20 cents per pound, as compared with some 50 cents per pound for oil engines. Furthermore, the weight per horse-power for oil engines of large output is several times the corresponding figure for steam turbines of the same output. The handicap in the matter of cost is so great that it is far from being offset by the cost of the steam-raising plant in the case of the steam turbine. Moreover, the fuel cost per brake horse-power-hour is at present much greater for oil than for coal. In electric propulsion, the very highest turbine speeds may be adopted, since in a self-contained plant such as that on board ship, the particular periodicity employed is of no consequence.

each of two propeller shafts), the same vessel speed could be obtained by supplying only 45,500 shaft h.p. to the two 86-r.p.m. propellers as is now obtained by supplying 69,000 h.p. to the four 188-r.p.m. propellers which are actually fitted to the ship.

The calculations in Ljungström's comparison are given in tabular form in his letter and include cost estimates.

58. Study of electric drive for the destroyer "Hugin." Ljungström has also worked out estimates for an electric drive for the 348-ton Swedish destroyer "Hugin," which is now equipped with Curtis turbines of 10,400 shaft h.p., 850 r.p.m., and direct-connected to the propeller shafts. The corresponding vessel-speed is 31.2 knots. By substituting a Ljungström turbo-electric transmission, it is estimated that the propelling power would be reduced to 6,500 shaft h.p. and the coal consumption to 42 per cent. of its present value; the weight would be decreased by 75 tons and the floor space by 33 per cent. This turbo-electric alternative comprises three turbo-generators driving electric motors at 500 r.p.m. normal speed.

59. Study of electric drive for the cargo boat "Vespasian." Ljungström has also described an electric transmission which he proposed for the cargo boat "Vespasian." He states that "the electric motors, intended for 100 periods, are two in number and *geared* to the shaft." On p. 106 of Hobart's "The Electric Propulsion of Ships," this same plan was earlier advocated in the following words: "The disabilities of low-speed induction motors may be escaped and advantage may be taken of their good qualities by arranging that high-speed motors shall drive the propeller-shafts at low speeds through double-helical speed-reduction gearing. The pinions of two (or even more) motors could be arranged to gear with a single low-speed gear-wheel on the propeller shaft, quite analogously to the way in which two steam turbines drove the 'Vespasian's' shaft in the tests made by Parsons. Usually the 2 per cent. loss in the gearing would be largely offset by the higher efficiency of the high-speed induction motor, and the weight and cost of the gearing would be partly offset by the lesser weight and cost of high-speed as compared with low-speed induction motors. The difficulties associated with finding space in ships for large diameters are also eliminated by this plan."

60. W. L. R. Emmet on electric propulsion. Mr. W. L. R. Emmet has read papers on electric ship propulsion before various engineering societies. References to these papers are given in the bibliography (Par. 78). In 1909 Mr. Emmet designed an electrical equipment for the battleship "Wyoming" and a proposal embodying these designs was made to the Government. Since that time Mr. Emmet has submitted several designs to the Government relating to equipments of battleships which have been built. In the spring of 1913 Mr. Emmet submitted a design which applied to a case like that of the "Pennsylvania." The estimates as to the results of this equipment as compared with those which will be accomplished by the equipment which is being put into the battleship "Pennsylvania" are shown by the following table:

	R.P.M. at 21 knots	H.P. required at 21 knots	Pounds of steam per hour, turbines alone, 21 knots	Pounds of steam per hour, turbines alone, 15 knots	Weight of driving machinery in tons
Turbine drive with geared cruising turbines as adopted.	222	31,700	374,000	106,000	749
Turbo-electric drive.........	160	29,200	205,000	91,000	598

Mr. Emmet states* that if in 1909 his first design for a warship had been accepted by the Navy Department, the vessel produced would have been

* In a paper read on Dec. 11, 1913, before the Society of Naval Architects and Marine Engineers.

30 h.p. each, and operating at a speed of 1,700 r.p.m. One end of the shaft f each of these turbines is connected to a large centrifugal fire pump and the ther end is connected to a 200-kw. direct-current generator. The boats are ropelled by twin screws and the speed and direction of each motor is conrolled by manipulation of the field of the generator which drives it."

These Chicago fire boats have a length of 120 ft. and are of 28 ft. beam nd 10 ft. draught. On page 389 of *Engineering* for Sept. 20, 1912, will be ound scale drawings of the general arrangement of the machinery in these oats.

Mr. Emmet has made tests directed toward studying the propeller characeristics of these boats and has published the results in a paper presented in Jew York in November, 1911, before the Society of Naval Architects and Marine Engineers.

67. The "Electric Arc." In 1910 and 1911 Mr. Henry A. Mavor quipped with electric gearing a 50-ft. steel-built vessel, and subjected it to a series of tests. This boat, the "Electric Arc," was launched in February, 1911. See description in Par. 68.

68. The "Multiple" squirrel-cage motor. The generator supplied three-phase current to a squirrel-cage induction motor, also of a type invented by Mr. Mavor (British Patent No. 12,917 of 1909) and to which he applies the designation of "multiple" motor. This motor drives the propeller at one or other of two speeds, in accordance with the following plan:

The stator is provided with two independent windings for two different pole numbers. At its normal speed, the generator provides periodicities which bear to one another the ratio of these two different pole numbers. By connecting the winding of higher pole number to the supply of lower periodicity an efficient running speed of low value is obtained. For higher speed and power, the winding of higher pole number is transferred to the supply of higher periodicity and the winding of lower pole number, which was idle for the lower speed and power, is connected to the supply of lower periodicity. Consequently, at full speed and power, both sources of supply and both motor windings are fully utilized, and cooperate in driving the propeller. With this "multiple" motor it is thus possible to integrate in a single motor the power from several prime movers and also to obtain two or more efficient speeds without resorting to a motor with moving contacts.

69. The United States Collier "Jupiter." Certain leading data of this vessel have already been given (Par. 53) and an illustrated description appeared in an article entitled "Electrical Equipment for the Propulsion of the U. S. Collier Jupiter," by Mr. Eskil Berg at page 490 of the *General Electrical Review* for August, 1912. The "Jupiter," a vessel of 20,000 tons displacement and designed to carry about 12,000 tons of coal and oil, was built at the Mare Island Navy Yard. The contract for the equipment was awarded to the General Electric Co., in June, 1911. The machinery was designed by, and constructed under the direction of, Mr. W. L. R. Emmet. The contract price of the electrical propelling machinery was stated in the article in the *General Electrical Review*, to be $13.75 per horsepower. The turbo-electrical propelling machinery comprises a 9-stage, 2,000-r.p.m. Curtis turbine driving a 2-pole, three-phase, 2,300-volt, 33⅓-cycle, 5,500-kv-a. generator. The two 36-pole, 110-r.p.m. induction motors each have a normal rating of 2,750 h.p. The rotors are provided with three-phase windings leading to slip rings. By means of these slip rings, the rotor current, at starting, reversing and manœuvring, is carried to water-cooled resistors which are short-circuited when the ship is proceeding normally. The heat is removed from the active material of these resistors by the circulation of sea water through them.

An interesting feature of the arrangement of the machinery relates to the provision of sheet-metal ducts so connected to the air outlets from the generator and motors as to lead the heated air to the suction of the fire-room blowers, thus avoiding needless heating of the engine room.

70. Performance of the "Jupiter." The "Jupiter" was put in commission September 15, 1913. After a period of preliminary trials in San Francisco Bay and at sea, the ship was docked. After cleaning her bottom, a set of standardization runs and a 48-hour unofficial trial were made.

of Glasgow, a canal-type tank barge for service on the Canadian lakes and through the Welland Canal. The vessel was built for operation by the Montreal Transportation Company, and was designed and fitted under the supervision of Messrs. John Reid and Henry A. Mavor. The "Tynemount" was described, with drawings, in a paper by these gentlemen read in June, 1913, before the Institution of Naval Architects and entitled "A Case for Electric Propulsion." The power equipment consists of two four-stroke-cycle, 400-r.p.m., 6-cylinder, Diesel engines, each direct-connected to a three-phase 235-kv-a., 500-volt generator. These two generators are wound respectively with 6 and 8 poles and thus constitute sources of different periodicity, the one supplying 20 cycles per second and the other 26.6 cycles per second. An exciter is fitted on an extension of the shaft of each generator. Each exciter gives normally about 30 amp. at 100 volts and is capable of supplying a considerable overload. The propeller is driven by a "multiple" motor of the type invented by Mr. Mavor and already decribed (Par. 68). This motor is of the squirrel-cage induction type and is

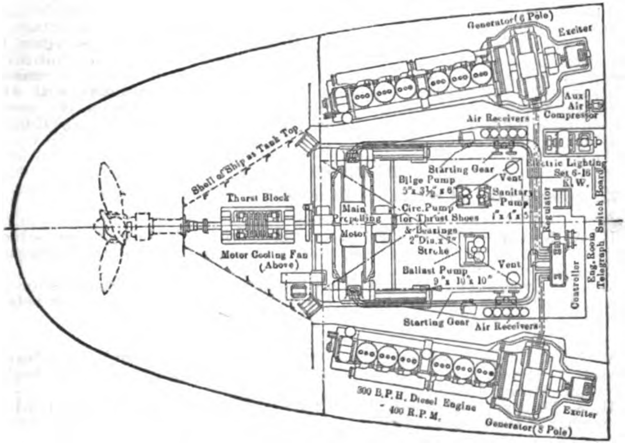

Fig. 4.—Plan of arrangement of the "Tynemount's" machinery.

provided with two stator windings for 30 and 40 poles respectively. At the vessel's normal speed the power of the two Diesel engines is integrated at this motor, the 20-cycle supply being absorbed in the 30-pole winding and the 26.6-cycle supply in the 40-pole winding. Under these conditions the synchronous speed is 80 r.p.m. Allowing for slip in the rotor of this motor the propeller speed is about 78 r.p.m. By changing the 40-pole winding to the 20-cycle generator and leaving the 30-pole winding of the motor and the 26.6-cycle generator out of circuit, the speed is lowered to 75 per cent. of full speed, *i.e.*, to some 58 r.p.m. The 26.6-cycle set may then be shut down thus leaving the 20-cycle set alone to propel the ship and consequently providing as good economy at this low speed and load as at the higher speed and load. The vessel is designed to carry about 2,400 tons dead weight of cargo, fuel, fresh water and stores on a 14-ft. mean draught in fresh water. On, p. 412 of Engineering for Sept. 27, 1912, the cost of the Tynemount is given as £30,000 ($150,000).

The dimensions of the ship and of her propeller are determined by the dimensions of the canal locks through which she must pass. The system adopted has permitted of increasing the carrying capacity to 250 tons more than would have been practicable with steam equipment. This saving is a consequence of:

H. M. Hobart.—"The Electric Propulsion of Ships." Harper Brothers London, and D. Van Nostrand Co., New York (1911).

W. L. R. Emmet.—"Automatic Record of Propeller Action in an Electrically Propelled Vessel." (Paper read on Nov. 16, 1911, before the Soc. of Naval Architects and Marine Engineers of New York.)

1912

B. Ljungström.—"Electric Ship Propulsion with Ljungström Turbo-Generators." *Engineering*, April 19, 1912, p. 536.

Eskil Berg.—"Electrical Equipment for the Propulsion of the U. S. Collier Jupiter." (Article on p. 490 of the *General Electric Review* for August, 1912.)

H. A. Mavor.—"Marine Propulsion by Electric Transmission." (Paper read in September, 1912, at the Dundee meeting of the British Association. Published on p. 1023 of *The Electrician* for September 27, 1912.)

W. L. R. Emmet.—"Contribution to a discussion at a meeting of the North East Coast Institution of Engineers and Shipbuilders on Apr. 26, 1912." Contains weight and cost estimates for a 17,000-h.p. liner with electric propelling machinery and data of the Jupiter equipment.

1913

Editorial.—"The Electric Propulsion of Ships." *Engineering*, Jan. 17, 1913, p. 89.

John Reid and H. A. Mavor.—"A Case for Electric Propulsion." (Paper read before the Institution of Naval Architects in June, 1913.)

————"The Electric Motor Ship 'Tynemount.'" *The Engineer*, Oct. 10, 1913, p. 381. (A description of the "Tynemount" accompanied by twelve illustrations.)

W. L. R. Emmet.—"Electric Propulsion on the U. S. S. 'Jupiter.'" (Paper read before the Society of Naval Architects and Marine Engineers at meeting held in New York, December 11, 1913.)

1914

Editorial.—"Electric Propulsion and Steam Engine Efficiency." *Shipbuilding and Shipping Record*, March 19, 1914, p. 349.

SECTION 19

ELECTROCHEMISTRY

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CONTENTS

(*Numbers refer to Paragraphs*)

The figures placed below the chemical symbols are the molecular weights. The equation states that when 56.1 kg. of burned lime combine with 36 kg. of coke, there are formed 64.1 kg. of calcium carbide and 28 kg. of carbon monoxide. Instead of kilogram, we could use just as well any other unit of weight (pound, ton, etc.), since the chemical equation gives only the *relative* weights of combination. The table of atomic weights is given in Sec. 4.

RELATION BETWEEN VOLUME, PRESSURE AND TEMPERATURE IN GASES

6. Avogadro's law. If any of those substances taking part in a reaction at a certain temperature is in the gaseous state and we know the pressure, we can find its volume directly from the equation of the reaction; or if we know its volume we can directly find the pressure. According to Avogadro's rule, equal numbers of molecules of different gases fill equal volumes under the same conditions of temperature and pressure. One gram-molecule of any gas (for instance, 2 g. hydrogen, H_2, or 32 g. oxygen, O_2) at atmospheric pressure (760 mm. mercury) and at a temperature of 0 deg. cent. fills 22.42 liters. One kilogram-molecule fills 22.42 cu. m.

Example: The 28 kg. of carbon monoxide gas set free in the formation of 64.1 kg. of calcium carbide according to the above equation (Eq. 1, Par. 5) are 1 kilogram-molecule and will therefore fill 22.42 cu. m. when brought to a temperature of 0 deg. cent. and to a pressure of 1 atmosphere.

7. Boyle-Mariotte-Gay-Lussac law. To calculate the volume for other temperatures and pressures, the Boyle-Mariotte-Gay-Lussac law is to be applied, according to which

$$p\,v = R\,T = R \times (273 + \text{deg. cent.}) \qquad (2)$$

In this equation p is the pressure, v the volume; hence $p\,v$ the work done in the expansion of the gas. T is the absolute temperature = temperature in degrees centigrade plus 273. R is the gas constant. If we measure the pressure in atmospheres and the volume in liters, then Avogadro's rule states that for $p = 1$ and $T = 273$, 1 gram-molecule of gas fills the volume $v = 22.42$, hence $R = 22.42/273 = 0.0821$. Hence for 1 gram-molecule, if we give

$p\,v$ in liter-atmospheres, $R = 0.0821$
$p\,v$ in kilogram-meters, $R = 0.848$
$p\,v$ in gram-calories, $R = 1.987$.

For n gram-molecules the value of $p\,v$ is n times the value found from the above equation.

Example: If we electrolyze a dilute acid or alkaline solution for the purpose of producing oxygen and hydrogen gas and if we wish to use the hydrogen, for instance, for filling a balloon, then the main reaction is simply the decomposition of water.

$$H_2O = H_2 + O; \qquad (3)$$

i.e., 1 kilogram-molecule or 18 kg. H_2O are decomposed into 1 kilogram-molecule or 2 kg. H, occupying 22,420 liters at 0 deg. cent. and atmospheric pressure, and 0.5 kilogram-molecule or 16 kg. O, occupying 11,210 liters under the same conditions of temperature and pressure. If the hydrogen gas is contained in a balloon which is to rise in the atmosphere, it will be under atmospheric pressure, and the hydrogen produced from 18 kilograms of water, will under this condition fill 22,420 liters at 0 deg. cent. If the temperature is higher, for instance t deg. cent., and the pressure less, for instance, $760-x$ mm. of mercury (when the balloon rises), then the volume in liters $= \dfrac{22{,}420 \times 760 \times (273+t)}{(760-x) \times 273}$.

8. Units employed. The calculation is quite as simple for English units instead of metric units. As J. W. Richards[1] has remarked, the same numerical factor can be used as in the metric system. This coincidence is due to the fact that there is practically the same relation between an ounce (av.) and a kilogram, as between a cubic foot and a cubic meter, the difference being negligible. Hence 1 ounce-molecule of a gas (for instance 28 oz. carbon monoxide) at 0 deg. cent. and 1 atmosphere fills 22.42 cu. ft.

9. Gas mixtures. If we have a mixture of different gases in the same space, two different views are *a priori* possible. Instead of $p\,v = R\,T$ we

[1] Richards, J. W. "Metallurgical Calculations," 1912; Vol. I, p. 3.

freely to the outside—just as a gas inside a reservoir exerts a pressure on the walls, because it cannot follow its tendency to pass outward. Moreover, for the osmotic pressure and the gaseous pressure the same numerical law holds true as shown above (Par. 13). In the case of the sugar solution the osmotic pressure exerted by the dissolved sugar molecules is numerically equal to the gas pressure which the same molecules would exert if the same weight of sugar existed in gaseous form in the same volume and at the same temperature. This is the foundation of **Van't Hoff's theory of solutions.** Instead of measuring the osmotic pressure directly, it is possible to calculate it from the changes of the vapor pressure or of the freezing point, due to the addition of the solute to the solvent.

15. Electrolytes form an exception. However, the above law does not hold good in general and all aqueous solutions which are electrolytes form an important exception, if we base the calculation on ordinary molecular weights in the same way as in the above case of sugar. This discrepancy is removed by the hypothesis of an electrolytic dissociation in solutions (Planck and Arrhenius). According to Arrhenius not all the molecules of the dissolved substance are electrolytically active, but only those which are "dissociated" into electrically charged ions; this is the foundation of the **electrolytic dissociation theory.** In applying the laws of the osmotic pressure to electrolytes a larger number of molecules must therefore be assumed according to the degree of dissociation.

RELATION BETWEEN MASS AND ELECTRIC QUANTITY IN ELECTROLYTIC REACTIONS

16. Faraday's first law gives the exact relation between the weight of the products of electrolysis and the quantity of electricity passing during the electrolysis. There are always two reactions. One is the anodic reaction, its product or products appearing at the anode. The other is the cathodic reaction, its product or products appearing at the cathode. Faraday's first law states that if nothing but the one desired reaction occurs at the anode or cathode as the result of the passage of the electricity, the quantities of material changed at the anode or cathode depend only on the quantity of electricity which passes, measured in coulombs or ampere-seconds; in other words, these quantities depend only on the product of the current in amperes and the time. With i amperes the same quantities of chemicals are changed in t seconds, as with i/n amperes in nt seconds, where n may be anything; the quantities depend only on the product of current and time and not on anything else, for instance, not on the voltage or on the size of the electrodes or on the temperature, etc. This should not be misunderstood; all these statements are valid under the supposition placed at the beginning of our statement of Faraday's first law, namely that nothing but the one desired reaction takes place. As long as this is true, the quantities of materials changed are strictly proportional to the quantity of electricity passing. But if, for instance, by raising the voltage, a new reaction is started, the conditions are of course changed.

17. Faraday's second law gives the numerical relation between the quantity of electricity and the quantity of material changed. It can be most easily expressed for the special case that the chemical reactions occurring at the anode and cathode are simply a liberation of a gas or a deposition of a metal. For this case Faraday's second law states that the quantity of gas set free or of metal deposited is proportional to the **equivalent weight** of the gas or metal, and that 96,540 coulombs deposit or set free 1 **gram-equivalent** of metal or gas. The equivalent weight, or gram-equivalent is defined as the atomic weight divided by the valency. For instance, 63.6 is the atomic weight of copper; the equivalent weight is $63.6/2 = 26.8$ for a bivalent salt, like copper sulphate, and 63.6 for a monovalent salt like cuprous chloride. Hence 96,540 coulombs deposit 26.8 g. of copper from copper sulphate, but 63.6 g. from cuprous chloride.

18. Faraday's law stated in general form. Faraday's law will now be stated in what appears to the writer to be the most general and complete form. It is valid for all electrolytic processes and all such processes require essentially direct current.

In any electrolytic process there is chemical reduction at the cathode and chemical oxidation or perduction at the anode. Reduction means a loss of bonds, perduction a gain of bonds. Exactly as many bonds are lost at the illustrated by a comparison of this process with that of Hoepfner which was devised later to compete with the Siemens and Halske process. While sulphate solutions are used in the latter, Hoepfner proposed to use a chloride solution. The ferric sulphate and cupric chloride are used for leaching the ore.

23. Example. The scheme of the **Hoepfner copper process** was essentially to deposit copper on copper cathodes from a cuprous chloride solution and oxidise simultaneously the cuprous chloride to cupric chloride at carbon anodes, the essential reaction being

$$\underset{198.1}{2CuCl} = \underset{134.5}{CuCl_2} + \underset{63.6}{Cu} \qquad (7)$$

The figures placed below the chemical symbols represent again the weights, found from the table of atomic weights. In this case Cu in the cuprous chloride CuCl, has one positive bond, while it has two positive bonds in cupric chloride $CuCl_2$. At the cathode the reduction of one CuCl to metallic Cu (which has no bonds) involves therefore a loss of one positive bond. At the anode the oxidation of one CuCl to $CuCl_2$ involves the gain of one bond. Hence in this case, we have a monovalent reaction, the change of bonds being 1, and we find that when 96,540 coulombs pass through the cell, 198.10 grams of CuCl are changed into 134.5 grams $CuCl_2$ and 63.6 grams Cu. The metallic copper is the principal product in the process, 96,540 coulombs deposit 63.6 grams of copper or 100,000 coulombs deposit 65 grams of copper, *i.e.*, just twice the amount obtained with the same current and in the same time by the Siemens and Halske process.

24. Explanation of different outputs in the two examples. (Par. **22** and **23**.) It is quite clear from the above argument what causes the different output of both processes; it is simply the fact that Cu has two bonds or is bivalent in $CuSO_4$ and has one bond or is monovalent in CuCl. It is also clear that to find the amount of an element set free from a compound it is not necessary to write down the whole equation of the reaction, as was done above for the sake of completeness. We can state that if 1 gram-atom of a metal is deposited in free metallic state by electrolysis, 96,540 coulombs are necessary for deposition from a monovalent compound (like CuCl), twice as many from a bivalent compound (like Cu_2SO_4), three times as many from a trivalent compound, etc. But this rule is only a special case and does not give any information, for instance, on the quantity of ferrous sulphate oxidised to ferric sulphate in the Siemens and Halske process.

25. Procedure in calculations. The **method of writing** down the whole **equation**, determining the number of bonds lost and gained and applying the above rule gives complete information in all cases on the relation between the quantity of electricity, which passes a cell and all the quantities changed thereby in chemical composition.

26. Method of calculation under the electrolytic dissociation theory. The above method of calculation becomes easier if we use the picture of the electrolytic dissociation theory. The equation of the Siemens and Halske process is then written in the form

$$Cu^{\cdot\cdot} + SO_4'' + 2Fe^{\cdot\cdot} + 2SO_4'' = Cu + 2Fe^{\cdot\cdot\cdot} + 3SO_4'', \qquad (8)$$

that is, instead of $CuSO_4$ in solution we write $Cu^{\cdot\cdot} + SO_4''$, the copper sulphate being dissociated into its ions, the positive copper ion $Cu^{\cdot\cdot}$ and the negative ion SO_4''. Each dot at the top of $Cu^{\cdot\cdot}$ represents a positive electric charge. Each stroke at the top of SO_4'' represents a negative electric charge. Each such charge, positive or negative, is 96,540 coulombs, if the chemical symbols represent gram-atoms or as we now say, gram-ions. The gram-ion $Cu^{\cdot\cdot}$ is bivalent and charged with 2×96,540 coulombs. Each gram-ion $Fe^{\cdot\cdot}$ (ferrous) is bivalent and charged with 2×96,540 coulombs. The gram-atom Cu (metal deposited on the cathode) is not charged. Each gram-ion $Fe^{\cdot\cdot\cdot}$ (ferric) is trivalent and charged with 3×96,540 coulombs. The above ionic equation may be somewhat simplified by writing

$$Cu^{\cdot\cdot} + 2Fe^{\cdot\cdot} = Cu + 2Fe^{\cdot\cdot\cdot} \qquad (9)$$

If this equation shall be right, not only the chemical symbols but the dots must balance on both sides, since otherwise free electrostatic charges would appear somewhere. In this case we see $Cu^{\cdot\cdot}$ has 2 charges and each of the two $Fe^{\cdot\cdot}$ has also 2 charges, hence the total sum is 6 charges on the left side of the equation. On the right side Cu has no charge, each of the two $Fe^{\cdot\cdot\cdot}$ has 3 charges, hence the total sum is again 6 charges.

while the cathodic reaction is $Cu^{\cdot\cdot} = Cu + 2F$, one Cu ion giving off its two positive electrons to the cathode.

33. Use of larger units in practical work. In the above we have based the calculation on 96,540 coulombs as the charge of 1 gram-ion. This is the laboratory unit, but although universally used in discussions of Faraday's law, it seems too small for practical purposes. If one monovalent gram-ion carries 96,540 coulombs, then one monovalent kilogram-ion carries a charge of 96,540,000 coulombs or 26,817 amp-hr. Hence, if the symbols in the equation of the reaction represent kilogram-atoms, then the reaction requires 26,817 amp-hr. if monovalent, $2 \times 26{,}817$ amp-hr., if bivalent, etc.

34. Practical use of the gram-equivalent. Finally the above numerical relations may be very briefly stated by using the term **gram-equivalent** which means gram-ion divided by the valency, so that one gram-equivalent equals a gram-ion if it is monovalent, but one-half gram-ion if it is bivalent as already explained in Par. 24. In the same way the term kilogram-equivalent means kilogram-ion divided by valency. Then Faraday's law states that 1 gram-equivalent of any chemical composition whatever carries an electric charge of 96,540 coulombs. One kilogram-equivalent carries an electric charge of 26,817 amp-hr.

35. Johnson's rule for balancing equations. In the procedure recommended above for the application of Faraday's law a difficulty may be found in writing down the equation of the reaction. Since in any electrolytic process we have to do with reduction and oxidation the following rule of Prof. O. T. Johnson for **balancing equations** of this kind may be found useful. This rule states that "the number of bonds changed in one molecule of each shows the number of molecules of the other which must be taken," the words "each" and "other" referring to the oxidizing and reducing agents. One example may illustrate this rule, which appears to be purely formal from a chemical point of view, while its electrical meaning will be shown below. In the Bunsen cell Zn is oxidised; it becomes $ZnSO_4$. The metal Zn has no bond. Zn in $ZnSO_4$ has two bonds, hence the increase in bonds is two. There are several actions possible at the other electrode. We may consider that NO is developed. N in HNO_3 has five positive bonds, while in NO it has two positive bonds, hence the decrease in bonds is three. Now Johnson's rule states that we have to take three molecules of Zn and two molecules of HNO_3 and we get the equation

$$3Zn + 3H_2SO_4 + 2HNO_3 = 3ZnSO_4 + 2NO + 4H_2O. \qquad (12)$$

36. Application of Johnson's rule. This rule becomes self-evident if applied to an electrochemical action. It simply means that just as much electricity passes from the anode into the electrolyte as from the electrolyte into the cathode. In the case of the Bunsen cell if the chemical symbols represent gram-atoms, then, as Zn gains two bonds and as we have three Zn atoms, $3 \times 2 \times 96{,}540$ coulombs pass into the electrolyte from the anode. On the other hand, N loses three bonds, and, as two N are reduced, $2 \times 3 \times 96{,}540$ coulombs are given off to the cathode. Of course we may also consider HNO_3 to be ionised into H and NO_3 ions, both monovalent, etc. The result is the same. Johnson's rule for balancing equations enables one to write down the equation which represents the electrochemical action, and in the further calculation there is no mistake possible if one keeps in mind that each bond corresponds to 96,540 coulombs, providing the chemical symbols represent gram-atoms.

37. Faraday's law is always exactly fulfilled in the sense that the anodic oxidation and cathodic reduction of given quantities of materials require a certain amount of coulombs, not more nor less. For instance, the deposition of 1 gram-atom or 63.6 g. of copper from the solution of a monovalent cuprous salt requires 96,540 coulombs. But this does not mean that if we send 96,540 coulombs through such solution, we must always deposit 63.6 g. of copper on the cathode. It may be that we have a second reaction at the cathode besides copper deposition, for instance, evolution of hydrogen gas. The conditions may be such that, say 75 per cent. of the coulombs only deposit copper; then we get $0.75 \times 63.6 = 47.7$ g. of copper. The other 25 per cent. of the coulombs deposit hydrogen and therefore evolve 0.25 gram-atom = 0.25 g. hydrogen. Thus Faraday's law is fulfilled, but in practice we are interested in this case only in the copper temperature. In such cases the following consideration is often useful, if the specific heats of all substances which are represented in the equation are known. Suppose a certain reaction evolves a calories at the temperature, t_1, and we want to find the reaction heat at the higher temperature, t_2. Then we consider the materials on the left hand of the equation, *i.e.*, the starting materials, and raise them from t_1 to t_2; the heat, necessary for this purpose, may be b calories and is directly found from the specific heats of the starting materials and the temperature difference, t_2-t_1. That is b more calories are now stored in the system than were in it at the temperature, t_1. We now let the desired chemical reaction go on at the temperature, t_2. This may evolve, x, calories, which is the figure to be determined. If we finally cool the system back to the temperature, t_1, it gives out a certain amount of heat, c, which can be found for the temperature difference, t_2-t_1, and the specific heats of the end products. Then we know that the system has stored in it $(b-x-c)$ more calories than at the start, which according to the principle of the conservation of energy must be equal to $-a$, or $x=a+b-c$.

CHEMICAL AND MECHANICAL ENERGY

44. Definition of liter-atmosphere. If as a result of a reaction between solid or liquid bodies a gas is evolved, work is done against the pressure of the atmosphere. The work done by the evolution of 1 liter of gas under atmospheric pressure is 1 liter-atmosphere.

$$\begin{aligned} 1 \text{ liter-atmosphere} &= 10.333 \text{ kg-m.} \\ &= 24.2 \text{ g-cal.} \\ &= 101.3 \text{ watt-sec.} \\ &= 0.136 \text{ horsepower-second.} \end{aligned} \qquad (15)$$

45. Work performed by evolution of gas. For instance, if hydrogen and oxygen gas are produced under atmospheric pressure by electrolysis of a dilute acid or alkaline solution, 18 kg. water yield 2 kg. H, occupying 22,420 liters at 0° C, and the work done in expanding the hydrogen gas against the pressure of the atmosphere is 22,420 liter-atmospheres = 543 kg-cal. = 2,271 kw-sec. Simultaneously 16 kg. O, occupying 11,210 liters, are evolved and the work done in expanding the oxygen gas against the pressure of the atmosphere is 11,210 liter-atmospheres = 271 kg-cal. = 1,135 kw-sec. Hence the total work done in expanding both gases to 33,630 liters is 814 kg-cal. = 3,406 kw-sec. This energy consumed is, of course, not to be confounded with the energy required for the electrolytic decomposition of the water. It is simply the mechanical work performed in expanding the gases against the pressure of the atmosphere.

A very simple way to calculate this work approximately is to remember the formula $pv=RT$, in which R very approximately = 2, if pv is given in gram-calories and the mass of 1 gram-molecule is considered. In words, the work done in expanding 1 gram-molecule of any gas from a solid or liquid to gas at the absolute temperature T is 2T g-cal.; for instance, at 0 deg. cent. or 273 deg. absolute temperature it is 546 g-cal. (as compared with 543 found above). In the reverse change from gas to solid the same amount of work is performed upon the system or the same amount of energy is gained by the system.

46. Expansion of gas at constant pressure. The characteristic feature of processes like those just described is that they take place at constant pressure. In general if a gas expands at constant pressure, p, from volume, v_1 to v_2, the work done is $p\ (v_2-v_1)$. In the special case that a gas expands from a solid or liquid, the volume of the solid or liquid, which disappears is negligible compared with the gas formed and $v_1=o$, from which results at once the above calculation.

47. Expansion of gas at constant temperature. An entirely different case is the calculation of the work done when a given mass of gas expands its volume at constant temperature, the pressure decreasing correspondingly. For 1 gram-molecule, expanding from volume v_1 to volume v_2 at constant temperature, T, this work is

$$RT \log_e \frac{v_2}{v_1}, \qquad (16)$$

where $\log_e$ means the natural logarithm. In view of the parallelism between gaseous pressure and osmotic pressure in solutions, the above statements on gases may be made in an analogous way for solutions.

At ordinary temperatures this rule is, in general, approximately fulfilled and is therefore exceedingly useful for making a first approximate calculation.

54. Terminal voltage. The voltage, *e*, is the e.m.f. absorbed or produced in the electrochemical process. It is different from the voltage at the terminals. The voltage at the terminals of a battery equals the e.m.f., *e*, minus the voltage drop due to internal resistance. The voltage at the terminals of an electrolytic cell through which electricity is passed from an outside source, equals the e.m.f., *e*, of the reaction plus the voltage drop due to internal resistance.

CHEMICAL ENERGY, ELECTRICAL ENERGY AND HEAT

55. Error in Thomson's rule. Thomson's rule is wrong in principle because in an electrochemical action we never have an interchange of chemical energy and electrical energy alone, since heat is always involved. This does not mean the Joulean heat which, of course, is also present. We may assume we have an electrolytic system of such dimensions and design that its internal resistance is so small that the Joulean heat developed in it is negligible compared with the amount of energy involved in the reaction. Under such conditions we know from experience that the cell while electricity passes through it, either tends to cool or to heat. To maintain the temperature constant it is therefore necessary to supply heat from the surroundings or to carry it off to the surroundings. In the case of a battery, if it tends to cool, and we supply heat to maintain the temperature, not only chemical energy but also the heat supplied during discharge are changed into electrical energy; hence the e.m.f. at that temperature has a greater value than that found from Thomson's rule. If the battery tends to give up heat during the passage of the electricity, heat is given off to the surroundings, and the e.m.f. is smaller than found by Thomson's rule.

56. Distinction between energy of reaction and capacity for performing work. This question is intimately connected with the essential difference between the total energy of a reaction at a certain temperature, as defined in Par. **38 to 48** and its capacity of performing work. The reason is that among all different forms of energy, heat has an exceptional place. We can always change all other kinds of energy completely into heat, but we cannot do the reverse. In case of a chemical reaction we can change the chemical energy completely into heat and this is exactly what we are doing in thermochemistry when we determine the heat or **energy of a reaction.**

57. The capacity of performing work (mechanical work in the expansion of gases or electric work in case of a battery) is something different. As an example, let us assume a concentration cell, consisting of two different concentrations of the same salt solution, each containing an electrode made of the metal of the salt. If then the reaction is that at the anode metal is dissolved and forms more salt, while simultaneously salt disappears at the cathode, metal being deposited, then the energy corresponding to the solution of metal from the anode and deposition of exactly the same amount of metal on the cathode is zero. If we assume further that we have to do with solutions so diluted that the energy of further diluting them is zero, then the energy corresponding to the concentration changes in the cell is also zero. Hence the total chemical energy of the reaction in the cell is zero. Nevertheless the cell will give out electricity and will perform work, the electricity produced being in such a direction as to equalize the concentrations (*i.e.*, the electricity passes in the cell from the dilute to the concentrated solution, because under this condition more salt is formed in the dilute solution from the anode, while the concentrated cathode solution is diluted by metal being deposited on the cathode). Of course, the energy must come from some source, and under the conditions of the experiment it must come from heat; *i.e.*, the cell while giving out electricity tends to cool down, and heat must be supplied from the outside to keep the temperature constant. This is therefore a case in which the chemical energy of reaction is zero, but its capacity of performing work has a positive value; correspondingly the e.m.f. would be zero according to Thomson's rule, but has in reality a positive value.

58. Helmholtz equation of energy. If $W =$ energy of the chemical reaction at a certain absolute temperature T and if W_0 is the maximum amount of work which it is capable of performing at that temperature under and radiation per unit of the surface of the furnace, *i.e.*, on the kilowatts lost per square meter. Hence if the size of an electric furnace is increased, then *ceteris paribus* the generation of heat from electricity increases as the third power of the dimension, and the losses as the square of the dimension; hence the thermal efficiency of an electric furnace is the higher, the larger the size. The maximum size of a furnace is limited by the consideration that the more we increase the size, the greater becomes the difficulty of maintaining uniform conditions of operation.

ENERGY BALANCE, REFRACTORIES

63. Analysis of energy required. The energy per unit of mass is, in general, consumed in five different items, viz.:

(*a*) To produce the heat necessary to raise the starting materials to the temperature of the reaction.

(*b*) To provide the energy required for any change from solid state to liquid or from liquid to gas or from solid to gas.

(*c*) To provide the energy for the chemical reaction.

(*d*) To supply the heat lost by conduction.

(*e*) To supply the heat lost by radiation.

64. Heat necessary to raise starting materials to operating temperature. The heat necessary to raise the starting materials, if cold, to the temperature of the reaction (Par, 63a) equals the weight of charge multiplied by temperature difference multiplied by mean specific heat.* To reduce this item of energy as much as possible, the starting materials are often preheated by waste gases, etc. It is often advantageous to divide the heating of the charge into two stages, the lower ranges of temperatures being obtained by burning fuel and only the higher range of temperatures from electrical heat.

65. Heat necessary for change of state. The heat required for a change of the charge from solid to liquid or from liquid to gas or from solid to gas (Par. 63b) is equal to the weight of the charge multiplied by the latent heats (see J. W. Richards, "Metallurgical Calculations," Vol. I). This item of energy expense should also be eliminated wherever possible. For instance, for electric steel refining, the steel is preferably supplied to the electric furnace in molten state from the open-hearth furnace or Bessemer converter. If a gas is evolved from solid materials, the work done in the expansion of the gas must also be considered. See (44).

66. The energy required for the chemical reaction (Par. 63c) at the temperature of the reaction (Par. 48 to 54), is an item of expense, only if the reaction absorbs energy. If the reaction evolves energy, this energy is added to that of the electric current and changed into useful heat, so that the amount of electrical energy to be supplied from the outside is reduced.

67. The loss of heat by conduction (Par. 63d) depends on the difference of temperature inside the furnace and outside and on the thermal conductivity of the furnace walls. To reduce this loss as much as possible, the furnace walls are built up of highly insulating refractory materials. In the choice of the material its heat-insulating property must be taken into consideration as well as the maximum temperature which it is intended to stand and the chemical nature of the reactions for which the furnace is to be used; further, the ability to withstand expansion and extraction must be taken into consideration. See Par. 69 to 89.

68. The loss of heat by radiation (Par. 63e) is treated in Par. 90.

69. Loss of heat through terminals. All electric furnaces, except the induction furnace, have terminals (often called electrodes) for introducing the electrical energy into the furnace, and these represent the weakest point in the heat insulation. But the conduction of heat through an electrode (due to the temperature difference between its two ends) is a more complicated phenomenon than the single heat conduction through the refractory wall, because in the former case each particle of the electrode is not only a conductor of heat, but a seat of generation of new heat (from electrical energy). There is a superposition, therefore, of two phenomena; first, simple heat con-

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* For tables of specific heats see J. W. Richards, "Metallurgical Calculations," Vol. I, also Sec. 4.

lating properties of the silico-carbide. Further, if the article is exposed at high temperatures to an oxidizing atmosphere the carbon residue which acts as the binding agent is burnt out. If this happens the article will disintegrate, unless the temperature and oxidising conditions are such as to cause oxidation of the silico-carbide and consequent binding together of the particles. When, therefore, the article is exposed to oxidizing actions at a comparatively low temperature, it is better to use sodium silicate as the binding agent. But where the conditions are such that neither oxidation or serious current leakage is to be feared, the tar bond is very satisfactory, giving articles of considerable mechanical strength.

When an article of great mechanical strength is required, and the use of tar is objectionable, the best method of making the article is, according to FitzGerald, to cause the particles of the silico-carbide to frit together by oxidation. To accomplish this result the silico-carbide is mixed with some temporary binding agent, such as a solution of glue in water and then heated to a high temperature for several hours in a strongly oxidising atmosphere. By this treatment the grains of the silico-carbide are superficially oxidized.

75. Siloxicon. When siloxicon is heated to, or above, 2,674 deg. fahr. (Acheson) or 1,468 deg. cent. in an oxidizing atmosphere, decomposition takes place. If the siloxicon be in the form of a brick or other moulded mass the reaction occurs on the surface, producing a vitreous glaze. In the absence of free oxygen or in a reducing atmosphere, no such decomposition occurs, and the temperature may be raised to the point of the formation of carborundum, approximately 5,000 deg. fahr. (Acheson) or 2,760 deg. cent., solid crystalline carborundum remaining while the vapors of silicon and carbon monoxide are given off. For higher temperatures carborundum is a useful refractory; it is suitable up to such temperatures where it decomposes.

76. Refractories for very high temperatures. When the temperature to which the refractory material is submitted may be up to or above that of the formation of carborundum, it may be advisable, according to FitzGerald, to use **cyrstalline silicon-carbide** in the first place, allowing it to be converted into **carborundum** in situ. If this is done the silico-carbide should first be analyzed to determine whether oxygen compounds are present or not. If oxygen compounds are present in appreciable quantities the silico-carbide may be unsuitable for the work, since at the temperature of the formation of carborundum, silicon will be reduced and the refractory lining will be impregnated with metallic silicon, or the furnace will be filled with silicon vapor. When the presence of the silicon is unobjectionable this reaction may be disregarded; otherwise there are two courses open; the silica may be removed or a material free from silica obtained; or from the analysis of the material the amount of carbon necessary to eliminate the oxygen and to form carborundum may be added to the mixture.

77. Carborundum as a refractory material. When it is desired to use carborundum directly as a refractory material the binding agents suggested in Par. **73** and **74**, for silico-carbides may be used. Carborundum may also be made into a strong article by the oxidation or fritting method described in **74**. Another method of making articles of carborundum is by recrystallization. The carborundum in the form of grains or powder is mixed with some adhesive substance, such as a solution of glue in water, the mixture moulded in the desired form and the article then placed in an electric furnace and heated to the temperature of formation of carborundum. This causes a recrystallization of the carborundum and forms a strong article which preserves perfectly the form in which it was moulded. Neither the **silico-carbides** nor **carborundum** can be used as refractory materials where they come **in contact with fused alkalies**, since these produce rapid decomposition. They are also attacked by chlorine at high temperatures.

78. Binder for carborundum refractories. For using **carborundum** (silicon carbide) **as refractory**, E. K. Scott (*Electrochemical and Metallurgical Industry*, Vol. III, p. 140) recommends that the carborundum be ground up very fine and mixed in the proportion of three parts by weight of carborundum to one part by weight of silicate of sodium (water-glass). After thoroughly brushing the newly set fire-brick to get rid of dust, etc. (the mixture will not stick to a surface which has already been fired), the carborundum is painted on to the depth of about half a millimeter. It is then left for 24 hr. to dry, and afterward the firing started up gradually.

rochem. and Met. Ind., Vol. III, 1905, p. 291, and S. Wologdine and A. L Queneau, *Electrochem. and Met. Ind.*, Vol. VII, p. 383. The figures taken from Hutton are marked (H); most of the granular powders tested by Hutton and Beard just passed through a sieve with 600 meshes per sq. cm. The figures taken from Wologdine are marked (W). All the conductivities λt are given in centimeter-gram-second units, *i.e.*, each figure represents the quantity of heat in gram-calories, which is transmitted per sec. through a plate 1 cm. thick per sq. cm. of its surface when the difference of temperature between the two faces of the plate is 1 deg. cent. The thermal conductivity of various other substances is given elsewhere (see index). The figures under *t* represent the ranges of temperature in deg. cent. within which the conductivity figures are valid. The figures found by different investigators are considerably at variance. Probably those marked (W) are the best available at present for the grade of refractory materials on the marked for everyday furnace work. Concerning the method of measuring the thermal conductivity of refractories see Clement, *Met. and Chem. Eng'ing*, Vol. VIII, p. 414.

84. Table of Thermal Conductivities of Various Substances

Substance	*t*	λ_t
Graphite brick (W)	100°–1000°	0.025
Carborundum brick (W)	100°–1000°	0.0231
Gas-retort carbon, solid	0°–100°	0.01477
Magnesia brick (W)	100°–1000°	0.0071
Magnesia brick	0°–1300°	0.00620
Chromite brick (W)	100°–1000°	0.0057
Masonry	—	0.0058 0.0036
Fire brick (W)	100°–1000°	0.0042
Checker brick (W)	100°–1000°	0.0039
Gas retort brick (W)	100°–1000°	0.0038
Building brick (W)	100°–1000°	0.0035
Bauxite brick (W)	100°–1000°	0.0033
Fire-brick	0°–1300°	0.00310
Fire-brick (Clement)	400°–750°	0.0021 to 0.0036
Glass pot (W)	100°–1000°	0.0027
Terra cotta (W)	100°–1000°	0.0023
Alumina brick	0°–700°	0.00204
Silica brick (W)	100°–1000°	0.0020
Kieselguhr brick (W)	100°–1000°	0.0018
Marble, white	—	0.0017
Water, uncirculated	—	0.0016 0.0012
Glass	10°–15°	0.00150
Fire-brick	0°–500°	0.00140
Plaster of Paris	—	0.0013
Water	—	0.00120
Clinker, in small grains	0°–700°	0.00110
Slate	—	0.00081
Cork	—	0.00072
Pumice	—	0.00060
Oak wood	—	0.00060
Quarts sand	18°–98°	0.00060
White Calais sand (H)	20°–100°	0.00060
Coarse carborundum (H)	20°–100°	0.00051
Fine carborundum (H)	20°–100°	0.00050
Magnesia "Mabor" brick, powder (H)	20°–100°	0.00050
Carborundum sand	18°–98°	0.00050
Rubber	—	0.00047
Pine wood	—	0.00047
Magnesia, fused, granular (H)	20°–100°	0.00047
Magnesia calcined, Grecian, granular (H)	20°–100°	0.00045
Powdered coke	0°–100°	0.00044

87. Example of thermal calculations. As an illustration of the simplicity of the calculations when these units are used, let the inside of a small furnace be a 6-in. cube; let the wall consist of a 4-in. layer of silica brick on the inside and 4 in. of brick on the outside. The true average cross-section of the layer of silica brick perpendicular to the heat flow (namely, the geometric mean, that is, the square root of the product of the extreme sections) for the whole furnace will be 504 sq. in. If its resistivity from the above table is 47 thermal ohms, its resistance will be

$$R = \frac{r \times l}{S} = \frac{47 \times 4}{504} = 0.37 \text{ thermal ohm.}$$

A similar calculation for the outside layer of fire-brick having a resistivity of 22 thermal ohms gives its resistance as 0.048 thermal ohm. Hence, the total is the sum of these two, which is 0.42 thermal ohm. Incidentally, it shows what a very much smaller insulating effect this much larger outside layer has.*

Suppose the drop of temperature through the wall to be 1,500 deg. cent. Then, according to the thermal ohm's law, the loss of heat will be

$$W = \frac{T}{R} = \frac{1{,}500}{0.42} = 3{,}580 \text{ watts, or about 3.6 kw.}$$

The analogy between heat flow and electric flow has been analyzed very carefully by E. F. Northrup† with applications of the results to an analysis of methods for measuring thermal resistances.

88. Formulas for flow of heat through plates. The ordinary formula for the flow of heat through plates or rods of solid materials may be written:

$$W = (A/t)k\ (T - To) \tag{23}$$

Where W = the heat flow, expressed in watts, A = area of plate or cross-section of the rod, t = thickness of the plate or length of the rod, $T - To$ = the difference of temperature between the two sides of the plate or between the ends of the rod, and k = heat conductivity of the material of the plate or rod in watts per cm. per deg. In most practical cases of heat flow the problem is more complicated than this. Usually the heat is not flowing between parallel surfaces, or at least the areas of the two bounding surfaces are different. The above equation as it stands, applies only between parallel surfaces through a body of uniform cross-section. For bodies of other shapes Langmuir treats the case as follows. While A will vary along the path of heat flow, yet if the area of inflow and outflow is fixed, the ratio A/t will have a definite value, depending only on the shape of the body. This quantity Langmuir terms the shape factor, and represents it by S. The formula (Eq. 23) thus becomes:

$$W = Sk\ (T - To) \tag{24}$$

In case the heat conductivity is a function of the temperature, the equation should be written:

$$W = S \int_{To}^{T} k\,dT \tag{25}$$

S, the shape factor, is a quantity of the dimension of a length which depends only on the shape and size of the body and the position of the surfaces by which the heat enters and leaves the body.

Langmuir‡ has given formulas for the shape factor for parallel places, concentric cylinders, concentric spheres, square edges, square corners, plane edges, plane corners, small square rods, small cubes, and for rec-

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* A series of articles on heat insulations of furnace walls and the flow of heat through furnace walls has been published by Carl Hering in *Met. and Chem. Eng'ing*, Vol. IX, p. 189, 590, 652 (where there is a further table of thermal resistivities in thermal ohms); Vol. X, p. 97 and 159; Vol. XI, p. 183. On heat losses of electric furnaces see also F. A. J. FitzGerald, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 281, and *Met. and Chem. Eng'ing*, Vol. X, p. 286.

† *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 85.

‡ *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 53.

contained a special carbon crucible in which the material to be heated was placed. The upper block was slightly rounded out directly above the arc. By the strong heat of the arc the surface of the lime was fused and highly polished so as to form a perfect reflector sending all the heat down upon the crucible.

94. Direct and indirect arc furnaces. In the former the furnace charge is directly exposed to the arc, in the latter it receives the heat of the arc by radiation and by reflection from the roof and walls. It is clear that in many cases there is combined direct and indirect heating. A typical example of indirect arc heating is the **Stassano furnace.** For operation by three-phase currents, there are three electrodes at the top. The arcs play between the ends of the three electrodes and heat the metallic bath below by radiation (there being no arcs between the electrodes and the bath itself). To mix the charge thoroughly, the furnace is built revolvable. (*Electrochem. & Met. Ind.*, Vol. VI, p. 315.)

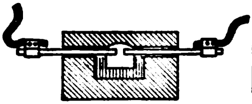

FIG. 1.—Moissan Arc Furnace.

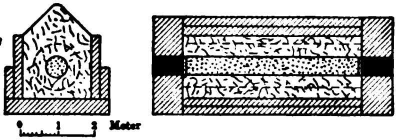

FIG. 2.—Acheson Carborundum Furnace.

95. A typical resistance furnace is the carborundum furnace of E. G. Acheson, shown in plan and vertical section in Fig. 2, the dimensions referring to a capacity of 750 kw. The charge which consists of carbon, silica sand and salt, surrounds a carbon core which acts as resistor and is placed in the centre of the furnace. It runs through the furnace from end to end and is connected at both ends with the carbon terminals or electrodes in the end walls of the furnace. (For further details see F. A. J. FitzGerald, *Electrochem. and Met. Ind.*, Vol. IV, p. 54.) The current through the resistor produces heat which passes outward into the charge, resulting in the production of carborundum.

96. Resistance furnaces may again be **subdivided** according to the nature of the resistor, whether the electric heat is produced in the charge itself or in a special resistor, in contact with the charge. The former is possible only if the charge itself is a conductor of electricity; an example is the induction furnace for melting steel, etc. In case the furnace charge is not itself a conductor of electricity, a special resistor must be provided in contact with the charge; the electricity takes a predetermined path in passing through the resistor in which the heat is thereby developed. An example is the carborundum furnace described above. Finally it is possible to so arrange the resistor that it is not in direct contact with the charge, but is arranged above it and heats the charge by radiation.* Concerning materials suitable for resistors see Par. 111.

No sharp distinction is always possible between the two subclasses of resistance furnaces with or without a special resistor. For instance, in the Acheson furnace for changing carbon electrodes into graphite electrodes, the electrodes are embedded in granular graphite; most of the heat is developed in the latter, but since the electricity also passes through the electrodes themselves, some heat is also directly produced within the same. An example of a furnace operation which changes in character during a run is Acheson's furnace for producing graphite in bulk; in the centre of the anthracite coal, coke, etc., to be graphitized the resistor in form of a series of carbon rods, is placed through which the electricity first passes exclusively; when the anthracite coal next to the core is changed by the heat into graphite, the electricity also passes through it and so on. Therefore, while the electricity had first only a restricted definite path, its path gets broader and broader during operation.

97. Pinch phenomenon. A peculiar limitation of the temperature obtainable in that class of resistance furnaces in which the charge itself forms

* FitzGerald. *Met. & Chem. Eng'ing*, Vol. VIII, p. 317; Vol. IX, p. 29.

furnace. It is essentially a transformer, the secondary of which is a single turn, represented by an annular channel which contains the charge. It is necessarily operated by alternating current which is fed to the primary winding, thus setting up an alternating magnetic flux in the transformer core of laminated iron; this again produces alternating current in the furnace charge in the secondary annular channel, thus heating the charge directly by the Joulean effect. A tilting induction furnace for melting metals (A. E. Colby, F. A. Kjellin) is shown diagrammatically in Fig. 4.

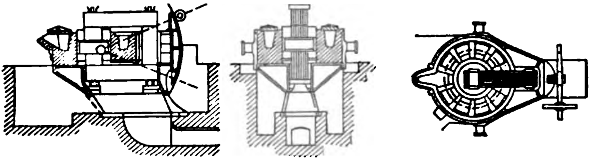

Fig. 4.—Colby-Kjellin Induction Furnace.

The **chief advantage** of this type of furnace lies in the fact that there are no electrodes which could contaminate the bath, so that the chemical composition of the bath can be absolutely controlled by carefully selecting the raw materials. The nature of the atmosphere in which the reaction takes place is also in absolute control of the operator. It is also possible to heat up such a furnace very quickly. (FitzGerald, *Electrochem. & Met. Ind.*, Vol. VII, p. 10, 1909.)

The **losses of energy** in transfer from the primary to the secondary are calculated exactly as in the case of the ordinary transformer (Sec. 6). The induction furnace differs (quantitatively, not qualitatively) from commercial alternating-current transformers, since it has necessarily considerable magnetic leakage fluxes due to the necessity of careful insulation of the fused-bath channel from the primary winding. The **power-factor** is low, due to two causes: the low resistance of the secondary and its high self-induction, due to its wide separation from the primary. The power-factor can be improved by any of the following means: decreasing the frequency of the alternating current, or increasing the ohmic resistance of the fused charge, or increasing the magnetic reluctance of the two leakage fields.

103. The Roechling-Rodenhauser combination furnace is a modification of the simple induction furnace. It is heated by a superposition of two heating effects: firstly, according to the simple induction principle; secondly, an auxiliary secondary circuit is provided, the ends of which are connected to metallic pole plates embedded in the furnace walls. When the furnace is started, it is first heated by induction alone. When the refractory layer which separates the pole plates from the metallic bath thereby becomes hot, it becomes an electric conductor and supplementary heat is now produced by the electric current passing between the pole plates through the furnace charge. The advantages of this furnace over the simple induction furnace are that it can be used for refining (not only melting) purposes and that it can be built with ordinary commercial frequencies for large charges so as to operate with a good power-factor. (*Electrochem. & Met. Ind.*, Vol. VI, pp. 10, 143, 438, 458; *Met. & Chem. Eng'ing*, Vol. VIII, p. 338, Vol. X, p. 263, Vol. XI, pp. 99 and 599; *Transact.* Am. Electrochem. Soc., Vol. XX, p. 293.) Another combination of arc and resistance furnace is the "paragon furnace" (Harden, *Met. & Chem. Eng'ing*, Vol. IX, p. 38, 595).

104. Electrodes. If the electrical energy is introduced into the furnace through terminals, they consist almost always either of amorphous carbon or of graphite, at least for large furnaces. In this country amorphous carbon electrodes are generally made from petroleum coke, while in Europe electrodes made from anthracite coal are also used. However, artificial graphite electrodes made by the Acheson process in the electric furnace, are very extensively employed now. They are more expensive, but can be easily machined into any shape (C. E. Collens, 2nd, *Transactions* of the American Electrochemical Society, Vol. I; *Electrochemical Industry*, Vol. I, p. 26 and Vol. II, p. 277; W. McA. Johnson, *Electrochemical Industry*, Vol. II, p. 345), *Transactions* Am. Electrochem. Soc., Vol. XV, p. 279, Vol. XVI, p. 329, *Electrochem. & Met. Ind.*, Vol. VII, pp. 358, 389; E. F. Roeber, *Transactions* Am. Electrochem. Soc., Vol. XVI, p. 363; J. Forssell, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 26 and 177; A. E. Kennelly, *Proc.* Am. Inst. Elec. Eng., March, 1910, p. 267.

106. Regulation of the heat production is of greatest importance; this is, of course, identical with regulation of the electric energy supply. In arc furnaces this is obtained by adjusting the position of the electrodes, which may be done either by hand or automatically. A simple automatic method in case of a furnace with one electrode, the crucible forming the other terminal, is to control the position of the electrode by an electromagnetic device, the magnet winding being in shunt with the crucible and the electrode, so that the exciting current of the magnet depends on the current through the furnace. In the single-phase Héroult steel furnace which has two electrodes, there being current from one electrode through the slag to the other electrode, it is important to know that both arcs are playing properly. For this purpose a voltmeter is connected in parallel with each of the electrodes and the molten furnace charge; one terminal of the voltmeter is connected with the electrode and the other with some contact in the molten steel charge. Each voltmeter may, of course, be provided with an automatic regulating attachment.

107. In the operation of resistance furnaces it is a fact of great importance that the resistance is a variable quantity during the run of the furnace, both on account of variation of temperature and of the chemical changes in the charge. In order to work economically, it is usually important that the maximum power available be used throughout the furnace run, and if the resistor changes its resistance it is necessary to provide some means of regulating the voltage, and the maximum and minimum voltages attainable must have to each other the ratio of the square roots of the maximum and minimum resistance of the resistor (FitzGerald). If carbon is used as a resistor, it is advisable to raise it previously to the maximum temperature to which it will be submitted in practice. The best plan is to use graphitized carbon, for that form of carbon is stable in its physical characteristics so that the only change that is experienced when using it as a resistor is temporary and due to the increase in temperature.

108. Direct current and alternating current may both be used for operation of an electric furnace, but alternating current has two advantages: first, electrolytic effects which are not desired in pure electric-furnace reactions, are excluded; second, alternating current permits easier regulation. The induction furnace always requires alternating current.

109. Rheostats. As rheostats for voltage regulation, water rheostats or granular-carbon rheostats are suitable. (For details see F. A. J. FitzGerald, *Electrochemical and Metallurgical Industry*, Vol. III, p. 9).) Rheostat design, see Sec. 5).

110. Tube furnace. A special type of resistor furnace for experimental work which permits very exact regulation of temperature, is the tube furnace, *i.e.*, an electric furnace in which the resistor has the form of a tube. For various designs of such furnaces see Hutton and Patterson, *Electrochemical and Metallurgical Industry*, Vol. III, p. 455; S. S. Sadtler, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 434; S. A. Tucker, *Electrochemical and Metallurgical Industry*, Vol. V. p. 227; J. A. Harker, *Electrochemical and Metallurgical Industry*, Vol. III, p. 273; William C. Arsem, *Transactions* American Electrochemical Society, Vol. IX; and especially the elaborate designs of H. N. Potter, U. S. Patents, 715507; 715508; 715509; Dec. 9, 1902; 719507, Feb. 3, 1903; 756891, April 12, 1904; 770312, Sept. 20, 1904; 814726 and 814727, March 13, 1906. Tube furnaces may be so constructed as to carry out the reaction either under increased or reduced pressure, as in the furnace of Arsem and the last two patents of Potter.

111. In another special type of resistor furnace, due to FitzGerald and Thomson, the charge is heated by radiation from a resistor above the charge; this furnace has been applied for zinc smelting (*Met. & Chem. Eng'ing*, Vol. VIII, pp. 289, 317). Various materials are suitable for the resistors, according to the special design of the furnace, such as granular carbon ("kryptol"), carbon rods, silundum rods, platinum strip or wire, nickel strip

860 kg-cal. from burning $\frac{10}{m}$ kg. coal is $\frac{a}{90.7\,m}$ dollars. On the other hand, if the cost of 1 kw-hr. is b cents and if the efficiency of producing heat from electrical energy is n per cent. then the cost of 860 kg-cal. from $\frac{100}{n}$ kw-hr. is $\frac{b}{n}$ dollars. Hence electric heat will be cheaper than heat produced by combustion of fuel if an is greater than 90.7 bm.

If we assume efficiency figures which are not unfair under practical conditions, namely an efficiency $m = 25$ per cent. for fuel heating and an efficiency $n = 75$ per cent. for electric heating, then electric heat is cheaper than fuel heat if a is larger than 30.2 b, *i. e.*, if the cost of 1 ton of coal in dollars is more than 30.2 times greater than the cost of 1 kw-hr. in cents. For instance to compete with coal at $6 per ton, the electric kilowatt-hour would have to cost less than ¼ cent. This shows that were it not for its other important features, electric heat could not compete with fuel heat under ordinary conditions. If we had an electric furnace process which would work continuously with full load all year, then the cost of the electric horsepower-year will be 65.7 b dollars; hence electric heat will be cheaper than fuel heat if the cost of 1 ton of coal in dollars is more than $\frac{30.2}{65.7}$ or say, one-half the cost of the electric horsepower-year. This is apparently a more favorable view of the situation, especially in neighborhoods where fuel is expensive and water-power is really cheap (say below $10 per electric horsepower-year). But unless absolute continuity of the process is assured, it is safer to base such calculations on the cost of the kilowatt-hour instead of the horsepower-year.

COMMERCIAL PRODUCTS OF THE ELECTRIC FURNACE

118. A brief summary of the most important commerical products of the electric furnace will now be given. Concerning the production of various modifications of carbon (including artificial diamonds) and the production of chromium, manganese, molybdenum, tungsten, uranium, vanadium, zirconium, as well as carbides, silicides, borides, phosphides, arsenides and sulphides on an experimental scale, see Moissan's "Electric Furnace." A very useful bibliography on borides and silicides may be found in O. P. Watts, "Investigation of the Borides and the Silicides," Bulletin University of Wisconsin, No. 145. A. Stansfield's "Electric Furnace" is a reliable and concise descriptive book. Askenasy's "Einführung in die technische Elektrochemie," Vol. I (Electrothermie) contains valuable information on various electric furnace processes. Concerning new proposed applications of the electric furnace the reader is referred to the current abstracts of new electrochemical patents in *Met. & Chem. Eng'ing.* The following list includes only the most important products which are made in the electric furnace on an industrial scale.

119. Artificial graphite is made by the processes of E. G. Acheson in three forms: hard graphite in bulk, suitable for paint, pigment, etc.; artificial graphite electrodes for electric furnace and electrolytic work; soft graphite suitable as lubricant, stove polish, etc. See descriptions of the three processes in *Electrochemical and Metallurgical Industry*, Vol. III, p. 416 and Vol. IV, p. 502, Vol. VII, p. 187.

Concerning the conditions of transformation of amorphous carbon into graphite see Arsem, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 105.

120. Silicon Carbide* (trade names carborundum, crystolon) is made by the process of E. G. Acheson from a charge of carbon, sand and salt, the essential reaction being $SiO_2 + 3C = SiC + 2CO$. The chief uses of carborundum are as an abrasive and a refractory.

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* Descriptions of the silicon carbide furnace in *Electrochem. & Met. Ind.* Vol. IV, p. 53; Vol. VII, 189; *Met. & Chem. Eng'ing*, Vol. X, p. 519, 685. Concerning the temperature of the silicon carbide furnace, see Saunders. *Met. & Chem. Eng'ing*, Vol. X, p. 287.

V, p. 407). Concerning the electric distillation of turpentine see F. T. Snyder, *Transactions* Am. Electrochem. Soc., Vol. XIII.

129. Calcium carbide (CaC_2) production is one of the largest and most important electric-furnace industries (T. L. Wilson, H. Moissan, L. M. Bullier). The reaction is

$$CaO + 3C = CaC_2 + CO, \tag{27}$$

the furnace charge consisting of burnt lime and ground coke. The chief use of calcium carbide is the production of acetylene gas C_2H_2 for lighting according to the equation:

$$CaC_2 + H_2O = CaO + C_2H_2, \tag{28}$$

acetylene gas being developed when calcium carbide comes into contact with water.* **Calcium cyanamide** is made from calcium carbide and nitrogen. See Par. **263**.

130. The application of the electric furnace in other branches of non-ferrous metallurgy is largely experimental.† Experiments have been made on electric smelting of copper ores,‡ nickel ores,§ and tin ores.‖

131. Ferro-alloys,¶ as well as other alloys, like copper-silicon, are made in the electric furnace according to the old process of A. H. Cowles, by treating a mixture of pig iron (or copper in the case of copper alloys), an oxide of the element to be alloyed with the iron (*e.g.*, silica in the case of ferrosilicon) and carbon. Various variations are possible. The production of ferro-alloys in the electric furnace is a commercial success; various alloys, especially those of high percentage and low in carbon, can only be made in the electric furnace. The usual reducing agent is carbon. But silicon or ferrosilicon or carborundum have also been proposed for the production of other ferro-alloys, free from carbon.

132. In the steel industry** the electric furnace is rapidly increasing in importance for three purposes. The first†† is the manufacture of high-grade steel in competition with the crucible steel process, being considerably cheaper on account of larger units and smaller wages, while the product of the electric furnace is as good as that of the crucible steel process and it is not necessary to use as pure and expensive starting materials. The second application‡‡ is a more recent one, for the refining of molten Bessemer converter metal or molten open-hearth metal for large-tonnage products, like rails of improved quality. For steel refining in the electric furnace the possibility of producing a higher temperature in the slag§§ is important, but of

* Concerning the thermodynamic theory of the process see Thompson, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 279 and 324.

† Concerning possible applications of the electric furnace to Western metallurgy, see Lyon and Keeney, *Met. & Chem. Eng'ing*, Vol. XI, p. 577. As to vacuum furnace metallurgy for the treatment of rebellious ores, such as sulphite, Nipissing ore, for the production of antimony from stibnite, see Fink, *Met. & Chem. Eng'ing*, Vol. X, p. 296. As to the use of the electric furnace for the treatment of tin dross concentrates from cyanide mills, etc., see Wile, *Met. & Chem. Eng'ing*. Vol. X, p. 495.

‡ Stephan, *Met. & Chem. Eng'ing*, Vol. XI, p. 22; Lyon and Keeney, Vol. XI, p. 522.

§ Morrison. *Transact.* Am. Electrochem Soc., Vol. XX, p. 315.

‖ Harden. *Met. & Chem. Eng'ing*, Vol. IX, p. 453.

¶ G. P. Scholl. *Electrochem. Ind.*, Vol. II, pp. 349, 395, 449; Keeney, *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 167. Concerning ferrosilicon see Pick and Conrad's German monograph, also Copeman, Bennett & Hake, *Met. & Chem. Eng'ing*, Vol. VIII, p. 133.

** A very good review of the situation in 1909 may be found in the symposium of papers on the electrometallurgy of iron and steel in *Transact.* Am. Electrochem. Soc., Vol. XV. See also Eugene Haanel's first Canadian Government report of 1904, and Neumann's Electrometallurgie des Eisen.

†† For instance, *Met. & Chem. Eng'ing*, Vol. VIII, p. 563.

‡‡ Description of South Chicago plant of the U. S. Steel Corporation, *Met. & Chem. Eng'ing*, Vol. VIII, p. 179. See also Walker, *Met. & Chem. Eng'ing*, Vol. X, p. 371, and Osborne, *Transact.* Am. Electrochem. Soc., Vol. XIX, p. 205.

§§ As to the function of slag see Amberg, *Met. & Chem. Eng'ing*, Vol. X, p. 601.

there is nothing but a heat effect. At the junction of a metal and an electrolyte there is either chemical oxidation or reduction according to the direction of the current. At the junction of two electrolytes there is neither oxidation nor reduction, though there may be a chemical change (*e.g.*, at the junction of NaCl and KOH, if the current is directed from the former to the latter, there will be formation of NaOH).

137. The most important electrolytes for industrial applications are: first, **solutions**, and especially aqueous solutions or solutions in water, and second, **fused salts**.

138. Cells. An electrolyte with two electrodes represents either a **galvanic cell**, *i.e.*, an electrochemical system through which a current will be voluntarily established when the two electrodes are electrically connected through an outside circuit (in other words an electrochemical system which can be used as a source of electricity), or an **electrolytic cell**, *i.e.*, an electrochemical system through which an electric current will be established if the outside circuit connected to the two electrodes contains a sufficiently strong source of electrical energy.

139. Galvanic cells. In the case of a galvanic cell or battery the **energy equation** written on the basis of Thomson's rule states that the chemical energy consumed in the cell is partly lost in form of Jourlean heat within the cell ($I^2R \times$ time) the balance being available in form of electrical energy in the outside circuit between the terminals of the cell. If this energy equation, the symbols of which represent gram-equivalents, is divided by 96,540 coulombs, *i.e.*, the electric charge of 1 gram-equivalent, the voltage equation is obtained which states that the electromotive force of the cell in volts equals the loss of the volts within the cell due to internal resistance (IR), plus the voltage available at the terminals of the cell. This is correct for a monovalent change. If the change of valency is n, the energy equation is to be divided by $96{,}540 \times n$.

140. Electrolytic cells. In the case of an electrolytic cell through which electricity is forced from the outside, the energy equation states that the electrical energy impressed upon the cell at its terminals from the outside is partly changed into the chemical energy required for the chemical process in the cell and partly changed into Joulean heat ($I^2R \times$ time). In many cases, when the process requires an elevated temperature, especially in the electrolysis of fused salts, this evolution of Joulean heat serves a useful purpose, since it is the easiest way of providing the requisite high temperature (as in the Bradley "internal heating" patent of the aluminium process). The corresponding voltage equation states that the voltage impressed at the terminals of the cell from the outside equals the electromotive force required for the chemical reaction according to Thompson's rule plus the volts lost in the cell due to internal resistance.

141. The model of migrating ions is a picture of electrolytic phenomena. It is a dynamical model which has been found exceedingly useful to illustrate what happens in an electrolytic cell. Any electrolyte contains positive ions or cations and negative ions or anions.

142. Typical anions are:

(a) **monovalent** (each gram-ion carrying a negative charge of 96,540 coulombs):

Br	in hydrobromic acid and bromides,
Cl	in hydrochloric acid and chlorides,
I	in hydriodic acid and iodides,
Fl	in hydrofluoric acid and fluorides,
OH	(hydroxyl ion) in hydroxides or hydrates,
BrO_3	in bromic acid and bromates,
ClO_3	in chloric acid and chlorates,
IO_3	in iodic acid and iodates,
NO_3	in nitric acid and nitrates,
CN	(cyanogen radical),
CHO_2	in formates,
$C_2H_3O_2$	in acetates.

(b) **bivalent** (each gram-ion carrying a negative charge of $2 \times 96{,}540$ coulombs):

SO_4	in sulphates,

146. The method of determining the mobilities, u **and** v, separately consists in determining their sum and their ratio. According to Faraday's law if q coulombs pass through a cell, $\frac{q}{96{,}540}$ positive monovalent gram-ions (or $\frac{q}{2\times 96{,}540}$ positive bivalent gram-ions, etc.) are concerned in the reduction at the cathode and the same number of negative gram-ions in the oxidation at the anode. According to the picture of migrating ions this means that when q coulombs pass, the sum of the number of positive monovalent gram-ions passing through any imaginary cross-section of the cell toward the cathode and of the number of negative monovalent gram-ions passing through the same cross-section in the opposite direction is $\frac{q}{96{,}540}$.

147. Conductivity proportional to the sum of the mobilities. In other words, when there is a current of i amperes through an electrolytic cell, the sum of the numbers of positive and negative monovalent gram-ions passing per sec. in opposite directions through any imaginary cross-section of the cell is $\frac{i}{96{,}540}$. This sum of the numbers of positive and negative gram-ions passing per sec. is, of course, directly proportional to the sum of their speeds or to the voltage drop per unit length of electric line of force multiplied by the sum of their mobilities. Hence, the sum of the mobilities, $u+v$, is proportional to the current in amperes divided by the voltage drop, hence proportional to the conductance and also proportional to the conductivity of the electrolyte.

148. Constant of proportionality. The statement that $u+v$ is proportional to the conductivity will now be supplemented by finding the constant of proportionality. For this purpose we necessarily need a further hypothesis as to the number of ions we have to assume for a given number of molecules.

149. Equivalent ionic concentration. Formerly it was silently assumed that in a fused salt all the molecules of the salt participate equally in the transport of electricity, while in the case of solutions the solvent (for instance, water) was assumed to be inert, and all the molecules of the solute (the dissolved salt) were assumed to participate equally in the transport of electricity. Hence for a fused salt the equivalent ionic concentration was defined as the number of positive monovalent gram-ions per c.c. = number of negative monovalent gram-ions per cu. cm. = number of gram-molecules of the fused salt multiplied by valency per cu. cm. For a solution the equivalent ionic concentration was defined as the number of positive monovalent gram-ions per cu. cm. = number of negative monovalent gram-ions per cu. cm. = number of the gram-molecules of dissolved salt per volume multiplied by valency per cu. cm.

150. Dissociation theory. For fused salts our conceptions have not yet been decidedly changed, while a decided change has been brought about for solutions by Arrhenius' electrolytic dissociation theory. According to him only a certain number of the dissolved salt molecules are ionised and only these are active in the transport of the electricity, while the non-ionized dissolved salt molecules, like the molecules of the solvent, are electrically inert. If we write j for the ratio of the number of ionized molecules to the total number of dissolved molecules where j is smaller than unity, the equivalent ionic concentration is defined as the number of positive monovalent gram-ions per cu. cm. = number of negative monovalent gram-ions per cu. cm. $= jc$, where c is the number of gram-equivalents of dissolved salt per cu. cm.

151. Universal formula for use in calculations. We render our calculations general by using the factor j. For fused salts we have to make $j = 1$, while for solutions we are free to take our choice. If we make $j = 1$, we follow the old conception, while if we make j smaller than unity we are on the basis of the electrolytic dissociation theory. For a given fused salt of uniform constitution, c, has a fixed value depending on the density, while for a solution c is variable according to the degree of concentration. As can be easily shown, in the statement that conductivity is proportional to the sum of mobilities, the constant of proportionality has the value $96{,}540\,jc$. In other

156. Equivalent Conductivities of Aqueous Solutions at 18 Deg. Cent.

Gram-equivalents per liter	KCl	NaCl	KNO_3	$AgNO_3$	$\frac{1}{2}CuSO_4$	$\frac{1}{2}H_2SO_4$	HCl	CH_3COOH	KOH	NH_3	Liters in which gram-equivalent is dissolved
0.0001	129.07	108.10	125.50	115.01	109.95			107.		(66)	10000.
0.0002	128.77	107.82	125.18	114.56	107.90			80.		53.	5000.
0.0005	128.11	107.18	124.44	113.88	103.56	(368)		57.		38.0	2000.
0.001	127.34	106.49	123.65	113.14	98.56	361.	(377)	41.	(234)	28.0	1000.
0.002	126.31	105.55	122.60	112.07	91.94	351.	376.	30.2	(233)	20.6	500.
0.005	124.41	103.78	120.47	110.03	80.98	330.	373.	20.0	230.	13.2	200.
0.01	122.43	101.95	118.19	107.80	71.74	308.	370.	14.3	228.	9.6	100.
0.02	119.96	99.62	115.21		62.40	286.	367.	10.4	225.	7.1	50.
0.05	115.75	95.71	109.86	99.50	51.16	253.	360.	6.48	219.	4.6	20.
0.1	112.03	92.02	104.79	94.33	43.85	225.	361.	4.60	213.	3.3	10.
0.2	107.96	87.73	98.74		37.66	214.	342.	3.24	206.	2.30	5.
0.5	102.41	80.94	89.24	77.5		205.	327.	2.01	197.	1.35	2.
1. (normal)	98.27	74.35	80.46	67.6	25.77	198.	301.	1.32	184.	0.89	1.
2.	92.6	64.8	69.4			183.0	254.	0.80	160.8	0.532	0.5
3.	88.3	56.5	(61.3)			166.8	215.0	0.54	140.6	0.364	0.33
5.		42.7				135.0	152.2	0.285	105.8	0.202	0.2

Doubtful values are given parentheses.

157. The increase of equivalent conductivity with increasing dilution may be interpreted in different ways on the basis of the picture of migrating ions. Since conductivity $= 96{,}540\, j\, c\, (u+v)$, equivalent conductivity $= 96{,}540\, j\, (u+v)$.

First, according to the old view, all dissolved gram-equivalents participate equally in the transport of the electricity and $j = 1$; hence equivalent conductivity $= 96{,}540\, (u+v)$. Since the equivalent conductivity increases with increasing dilution, we must assume that the sum of the mobilities simultaneously increases.

Secondly, according to Arrhenius' electrolytic dissociation theory, u and v do not change, but the degree of ionisation j changes with dilution. With increasing dilution, j must be assumed to increase until for infinite dilution it reaches a certain definite value. j is the ratio of the number of ionized molecules to the total number of dissolved molecules. For infinite dilution $j = 1$, *i.e.*, all molecules are ionized. The less the dilution or the higher the concentration, the smaller is j, *i.e.*, the smaller the degree of ionization or the smaller the proportion of dissolved gram-equivalents which are ionized.

158. Conductivity of electrolytes. Concerning the measurement of the conductivity of electrolytes see Kohlrausch and Holborn's "Leitvermögen der Elektrolyte." This book contains an enormous amount of detailed information and of figures of conductivities of aqueous solutions. Concerning fused electrolytes see R. Lorenz' "Electrolyse geschmolzener Salze," 3 volumes (figures of conductivities in Vol. II).

159. Determination of the ratio of u to v. From Faraday's law and

The net result in the anode compartment is the setting free of 1 gram-atom Cl gas and the loss in solution of 0.4 gram-molecule NaCl.

In the cathode compartment we have;

Loss, by gas evolution at cathode, of	1 gram-ion H,
Loss, by ionic export to anode compartment, of	0.6 gram-ion Cl,
gain, by ionic import from anode compartment, of	0.4 gram-ion Na,
gain, by chemical formation of NaOH of	1 gram-ion OH,
Loss, by the same reaction, of	1 gram-molecule H_2O.

The net result in the cathode compartment is the setting free of 1 gram-atom H gas, the loss in solution of 1 gram-molecule of water, while the solute NaCl has now been changed into a mixture of NaCl and NaOH since the positive ions have been increased by 0.4 Na gram-ions, while the negative ions have gained 1 OH gram-ion and lost 0.6 Cl gram-ion. This latter change we may chemically express in the statement that 0.6 gram molecule NaCl have disappeared and 1 gram-molecule NaOH has been formed. (For a somewhat different and more detailed discussion of this reaction see W. H. Walker, *Transactions* American Electrochemical Society, Vol. III, p. 177.)

162. Migration Mobilities of Cations

	u_{18}	α	β
H	318.	+0.0154	−0.000033
K	64.87	.0220	+ .000075
Na	43.55	.0245	.000116
Li	33.44	.0261	.000142
Rb	67.6	.0217	.000069
Cs	68.2		
NH_4	64.4	.0223	.000079
Tl	66.00		
Ag	54.02	.0231	.000093
½ Ba	55.10	.0239	.000106
½ Sr	51.54	.0231	.000093
½ Ca	51.46		
½ Mg	45.94	.0255	.000132
½ Zn	46.57	.0256	.000133
½ Cd	47.35		
½ Cu	47.16	.0240	.000107
½ Pb	61.10	.0244	.000114

162. Migration Mobilities of Anions

	v_{18}	α	β
OH	174.	+0.0179	+0.000008
F	46.64	0.0232	.000094
Cl	65.44	.0215	.000067
Br	67.63		
I	66.40	.0206	.000052
SCN	56.63		
ClO_3	55.03	.0207	.000054
BrO_3	46.2		
IO_3	33.87	.0233	.000096
NO_3	61.78	.0203	.000047
ClO_4	64.7		
IO_4	47.7		
MnO_4	53.4		
CHO_2	46.7		
$C_2H_3O_2$	35.0	.0236	.000101
$C_3H_5O_2$	31.0		
$C_4H_7O_2$	27.6		
$C_5H_9O_2$	25.7		
$C_6H_{11}O_2$	24.3		
½ $(COO)_2$	62.6		
½ SO_4	68.14	.0226	.000084
½ CrO_4	72.0		
½ CO_3	60.0	.0269	.000155

167. Electric endosmosis. Since the above reaction is that of the so-called diaphragm processes of brine electrolysis, it should be mentioned here that the introduction of a diaphragm into an electrolytic cell involves a further complication since it causes the phenomenon of electric endosmosis. Solution is bodily carried through the diaphragm, the amount depending on the nature of the diaphragm. This phenomenon may upset all results of calculation of concentration changes from the transport numbers of ions. This phenomenon is the reverse of the migration of colloids in solutions under the action of a current. The colloids correspond to the diaphragm in our former case, but the colloids are movable, while in our former case the diaphragm was fixed. Hence in our former case the liquid will be displaced with respect to the diaphragm. In the latter case the colloids move with respect to the stationary liquid.

168. Short-cut calculations of electrochemical reactions. It is strongly recommended to proceed in the way outlined above in making all calculations on electrochemical reactions; since in this way not only all questions as to details of the reaction are answered, but a clear picture of the mechanism of the reaction is obtained. With ordinary care it is then almost impossible to make a mistake. Nevertheless, for checking results thus obtained or for quick preliminary calculations, tables of electrochemical equivalents are found useful. We give two of them: Par. **166** referring to the electrochemical equivalents of all ordinary ions, Par. **170 to 172** to the electrochemical equivalents of the elements.

From Par. **166** one can find immediately by simple addition for most compounds of ordinary practice the **quantity of material involved in electrolysis.** For instance, for the reaction of sodium chloride electrolysis in a diaphragm cell

$$NaCl + H_2O = NaOH + Cl + H, \qquad (33)$$

we find directly from the table that 1 amp-hr. produces 0.03759 g. H and 1.322 g. Cl. We can further find the quantity of NaCl decomposed per ampere-hour, by adding the figures 0.860 (Na) and 1.322 (Cl), which gives 2.182 grams NaCl. In the same way the quantity NaOH formed per ampere-hour is found by adding 0.860 (Na) and 0.634 (OH), which gives 1.494 g. NaOH.

An important precaution which one has to take in the use of this table, is to **select** the ion of the **proper valency.** Thus it will be seen that figures are given for the monovalent $Cu^{\cdot}$ and for the bivalent $Cu^{\cdot\cdot}$ ion. In case of the bivalent compound $CuSO_4$, for instance, one has to select the figure for $Cu^{\cdot\cdot}$ and finds the quantity of $CuSO_4$, decomposed per hr. = 1.186 + 1.791 = 2.977 g. (Concerning the necessity of using this table cautiously and judiciously, see also Par. **169.**)

Par. **170** to **172** are tables of electrochemical equivalents of elements and answers directly the question as to the **quantity of the element oxidized at the anode or reduced at the cathode.** Since oxidation and reduction are special cases of change of valency, column 4 is headed "change of valency," as this covers the most general case. In the special case that a metal is deposited from a solution or that a gas is evolved at an electrode, it is to be considered that the metal or the gas has no bonds in the free elementary state, so that in this case the change of valency is equal to the valency in the compound. For instance, in the reduction of Cu from CuCl the change of valency is 1, while in the reduction of Cu from $CuSO_4$, it is 2.

In column 4 those changes of valency are given which are most likely to occur in practice. Thus, for iron, Fe, the figures are given for the changes of valency 1, 2, 3. In the reduction of a ferric salt to a ferrous salt the change of valency is 1; in the reduction of a ferric salt to metallic iron it is 3; in the reduction of a ferrous salt to metallic iron it is 2. But for every element the figures are also given for the indefinite change of valency, *n*, so as to cover any possible case which may ever arise in practice. To give an example of the application of this table, let us assume that in the Bunsen cell nitric acid, HNO_3, is all reduced to nitric oxide, NO, and let us calculate the quantity of nitric acid thus consumed per ampere-hour. Since the valency of N is 5 in HNO_3 and 2 in NO, the change of valency of N is 3. From the table we find directly that for this change of valency 0.174 g. of N are involved in the reduction per ampere-hour. The amount of HNO_3 consumed and of NO produced is then found by the ordinary chemical method. The atomic weight of N is 14, the molecular weight of HNO_3 is $1+14+3\times16=63$, the

170. Electrochemical Equivalents of Elements.—(*Continued*)

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Chromium..........	Cr	52.1	3	0.648	1.544
			n	1.943 ÷*n*	0.515 ×*n*
Cobalt.............	Co	59.0	2	1.100	0.909
			n	2.200 ÷*n*	0.4545×*n*
Columbium.........	Cb	94.	2	1.753	0.571
			n	3.505 ÷*n*	0.2853×*n*
Copper............	Cu	63.6	2	1.186	0.843
			1	2.372	0.4216
			n	2.372 ÷*n*	0.4216×*n*
Erbium............	Er	166.	3	2.063	0.4846
			n	6.19 ÷*n*	0.1615×*n*
Europium..........	Eu	152.	*n*	5.67 ÷*n*	0.1764×*n*
Fluorine...........	F	19.0	1	0.709	1.411
			n	0.709 ÷*n*	1.411 ×*n*
Gadolinium	Gd	156.	*n*	5.82 ÷*n*	1.719 ×*n*
Gallium...........	Ga	70.0	3	0.870	1.149
			n	2.610 ÷*n*	0.383 ×*n*
Germanium........	Ge	72.5	4	0.676	1.480
			2	1.352	0.740
			n	2.704 ÷*n*	0.3699×*n*
Glucinum..........	Gl	9.1	2	0.1697	5.89
			n	0.3393÷*n*	2.947 ×*n*
Gold..............	Au	197.2	3	2.451	0.4080
			2	3.677	0.2720
			1	7.35	0.1360
			n	7.35 ÷*n*	0.1360×*n*
Helium............	He	4.0	*n*	0.1492÷*n*	6.70 ×*n*
Hydrogen..........	H	1.008	1	0.03759	26.60
			n	0.03759÷*n*	26.60 ×*n*
Indium............	In	115.0	3	1.429	0.700
			n	4.288 ÷*n*	0.2332×*n*
Iodine.............	I	126.97	1	4.735	0.2112
			n	4.735 ÷*n*	0.2112×*n*
Iridium............	Ir	193.0	3	2.399	0.417
			1	7.20	0.139
			n	7.20 ÷*n*	0.139 ×*n*
Iron...............	Fe	55.9	3	0.695	1.439
			2	1.042	0.959
			1	2.085	0.4797
			n	2.085 ÷*n*	0.4797×*n*

170. Electrochemical equivalents of elements.—(*Continued*)

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Potassium........	K	39.15	1	1.460	0.685
			n	1.460÷n	0.685×n
Praseodymium....	Pr	140.5	3	1.746	0.573
			n	5.24 ÷n	0.1909×n
Radium..........	Rd	225.0	n	8.39 ÷n	0.1192×n
Rhodium.........	Rh	103.0	2	1.921	0.521
			1	3.841	0.260
			n	3.841÷n	0.260×n
Rubidium........	Rb	85.5	1	3.188	0.3136
			n	3.188÷n	0.3136×n
Ruthenium.......	Ru	101.7	4	0.948	1.055
			2	1.896	0.5274
			1	3.792	0.2637
			n	3.792÷n	0.2637×n
Samarium........	Sa	150.3	3	1.868	0.535
			n	5.61 ÷n	0.1784×n
Scandium.........	Sc	44.1	3	0.548	1.824
			n	1.645÷n	0.608 ×n
Selenium.........	Se	79.2	4	0.738	1.354
			2	1.477	0.677
			n	2.953÷n	0.3386×n
Silicon...........	Si	28.4	4	0.2648	3.777
			n	1.059÷n	0.944 ×n
Silver............	Ag	107.93	1	4.025	0.2485
			n	4.025÷n	0.2485×n
Sodium...........	Na	23.05	1	0.860	1.163
			n	0.860÷n	1.163 ×n
Strontium........	Sr	87.6	2	1.633	0.612
			n	3.267÷n	0.306 ×
Sulphur..........	S	32.06	2	0.598	1.673
			1	1.196	0.836
			n	1.196÷n	0.836 ×n
Tantalum........	Ta	181.0	5	1.350	0.741
			n	6.75 ÷n	0.1482×n
Tellurium.........	Te	127.6	4	1.190	0.841
			2	2.379	0.4203
			n	4.758÷n	0.2102×n
Terbium..........	Tb	159.2	3	1.979	0.505
			n	5.94 ÷n	0.1684×n

To find **ampere-seconds per milligram** multiply ampere-hours per gram (column 6) by 3.6.

To find **grams per watt-hour** or **kilograms per kilowatt-hour**, divide grams per ampere-hour (column 5) by volts.

To find **watt-hours per gram** or **kilowatt-hours per kilogram**, multiply ampere-hours per gram (column 6) by volts.

To find **kilograms per horsepower-hour**, multiply grams per ampere-hour (column 5) by 0.74565 (about ¾) and divide by volts.

To find **horsepower-hours per kilogram**, multiply ampere-hours per gram (column 6) by 1.3411 (about ⁴⁄₃) and by volts.

To find **kilograms per electric horsepower-year**, multiply grams per ampere-hour (column 5) by 6,532 and divide by volts.

THE E.M.F. OF ELECTROLYTIC REACTION

173. E.m.f. and terminal voltage. We have before explained that it is necessary to distinguish clearly between the voltage at the terminals of an electrolytic cell, and the e.m.f. of the electrolytic process proper (Par. **140**). We have also shown how to calculate approximately the latter e.m.f. by means of Thomson's rule from the total energy of reaction, while it should strictly be calculated from the free energy of reaction (Par. **58**). The easiest method to determine the latter, however, is by measurements of potential.

174. Single potentials of elements are determined against normal electrodes or standard electrodes. The most usual normal electrodes are the **hydrogen electrode** (platinized platinum, saturated and covered with hydrogen gas, in an acid solution of normal concentration of the hydrogen ions), and the **calomel electrode** (mercury covered with calomel, HgCl, in contact with a normal KCl solution). In order to have a zero point in the potential series of elements, Nernst proposes to make the potential of hydrogen zero. On this supposition the calomel electrode has the potential −0.283; in other words if we form a cell of a calomel electrode and a hydrogen electrode, it has the e.m.f. −0.283, the current in the cell being directed from the latter to the former. On the basis of a theory of Helmholtz on the surface tension of polarized mercury, Ostwald has endeavored to determine "absolute potentials;" in the absolute series the hydrogen electrode has the absolute potential −0.277 volt and the calomel electrode the absolute potential −0.560 volt. But this theory is very doubtful.

175. Potential of Various Elements in Order of Their Nobility

	Potential against hydrogen electrode	Absolute potential
Mn	+1.075 volt	+0.798 volt
Zn	+0.770	+0.493
Cd	+0.420	+0.143
Fe	+0.344 (0.660)	+0.067 (+0.383)
Tl	+0.322	+0.045
Co	+0.232 (0.450)	−0.045 (+0.173)
Ni	+0.228 (0.600)	−0.049 (+0.323)
Pb	+0.151 (0.148)	−0.126 (−0.129)
H	±0.0 (by definition)	−0.277
Cu	−0.329	−0.606
Hg	−0.753 (0.750)	−1.030 (−1.027)
Ag	−0.771 (0.798)	−1.048 (−1.075)
Cl	−1.353 (1.400)	−1.630 (−1.677)
Br	−0.993 (1.095)	−1.270 (−1.372)
I	−0.520 (0.628)	−0.797 (−0.905)

176. Order of nobility of elements. The table in Par. **175** gives in the first column the series of elements in the order of their nobility; those above H are called less noble than H, those below H are called more noble than H. A less noble metal passes into solution when in contact with hydrogen ions, a more noble metal is not attacked. The second and third columns give the potentials of the elements in a normal solution of one of their salts, for instance, silver in a silver salt solution. In the second column Nernst's these tables rests in giving the "thermochemical constants" and the corresponding voltages separately for the basic elements and the acid elements and acid radicals. This separation of the two constituents of a salt in solution is possible on account of the experimental fact that taking the heats of formation of salts plus their heat of solution in excess of water (usually called "heat of formation to dilute solution"), these quantities are found to be additive in their nature, such being composed of the sum of two quantities, one characteristic once for all of the base, in all its combinations, and the other being characteristic once for all of the acid radical, in all of its combinations. There is thus for each basic element a thermochemical constant, which represents the amount of heat it contributes to the formation-heat of a salt, the latter taken in dilute solution; and for each acid radical a similar thermochemical constant, representing in a similar manner the part which it contributes; the sum of these two thermochemical constants is the formation heat of the salt, from its elements, to dilute solution. The thermochemical constant is nothing more nor less, in the case of a base, than energy drop which represents the decrease of energy in the element as it passes from the free, uncombined state into the dissolved (ionic) state in dilute solution; in the case of an acid element, the statement is entirely similar; in the case of an acid (or basic) radical, it is the total energy drop from free elements to the ionic state as a radical.

The arbitrary basis selected to which to refer these thermochemical constants is that of hydrogen constant equal to zero. This makes the thermochemical constant of every basic element the heat evolved when it displaces hydrogen from a dilute solution of acid; and that of an acid element or radical the heat of formation of the acid in dilute solution.

The "corresponding voltages" given are therefore those which according to Thomson's rule should be found against a "hydrogen electrode." The figures may therefore be compared with the table in Par. 175 of voltages of various metals against a hydrogen electrode. The difference between the values of the two tables correspond to the differences in the free energy and the total energy. For many elements the agreement is quite good. Thus for Zn the voltage corresponding to the free energy is 0.770, that corresponding to the total energy is 0.75.

181. Thermochemical Constants of Basic Elements per Chemical Equivalent and Corresponding e.m.f.

(J. W. Richards)

	Calories	Volts		Calories	Volts
Li	+62,900	+2.73	Cd	9,000	0.36
Rb	62,000	2.69	Co	8,200	0.36
K	61,900	2.69	Ni	7,700	0.33
Ba	59,950	2.60	Fe (ferric)	3,230	0.14
Sr	58,700	2.55	Sn	1,900	0.08
Na	57,200	2.48	Pb	400	0.02
Ca	54,400	2.36	H	0	0
Mg	54,300	2.36	Tl	− 900	−0.04
Al	40,100	1.74	Cu	− 7,900	−0.34
$(N+H_4)$	33,400	1.45	Hg	−14,250	−0.62
Mn	24,900	1.08	Pt	−19,450	−0.84
Zn	17,200	0.75	Ag	−25,200	−1.10
Fe (ferrous)	10,900	0.47	Au	−30,300	−1.32

The thermochemical constants in Dr. Richards' table are given in every case for *one* chemical equivalent and not for the number of equivalents which are designated by the number of dots (positive bonds) or strokes (negative bonds). In using these tables, it must be borne in mind that the sum of the thermochemical constants for the basic and acid constituents of any salts, gives the heat of formation of the salt from the constituent chemical elements, in dilute solution. Conversely, the heat of formation thus obtained is the energy necessary to separate the salt in dilute solution into its constituent chemical elements. The sum of the voltages, corresponding to this amount of chemical energy, is the voltage necessary to decompose the salt in solution into its constituents, free chemical elements. If these elements re-combine in the process of decomposition to form other chemical compounds, then the whole chemical reaction must be taken into

183. Thermochemical Constants of Acid Elements
(J. W. Richards)

	Per chemical equivalent, calories	Corresponding e.m.f. volts	Salt
F_2'' (gas)	+52,900	+2.30	Fluoride
Cl_2'' (gas)	39,400	1.71	Chloride
Br_2'' (gas)	32,300	1.40	Bromide
Br' (liquid)	28,600	1.20	Bromide
Br' (solid)	27,300	1.18	Bromide
I_2'' (gas)	20,000	0.87	Iodide
I' (liquid)	14,600	0.63	Iodide
I' (solid)	13,200	0.57	Iodide
S'' (solid)	− 5,100	−0.22	Sulphide
Se'' (met.)	−17,900	−0.78	Selenide

INDUSTRIAL ELECTROLYTIC PROCESSES

184. Electroanalysis. As to electroanalysis reference should be had to the book of Edgar F. Smith or to that by A. Classen. The chief reason why electroanalytical methods have found introduction into industrial laboratories is the great ease and the very considerable reduction in time required for an analysis as a consequence of recent improvements mainly due to E. F. Smith and his school. The chief features of these improvements are the use of a rotating anode and of a mercury cathode. The mercury cathode absorbs the metal of the salt solution which is electrolysed. The anode is generally made of such a substance as to absorb the anion. The anode is rapidly revolved to provide such a circulation of the electrolyte that a high current density may be used with a corresponding reduction in the duration of an analysis. Concerning rapid methods of electroanalysis see the latest edition of Smith's "Electroanalysis."

185. Electrotyping. The object of electrotyping is to reproduce printers set-up type, engravings, medals, etc. A mould of the object to be reproduced is first made, for instance of wax, by impressing the object in wax. If the mould is a non-conductor of electricity, as in the case of wax, its surface is made conducting by giving it, with a brush, a coating of plumbago (graphite). (Instead of a plumbago coating, the mould may receive a metallic coating, for instance of copper as follows: Pour copper sulphate solution over the surface of the mould and dust on it from a pepper-box very finely divided iron filings, brushing the mixture over the surface.) By suitable electrical connections of clamps or wire to the surface of the mould the latter is then made cathode in an electroplating bath, which is made up by preparing an 8 to 10 per cent. solution of sulphuric acid in water and dissolving in it copper sulphate until the resulting solution is saturated at ordinary temperatures. The solution is maintained saturated by adding some crystals of copper sulphate, or by using a copper anode. In the case of reproducing type matter, always two cases containing prepared moulds are suspended back to back between two large copper anodes so that the conducting surfaces of the moulds directly face the anodes. The thickness of the copper deposit depends on the product of current (in amperes) and time; a certain circulation of the electrolyte is useful for the same reasons as in electroplating (see below). The copper shell is then separated from the mould on which it is deposited, and in order to give it the necessary strength for further use it is backed with type-metal.*

ELECTROPLATING

186. General principles of electroplating. The object which is to receive a coating of a metal, is employed as cathode in a solution of a salt of this metal. The anode may either be soluble and consist of the same metal or it may be inert; the object of the former arrangement is to get as much metal dissolved from the anode as is deposited upon the cathode

* Description of a modern electrotyping plant in *Met. & Chem. Eng'ing*, Vol. X, p. 442.

hydrogen) is plated out. The exact calculation of the decrease of concentration at the cathode resulting from the passage of a certain number of ampere-hours, for copper-plating with copper anodes and a sulphate solution was given before in the discussion of Hittorf's transport numbers. In any case, the higher the current density the quicker is the loss from the solution at the cathode of the metal ions to be plated out and the smaller is the chance for diffusion and convection currents to bring fresh concentrated solution to the cathode surface where it is needed. The higher the current density, the greater is, therefore, the importance of artificial circulation or stirring; for this purpose either one or both electrodes may be revolved or a special stirring device may be employed in the solution. It seems, for instance, that with a smooth copper, zinc or nickel cathode, a good copper, zinc or nickel deposit can be obtained, however high the current density may be raised, if only the cathode is revolved at an increasing and sufficiently high speed. Heating also aids circulation.

190. Junction between the metals. In contradistinction to electrotyping it is very important in electroplating to get a deposit which will stick to the metal on which it is plated. There must be an intimate junction between the two metals and, according to L. Kahlenberg (*Electrochemical Industry*, Vol. I, p. 201), this requires that the two metals form an alloy together. Thus nickel may be successfully plated on copper and its alloys (brass, bronze, etc.), since with these nickel alloys readily. On the other hand, if an object of lead is to be nickeled, it is first copper plated and then the nickel is deposited on the copper because copper alloys better with lead than does nickel.

191. In order to make the deposit stick to the metal underneath, it is also of fundamental importance that the surface metal before being plated is carefully cleaned both mechanically and chemically, and that all traces of fat and oil, etc., are thoroughly removed. To remove grease, a caustic soda solution or a caustic potash solution is suitable, the latter being preferable. Acid solutions for cleaning gold, silver, copper, brass and zinc surfaces are being recommended by Trevert as follows:

	Copper	Zinc	Silver	Iron
Water	100	100	100	100
Nitric acid	50	—	10	2 to 3
Sulphuric acid	100	10	—	8 to 12
Hydrochloric acid	2	—	—	2 to 3

192. The plating bath contains principally the salt of the metal which is to be plated out, together with the addition of a solution of high conductivity, so as to reduce the voltage drop. However, other additions have also been found useful, for the following reasons: At moderate current densities a bad deposit is practically always due to the precipitation of a non-metallic solid with the metal, especially of an oxide, hydroxide or basic salt of the metal. Whatever will dissolve the oxide, etc., readily under the conditions of the operation will prevent its deposition and should therefore improve the quality of the deposit. W. D. Bancroft ("Transactions International Electrical Congress," St. Louis, Vol. II, p. 27, and *Transactions* American Electrochemical Society, Vol. VI) shows that a large majority of the more important additions recommended for various plating baths act in the way just described.

193. Securing fine-grained deposits. It seems that a fine-grained deposit is favored by high-current density and potential difference, by acidity and alkalinity and by low temperatures. Solutions containing oxidizing agents appear to yield small crystals while larger crystals are obtained from solutions containing reducing agents.

194. To prevent the formation of "trees" a very small addition of a colloid has been found useful in several cases. In the deposition of lead from a solution of lead-fluosilicate, containing an excess of fluosilicic acid, A. G. Betts found that the formation of trees and the deposition of spongy lead could be completely avoided and the deposition of perfectly solid and dense lead could be assured by the simple addition of a very small amount of gelatine or glue added to the bath. Similar observations have been made with silver and copper. The general rule seems to be that density may be raised to 0.02 to 0.08 amp. per sq. cm. and with moderate circulation of the electrolyte good deposits 1 mm. thick may be obtained.

198. Difficulties in nickel plating. A difficulty in nickel plating was formerly found in the fact that the nickel anodes do not dissolve freely in the nickel-ammonium sulphate solution. Cast nickel anodes are said to dissolve better than rolled nickel anodes. For the same reason it is important to use as large a surface of nickel anodes as possible. This has led to the introduction of corrugated anodes, etc., and it has been recommended to make the nickel anode surface $\frac{3}{2}$ times the surface to be plated. W. D. Bancroft has recently suggested (*Transactions* American Electrochemical Society, Vol. IX, p. 217) that the greater effectiveness of the cast nickel anodes is due to the fact that they contain iron. For this reason they will dissolve better, but iron will also pass into solution, which is a disadvantage. He recommends the use of a pure nickel anode in a nickel-ammonium sulphate solution containing a slight percentage of ammonium chloride or nickel chloride. If this addition is made, the nickel will dissolve as quickly from the anode as it is plated out on the cathode. If iron is to be nickeled it should first receive a coating of copper.

199. Silver plating.* The standard solution for silver plating is the double cyanide of silver and potassium, with silver anodes. As to working on a large scale and the production of the silver cyanide from silver nitrate and potassium cyanide and the production of the double cyanide from silver cyanide and potassium cyanide the reader must be referred to special textbooks. A good silver plating solution is obtained by dissolving 25 g. pure silver cyanide in a solution of 25 g. potassium cyanide in 300 to 500 cu. cm. water and diluting the solution so as to form 1 liter. The best current density is 0.001 to 0.0045 amp. per sq. cm., with about 1 volt at the terminals of the cell. Another prescription for experimental work is to dissolve 3 oz. of silver chloride (rubbed to a thin paste with water) in a solution of 9 to 12 oz. of 98 per cent. potassium cyanide in a gallon of water. A current density of $\frac{1}{10}$ amp. per sq. in. is recommended in the latter case.

200. Gold plating.† The standard solution is the double cyanide of gold and potassium and the problems involved in gold plating are similar in many respects to those of silver plating. In view of the expensive material involved, great care is necessary in details and the reader must be referred to special books on the subject. Gold is generally plated on copper; other metals to be coated with gold first receive a coating of copper; see also (207).

201. Copper plating.‡ A copper sulphate solution, containing free acid, such as is used for electrolytic refining of copper, may be used for copper plating (see 206), but better results are obtained with a cyanide solution. van Horne gives the following formula: to each gallon of water add 5 oz. copper carbonate, 2 oz. potassium carbonate and 10 oz. chemically pure potassium cyanide. Dissolve about nine-tenths of the cyanide of potassium in a portion of the water and add nearly all of the copper carbonate, previously dissolved in a portion of the water; then add the potassium carbonate, also dissolved in water, slowly stirring until thoroughly mixed. Bring the solution to 160 deg. Beaumé, put in a small article and test the solution, adding cyanide or copper or both, until the solution deposits freely and uniformly.

F. Foerster recommends for copper plating a solution made as follows: 20 g. copper acetate are dissolved in 500 cu. cm. water, 20 g. potassium cyanide, 25 g. sodium sulphite crystals and 17 g. sodium carbonate crystals are dissolved in another 500 cu. cm. water. The first solution is then added to the second one and a current density of 0.003 amp. per sq. cm. is used with 3 volts at the terminals of the cell.

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* A voluminous summary of all recipes for electroplating silver on metals is given in a paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 25.

† All recipes for gold plating are collected in the paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 25.

‡ A summary and classification of the different solutions for copper plating is given in a paper by C. W. Bennett, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 233.

of a metallic coating from the surface of an article. This is generally carried out as an anodic reaction. The most important industry in this field is the detinning of tin scrap, which has assumed quite considerable dimensions in recent years as a consequence of the enormous growth of the tin-can industry. While formerly only the tin scrap of the tin-can factories (a pure material, consisting of sheet iron, covered with tin) was treated, the treatment of tin cans, tin boxes, etc., which have been in use, has recently been taken up on a commercial scale; since they contain many impurities, these must first be very thoroughly removed (carbonized, etc.).

The object of the electrolytic process is to remove the tin from the iron so as to get both the tin and iron separate and pure. The iron is sold as scrap to open-hearth steel works, etc., and must therefore be absolutely free from tin and in good condition. The process which has been most successful on a very large scale is that of the firm of Theodor Goldschmidt in Essen; it is a secret process and employs the scrap as anode in a solution of caustic soda. Since 1906 detinning with chlorine has entered into competition with electrolytic detinning. Detinning with chlorine may be considered as an electrolytic process only in so far as electrolytic chlorine (see **230**) is used. While the products of electrolytic detinning are tin and iron, those of chlorine detinning are tin tetrachloride and iron. (Karl Goldschmidt, *Electrochem. & Met. Ind.*, Vol. VII, p. 79.)

206. Other stripping processes. A comparatively small, but interesting application of electrolytic stripping is the process of C. F. Burgess for removing from bicycle frames the films of brass which are left there from brazing the joints. A sodium nitrate solution is used for this purpose. (For this and similar processes see C. F. Burgess, *Electrochemical Industry*, Vol. II, p. 8.) As an example of the cathodic removal of a surface coating, the process of C. J. Reed for removing an oxide scale from iron and steel may be mentioned. The iron sheets, rods or wire are treated as cathode in a 27 per cent. solution of sulphuric acid of specific gravity 1.20, with a current density of 0.25 to 0.5 amp. per sq. in. at a temperature of 60° C. Under these conditions the heavy scale on rolled iron rods is removed in from 2 to 3 min. The iron oxide is not reduced to metallic iron, but to a lower state of oxidation and is then dissolved, ferrous sulphate being produced. (*Transactions* American Electrochemical Society, Vol. XI.) Concerning the sharpening of tools by electrolytic etching see Schneckenberg, *Met. & Chem. Eng'ing*, Vol. IX, p 512.

ELECTROLYTIC REFINING OF METALS

207. Fundamental principles. In electrolytic refining of metals the starting material is a highly concentrated alloy and the purpose is to remove the last impurities and to recover not only the principal metal in pure form, but also the foreign metals, especially the precious metals. The impure metal is made the anode and the fundamental principle of the process is that by the electrolytic action the metal to be refined is dissolved from the anode, passes into the electrolyte and is deposited from the electrolyte on the cathode in pure form; the foreign metals (impurities) are intended either to remain back in the anode or anode slime without being dissolved, or if they are dissolved in the electrolyte, they are intended to remain in the electrolyte without being deposited on the cathode. This cannot be satisfactorily accomplished, except with a comparatively pure, high-grade anode; in American practice of copper refining the impure copper anode is generally 98 to 99.5 per cent. pure. The cost of the electrolytic-refining process is covered first by the higher price of the refined metal and secondly by the value of the foreign metals recovered, especially silver and gold.

208. Copper refining. The electrolyte is a copper sulphate solution containing free sulphuric acid. The copper should not exceed 3 per cent. at the most, or 12 per cent. if figured as bluestone. The acid may advantageously be run up to about 13 per cent.* (Usually a very small amount of a soluble chloride, like NaCl, is added to precipitate as chloride

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* Figures of the conductivity of mixtures of copper sulphate and sulphuric acid are given by Richardson and Taylor in *Trans.* Amer. Electrochem. Soc., Vol. XX, p. 179.

See also the monograph of T. Ulke on modern electrolytic copper refining. Concerning treatment of the slimes of copper refineries see below under silver refining, also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 417. A full description of the Great Falls refinery is given by Burns in *Bulletin* American Inst. Min. Engrs., August, 1913, p. 2011. Concerning the power problem in electrolytic copper refining see papers by Addicks, Longwell, and Newbury, Transact. Amer. Electrochem. Soc., Vol. XXV.

212. Silver refining. The chief commercial problem of silver refining relates to the treatment of the bullion produced by copper refineries, to recover the silver and gold. This bullion may be treated either with the old sulphuric acid parting process or electrolytically by one of the following methods (for a critical comparison see F. D. Easterbrooks, *Transactions* American Electrochemical Society, Vol. VIII, p. 125). In the electrolytic methods the electrolyte is a silver nitrate solution.*

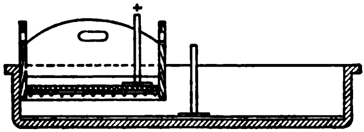

FIG. 7.—Balbach Cell.

213. Balbach process. The cross-section of a tank is shown in Fig. 7. The cathode is made of ½-in. Acheson graphite slabs fitted to the bottom. Two silver contact pieces rest respectively on the bullion to be parted and the graphite slabs. Bullion cast in thin square slabs is contained in a cloth case which is supported on a wooden frame suspended over the tank. The gold slimes accumulate on the under side of the bullion, between it and the cathode, increasing the resistance as the operation continues. Each tank has a cathode surface of 8 sq. ft., and a current density of 20 to 25 amp. per sq. ft. is used. The voltage averages 3.8 per tank, and an average ampere-hour efficiency of 93 per cent. is obtained on a continued run, while occasionally an efficiency of 98 per cent. is secured. The energy required is 31.5 watt-hr. per oz. of fine silver produced. At 20 amp. per sq. ft. about 32 per cent. of the daily output of each tank is held permanently in stock in electrolyte and contacts. (For a description of the Balbach refinery see *Electrochemical Industry*, Vol. II, p. 302.) Thum's modification of the Balbach process, as employed on the Raritan Copper Works, is described by Easterbrooks in *Electrochem. & Met. Ind.*, Vol. VI, p. 277.

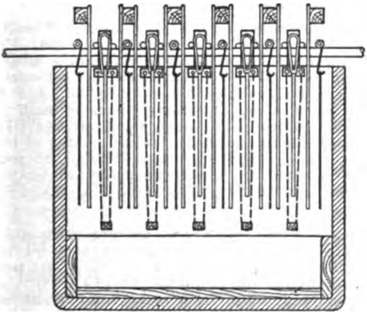

FIG. 8.—Moebius Cell.

214. Moebius process. The cross-section of a tank is shown in Fig. 8. They are arranged in units of 6 placed end to end, each unit being provided with apparatus for raising the boxes containing the deposited silver together with the anodes and cathodes, and with arrangements for imparting a reciprocating motion to the wooden scrapers. There is no system of circulating the electrolyte, but the scrapers moving back and forth agitate it. The anodes are contained in a cloth frame which holds the gold slimes, and the silver is brushed off from the silver cathodes by the wooden scrapers, and drops into a box with hinged bottom. It is removed by raising the boxes above the top of the tanks and emptying them into a tray placed beneath. This operation requires ½ hr. per day per unit. Each tank has a cathode surface of about 16.5 sq. ft., and a current density of 20 to 25 amp. per sq. ft. is used. The voltage

* See also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 443.

tails of electrolysis as carried out in England are not known; see, however, E. Guenther's "Darstellung des Zinks auf Elektrolytischem Wege." The latest advance* of the Siemens & Halske Co. in this field is the use of manganese peroxide anodes. The power consumption is 3.4 kw-hr. per kilogram Zn.

220. Iron refining. The **Burgess process** employs a solution of ferrous and ammonium sulphates with a cathodic current density of 6 to 10 amp. per sq. ft. and a slightly smaller anodic current density. The e.m.f. for each cell is slightly under 1 volt; the temperature of the electrolyte is about 30 deg. cent.; the anodes consist of ordinary grades of wrought iron and steel; the starting sheets for the cathode are of thin sheet-iron, previously cleaned of rust (*Electrochemical Industry*, Vol. II, p. 183). See also E. F. Kern, *Transactions*. Am. Electrochem. Soc., Vol. XIII.

As an electrolytic iron-refining process and as a plating operation may be considered the process of Cowper-Coles† for the production of iron sheets and tubes of nearly pure iron from anodes of pig iron. The electrolyte is a concentrated solution of ferrous chloride with addition agents.

221. Tin refining. According to the **Claus process** raw tin is electrolyzed in a 10 per cent. sodium sulphide solution at a temperature of more than 80 deg. cent. with a current density of 0.5 amp. per sq. dm. at a voltage at the electrodes below 0.2 volt. Pure tin plates or plates coated with pure tin must be used as cathodes. The anodes contain at least 90 per cent. tin: no circulation of electrolyte. Before introducing new tin anodes into the cell, it is necessary to dissolve in the electrolyte about 1 per cent. of its weight of sulphur, preferably in form of flowers of sulphur (O. Steiner, *Electrochemical and Metallurgical Industry*, Vol. V, p. 309).

222. Bismuth refining. The electrolyte is bismuth chloride containing free hydrochloric acid (7 per cent. Bi and 9 to 10 per cent. HCl). The cathodic current density is 20 amp. per sq. ft., the anodic current density is three times this amount, the voltage at the electrodes is 1.2. Silver and gold remain at the anode, but traces of the silver pass into the bismuth deposit. The anodes contain over 90 per cent. Bi, besides lead, silver, etc. The product is 99.8 per cent. pure, the chief impurity being silver. The arrangement of the cell is the same as in the Balbach silver-refining process. (A. Mohn, *Electrochemical and Metallurgical Industry*, Vol. V, p. 314.)

223. Cadmium refining. A cadmium sulphate solution containing free acid is electrolysed with a current density of 0.005 to 0.02 amp. per sq. cm. (F. Mylius and R. Funk, *Zeit, f. Anorgan. Chemie*, Vol. 13, p. 157.)

224. Miscellaneous refining processes. **Cobalt** is stated to be deposited from its sulphate and chloride solutions with the same ease and under the same conditions as nickel. Concerning **thallium** see F. Foerster "*Zeit, f. Anorg. Chemie*," Vol. 15, p. 71. Concerning **chromium** see M. Le Blanc's "Production of Chromium," (English translation by J. W. Richards), also Carveth and Mott, and Carveth and Curry, *Jour. Physical Chemistry*, Vol. IX, pp. 231 and 353, Le Blanc, *Transactions* of the American Electrochemical Society, Vol. IX, p. 315.

PRODUCTION OF HYDROGEN AND OXYGEN GASES BY ELECTROLYSIS OF WATER

225. General theory. In the electrolytic decomposition of water, as carried out on an industrial scale for the production of oxygen and hydrogen gases, instead of pure water which has too low an electric conductivity, either a 20 per cent. solution of sulphuric acid or a 15 per cent. solution of caustic soda is used as electrolyte, these concentrations corresponding to maximum conductivity. If sulphuric acid is used, the cathodic reaction is the dicharge of hydrogen ions and the setting free of hydrogen gas, while the anodic reaction may be written

$$SO_4'' + H_2O = H_2SO_4 + O, \qquad (35)$$

so that oxygen gas is set free and sulphuric acid is reformed. The quantity of sulphuric acid, therefore, remains constant and only water disappears.

* Engelhardt. *Met. & Chem. Eng'ing*, Vol. XI, p. 43.
† Palmaer and Brinell. *Met. & Chem; Eng'ing*, Vol. XI, p. 197.

first partial reaction consumes energy, hence it requires that a certain voltage be impressed on the cell from the outside. The second partial reaction evolves energy. Hence the total reaction requires energy equal to the difference of the energies of the two partial reactions. The voltage at the terminals of the whole is less than that required for the first partial reaction alone.

Newer mercury cathode cells are the Whiting cell and* the Wilderman cell.† The advantages of mercury cathode cells are high purity and high concentration of caustic soda with reduction of evaporation charges, and high ampere-hour efficiency. The drawbacks are comparatively high voltage and the first cost of the mercury.

231. Fused-lead-cathode process. While in the mercury-cathode cell an aqueous solution of sodium chloride is electrolysed, the fused-lead-cathode process (C. E. Acker) employs an electrolyte of fused sodium chloride. The sodium alloys with the fused lead. This alloy is carried off and decomposed in another vessel by means of a jet of steam. The principle is exactly analogous to the mercury-cathode process (C. E. Acker, *Transactions* American Electrochemical Society, Vol. I, p. 165). The process is no longer in commercial operation.

232. In the Glocken process or bell-process or gravity-process the anode is contained in a bell-formed non-conducting receptacle, open at the bottom and thereby in connection with the outside cathode compartment surrounding the bell. By force of gravity the anodic and cathodic products are held automatically separate and prevented from mixing and are continually carried off. Fresh saturated NaCl solution is continually supplied to the anode compartment (bell) and passes downward and prevents the OH ions from reaching the anode (O. Steiner, *Electrochemical and Metallurgical Industry*, Vol. V, p. 171).

233. In the Billiter-Leykam cell‡ the bell process has been modified by placing the cathodes (hooded to collect the hydrogen) immediately underneath the bell jar, and not around its sides.

234. In the diaphragm processes§ which are the oldest ones and of which there are quite a number, the electrolytic cell is divided into an anode compartment and a cathode compartment by means of a porous diaphragm which prevents the mechanical mixing of the two solutions. If the chloride solution is supplied to the cathode compartment, the solution cannot be highly saturated with caustic without trouble being produced by the OH ions passing to the anode. The only large industrial process in which this arrangement is used is the Griesheim Elektron process‖ used in Germany.

In most **other diaphragm cells** saturated sodium chloride solution is introduced into the anode compartment so as to flow through the diaphragm toward the cathode and counteract the tendency of the OH ions to pass to the anode. This is the case, for instance, in the cells of LeSueur, McDonald and others. A comparatively very small cathode compartment of special construction is the feature of the Hargreaves-Bird cell. This principle is carried still further in the Townsend cell, in which the cathode compartment contains no electrolyte whatever, but liquid kerosene. The caustic as soon as formed is absorbed in the kerosene and carried off. (C. P. Townsend, *Transactions* American Electrochemical Society, Vol. VII, p. 63; L. Baekeland, *Electrochemical and Metallurgical Industry*, Vol. V, p. 209 and Vol. VII, p. 313.)

Almost all diaphragm cells use vertical diaphragms. An exception is the Billiter-Siemens & Halske cell¶ in which horizontal diaphragms are used.

235. Data on alkali-chlorine cells. Allmand ("Principles of Applied Electrochemistry," p. 383) gives the following comparative table of electrochemical data of different alkali-chlorine cells, which holds for those conditions under which the cell in question is normally worked. Concerning

* *Transactions* Amer. Electrochem. Soc., Vol. XVII, p. 327.
† *Met. & Chem. Eng'ing*, Vol. XI, p. 628.
‡ *Met & Chem. Eng'ing*, Vol. XI, p. 20.
§ Theory by Guye, *Jour. Chim. Phys.*, Vol. I, pp. 121 and 212, Vol. II, p. 79, and Vol. V, p. 398.
‖ Lepsius. *Chem. Zeit.*, Vol. XXXIII, p. 299.
¶ *Met. & Chem. Eng'ing*, Vol. XI, p. 19.

cathodic products must be kept separate, the reverse requirement must be fulfilled for the electrolytic production of hypochlorites (bleaching liquors) by electrolysis of sodium chloride. Sodium hypochlorite is the result of the reaction of chlorine on caustic soda. To obtain the hypochlorite in the electrolytic cell itself, the electrodes are placed near together and the electrolyte is maintained in steady motion in order to mix the anodic and cathodic products together. For a description of commercial cells for the production of bleaching liquor see W. H. Walker, *Electrochemical Industry*, Vol. I, p. 439; Engelhardt and Abel, "Hypochlorite and Elektrische Bleiche," 2 volumes; Allmand, "Applied Electrochemistry," pp. 318 335. Concerning cost of operation see Engelhardt, *Met. & Chem. Eng'ing*, Vol. IX, p. 489.

Allmand's table (Par. 239) gives typical results yielded by different electrolyzers. They cannot be very closely compared, owing to varying conditions, but give an idea of the relative capabilities of the different types.

Concerning the Digby hypochlorite cell see *Met. & Chem. Eng'ing*, Vol. IX, p. 328.

241. Chlorate. The production of chlorate by electrolysis of sodium chloride requires interaction between caustic soda and chlorine under the conditions of a moderately high temperature, above 40 deg. cent. and an absence of reducing conditions. For the latter purpose the addition of chromate has been found especially useful. No diaphragms are used in modern chlorate cells (see the German monograph by Kershaw and Huth; also Allmand, Applied Electrochemistry, pp. 335–341). As to the use of electrolytically produced acid and alkali (obtained by electrolysis of a solution of chlorate or perchlorate of sodium) for producing bichloric phosphate fertilizers see Palmaer, *Met. & Chem. Eng'ing*, Vol. X, p. 581.

ELECTROLYSIS OF CHLORIDES OF COPPER, NICKEL AND ZINC

242. Reduction of copper-nickel matte. Besides the electrolysis of alkaline chlorides, which is now carried out on a very large industrial scale in the numerous processes, sketched above, chloride electrolysis has also been attempted in the metallurgy of copper, nickel and zinc. (Concerning the early work of Hoepfner in this field see Wm. Koehler, *Electrochemical*

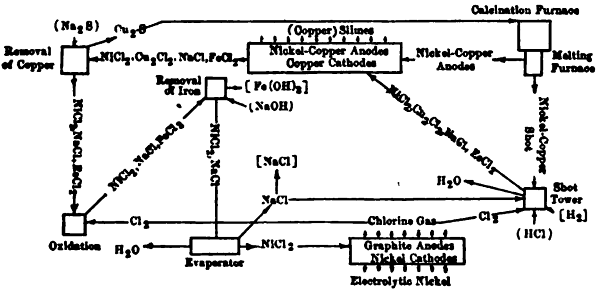

Fig. 9.—Separation of nickel and copper.

Industry, Vol. I, pp. 540, 568.) Success has been attained in this field by D. H. Browne for **separation of the nickel and copper from copper-nickel matte**, the scheme of the process being indicated in Fig. 9. The matte is roasted and melted and one-half of the fused copper-nickel is poured into anode form, the other half is poured into water, thus giving copper-nickel shot of a weight equal to that of the anodes. The anodes are placed in the nickel-copper chloride bath; the copper-nickel shot is brought into the shot tower in which the electrolyte for the copper-depositing baths is made. In these baths pure copper is deposited on the cathodes, nearly all the copper being separated from the nickel in solution. The small amount of copper remaining in solution is removed by means of sodium sulphide. The solution which is now a mixture of $NiCl_2$, NaCl, and a small amount of $FeCl_3$

the most important electrochemical industry. In the processes of Hall and Héroult the electrolyte is a fused solution of alumina (as solute) in the double fluoride of aluminium and sodium (as solvent). Carbon anodes are used, while the melted aluminium metal in the bottom of the pot forms the cathode. The temperature is 900 deg. cent. The alumina is decomposed by the current and fresh alumina is added at intervals to the bath. According to J. W. Richards the production of 1 kg. of aluminium requires 22 kw-hr. Aluminium is used for the manufacture of various utensils, for all purposes where lightness is an advantage, and especially for electric conductors as a substitute for copper. J. W. Richards' "Aluminium" is the standard book on this metal: concerning the theory of the process a different view is defended in the book by Minet, translated by L. Waldo.* According to the U. S. Geological Survey, the production of aluminium in the United States was 61,281 lb. in 1890; 920,000 lb. in 1895; 7,150,000 lb. in 1900; and 11,347,000 in 1905. It is estimated that the output in 1906 was 30 per cent. greater than the output in 1905, but a much greater rate of increase is expected in the future.

247. Properties of aluminium cells. The property of aluminium electrodes to let electricity pass in one direction (when the aluminium electrode is cathode), but not in the other, is made use of in **electrolytic rectifiers.** A. Nodon ("Transactions of the International Electrical Congress," St. Louis, 1904, Vol. I, p. 510) employs a neutral solution of ammonium phosphate in water as the electrolyte, with aluminium as one electrode and the other electrode of lead or polished steel. C. F. Burgess and Carl Hambuechen (*Transactions* American Electrochemical Society, Vol. I, p. 147) use a fused electrolyte of molten sodium nitrate with an aluminium and an iron electrode. If two aluminium electrodes are used, the system represents an **electrolytic condenser** (C. I. Zimmerman, *Transactions* of the American Electrochemical Society, Vol. VII, p. 309). This valve effect of the aluminium electrode is also made use of in the **electrolytic lightning-arrester** (see R. P. Jackson, *Electrical Journal*, August, 1907).

248. Metallic sodium is produced on a large scale by the **Castner process** from a fused NaOH electrolyte at a temperature not more than 10 or 15 deg. cent. above the melting point (which is at 308 deg. cent.). A gauze or screen is provided between the electrodes and a superposed dome for collecting the metallic sodium.

249. The Ashcroft process produces **sodium** from common salt in a double cell of the following construction. In the first half of the cell fused sodium chloride is electrolyzed with a carbon anode (at which chlorine is liberated) and a fused lead cathode (which absorbs the sodium). The same fused sodium-lead alloy forms the anode in the second half of the cell, fused NaOH being the electrolyte and the cathodes consisting of iron or nickel. In this second half of the cell sodium passes from the sodium-lead alloy into the bath and is deposited at the cathode, the fused bath remaining of constant composition. The first half of the process is in principle analogous to the Acker process, the second half to the Castner process, but with the exception that as much NaOH is formed back at the fused sodium-lead anode as is decomposed. The total result of the process is given by the simple equation $NaCl = Na + Cl$ (*Electrochemical and Metallurgical Industry*, Vol. IV, p. 218). (A good summary of various sodium processes is given by C. F. Carrier, Jr., in *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 442 and 475; also *Met. & Chem. Eng'ing*, Vol. VIII, p. 253.) The yearly production of sodium in the world (1906) is about 3,500 tons, of which 1,500 tons are used for making cyanide, 1,500 for peroxide and 500 are sold as metal.

250. Magnesium is produced by electrolysis from a fused dehydrated bath of carnalite, *i.e.*, a double chloride of potassium and magnesium or from a fused bath of magnesium chloride (Tucker and Jouard, Transact. Amer. Electrochem. Soc., Vol. XVII, p. 249).

251. Calcium is made by a process of the Allgemeine Elektricitats Gesellschaft by electrolysis of fused calcium chloride, the cathode being continually and slowly raised during process of electrolysis so that its end always just touches the surface of the bath (J. H. Goodwin, *Electro-*

* See also Neumann and Oesen, *Met. & Chem. Eng'ing*, Vol. VIII, p. 185; Clacher, Vol. IX, p. 146.

Lovejoy, Birkeland and Eyde, Schoenherr (Badische Company) and Pauling, all of which use electric discharges through air to produce a very high temperature. The object of the spark or arc is simply to produce the very high temperature required for the combination of the nitrogen with oxygen, which would go on in the same way if the same high temperature was produced by some other means. The gas mixture of air and nitrogen oxides thus produced is then treated with water or with alkaline solution (caustic soda, lime water, etc.) to give dilute nitric acid, nitrates, or a mixture of nitrates and nitrites.

The higher the temperature, the greater is the content of nitric oxide produced in the air and the quicker is the transformation. This is the reason why the electric arc is so effective. Besides the necessity of producing a high temperature, the second chief requirement is to remove the nitrogen oxide formed as quickly as possible from the high temperature zone and to cool it down as rapidly as possible; the reason is that with decreasing temperatures the opposite reaction takes place and the nitric oxide dissociates into nitrogen and oxygen, so that if the cooling of the mixture of air and nitric oxide is too slow the latter will break up into its constituents. Haber has shown, however, that at low temperatures the formation of nitrogen oxide by means of electric discharges cannot be considered as a purely thermal phenomenon; there seems to be a specific electric effect superposed upon it. At the temperature used in the commercial processes the thermal theory sketched above seems to hold strictly true.*

259. In the Bradley-Lovejoy process† mechanical means (rotation of a wheel carrying one set of electrodes which continually pass along an opposite and stationary set of electrodes) are employed to make and break continuously sparks (6,900 sparks per sec.) in the space through which the air is passed. While this process, which was tried for some years at Niagara Falls without attaining final commercial success, represents the era of the spark furnace, the desire to get larger units led to the construction of arc furnaces. The different types differ essentially in the way by which the produced gas mixture is quickly removed from the gas zone.

260. In the Birkeland-Eyde process‡ the arc is deviated magnetically by means of a single-phase magnet field, until the arc breaks; then a new arc is formed, etc. The Birkeland-Eyde process has been in successful commercial operation since 1905 in Norway (electric energy being very cheap at the plant, 0.094 cent per kw-hr.).

261. The Schoenherr furnace. The Badische Company used successfully for a time the Schoenherr furnace,§ the characteristic feature of which is the use of a very long alternating-current arc around which the air moves in a helical path. This plant has been taken over by the Birkeland-Eyde interests which now use exclusively the Birkeland-Eyde furnace as it has a higher efficiency in larger units.

262. Pauling process. Two plants in Tysol and in France employ the Pauling process,‖ using electric discharges quite similar to those obtained in a horn lightning arrestor. The results obtained in these three commercial processes were given in 1909 as follows (no later data being available):

	Grams HNO_3 per kw-hr.	Concentration in per cent. NO
Schönherr	75	2.5
Birkeland-Eyde	70	2
Pauling	60	1 to 1.5

* For a concise summary of the thermodynamical principles of the problem see, for instance, *Mineral Industry*, Vol. XIX, p. 58; also Guye, *Electrochem. & Met. Ind.*, Vol. IV, p. 136.

† *Electrochem. Ind.*, Vol. I, pp. 20 and 100.

‡ *Electrochem. Ind.*, Vol. II, p. 399; Vol. IV, pp. 295 and 360; Vol. VII, pp. 304, 305; *Met. & Chem. Eng'ing*, Vol. IX, pp. 340, 364, 436, 545; Vol. X, p. 617

§ *Electrochem. & Met. Ind.*, Vol. VII, p. 245; *Met. & Chem. Eng'ing*, Vol. IX, p. 73.

‖ *Electrochem. & Met. Ind.*, Vol. VII, p. 430; *Met. & Chem. Eng'ing*, Vol. IX, pp. 99 and 196. Concerning an experimental plant in North Carolina see *Met. & Chem. Eng'ing*, Vol. VIII, p. 555.

investigate the Zinc Resources of British Columbia" (Canadian Government publication, 1906, pp. 82 to 118) and in C. G. Gunther's book on "Electromagnetic Ore Separation." See also Ruhoff, *Met. & Chem. Eng'ing*, Vol. X, p. 278.

266. Electrostatic ore separators. The action of electrostatic separators depends on the difference in electric conductivity of the constituents of the ore mixture. According to the conductivity, the electrostatic charge acquired by the different constituents from the same source of electric charge in the same time is different. If the mixture consists of a finely crushed non-conductor and a finely crushed conductor and is brought in contact with a charged surface, the latter will receive a charge while the former remains uncharged. Electrostatic repulsions of the charged particles from the charged surface will then result, while the uncharged particles are not repelled. (See paper by Blake in *Electrochemical and Metallurgical Industry*, Vol. III, p. 181; MacGregor, *Transact.* Am. Electrochem. Soc., Vol. XVIII, p. 267, and Vol. XXIV; Wentworth, *Met. & Chem. Eng'ing*, Vol. X, p. 167.)

267. Dust precipitation by electrostatic means. The Cottrell process* is based on the old familiar phenomenon of the "electric wind." If a metallic needle point is placed opposite a flat metallic plate and the needle is connected to one pole and the plate to the other pole of a high-voltage direct-current supply line, electricity streams out of the needle point and charges the gas molecules in the space between needle and plate. The gas molecules thus receive an electric charge of the same sign as the needle point, hence opposite to the sign of the charge of the plate. They are, therefore, attracted by the plate and move toward it. Now if the space between the needle point and the plate is filled with a gas or fume in which particles of dust, etc., are suspended, these dust particles will be immediately charged with electricity and will, therefore, move toward the plate, stick to it and give up their charges. The speed of movement of the particles is proportional to their charge and to the electrostatic field intensity in the space between point and plate. Cottrell uses this principle for the precipitation of dust particles from smelter fumes, etc. He employs ordinary commercial high-voltage alternating-current and converts it into intermittent direct-current by means of a specially designed synchronous converter. This intermittent direct-current is directly used for charging the system of electrodes (needles and plates) in the flues which carry the gas under treatment. Instead of using needle points he twists asbestos filaments or mica scales with wires. The electricity passes from the wires by surface leakage over the asbestos or mica, and the fine filaments of the asbestos or edges of the mica provide the required (very fine) discharge points. The process is in successful use in smelters,† cement plants,‡ etc.

268. Smoke prevention. The same principle has been proposed for the electric precipitation of smoke (A. F. Nesbit, Elec. Rev., Oct. 31, 1914, p. 877).

BIBLIOGRAPHY

269. One of the best all-around books in English on industrial electrochemistry is Allmand's Principles of Applied Electrochemistry. Other general books are N. Monroe Hopkins, Experimental Electrochemistry; W. G. McMillan and W. R. Cooper, A Treatise on Electro-metallurgy; F. Mollwo Perkin, Applied Electrochemistry; M. de Kay Thompson, Applied Electrochemistry.

A very good general book on electric furnaces is Stansfield, The Electric Furnace. The application in the iron and steel industry is well treated in Rodenhauser and Schoenawa, The Electric Furnace in the Iron and Steel Industry (translated by vom Baur). Lyon, Keeney, and Cullen's, The Electric Furnace in Metallurgical Work (Bureau of Mines, Bull. 77) is very useful.

A standard work on the theory and practice of the electrolysis of aqueous solutions is Foerster's Elektrochemie wässeriger Lösungen. An equally excellent work on fused electrolytes is Lorenz's Elektrolyse geschmolzener Salze, 3 vols. Neither book is available in English.

The titles of the principal books on theoretical electrochemistry and on special fields of industrial electrochemistry are given in connection with their respective subjects.

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* Cottrell. *Met. & Chem. Eng'ing*, Vol. X, p. 172.
† Bradley. *Met. & Chem. Eng'ing*, Vol. X, p. 686.
‡ Schmidt. *Met. & Chem. Eng'ing*, Vol. X, p. 611.

SECTION 20

BATTERIES

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CONTENTS

(Numbers refer to Paragraphs)

the copper sulphate in contact with the copper plate of a Daniell or gravity cell, or the slightly soluble mercurous-sulphate paste of the standard Clark or Weston cell.

(b) A chemical compound is present at the negative plate, which is capable of furnishing negative ions to the solution because of its metal constituent possessing different valencies. Examples are the manganese peroxide of the Leclanché or dry cell, and the chromic acid of the bichromate cell. It is of advantage that such depolarizers be relatively insoluble, in order that they do not come in contact with the zinc electrode and thereby suffer reduction.

8. Measurement of internal resistance and polarization. The true internal resistance of a cell is obtained from the formula

$$r = \frac{(E - E_p) - V}{I} \qquad \text{(ohms)} \qquad (1)$$

in which E is the total e.m.f. of the cell on open circuit, E_p is the opposing polarization e.m.f. and V is the voltage at the cell terminals. If immediately after breaking the current, the cell voltage is determined by the condenser-ballistic galvanometer method, or otherwise, then $E_p = E - V$.

Upon open circuit, after the delivery of current, the opposing e.m.f. of polarization decreases, at first rapidly and then more slowly, owing to the gradual diffusion of the polarising substances. The curves, Fig. 1 are typical of a dry cell. The heavy curve shows the gradual drop in voltage, the cell being closed through a constant resistance, while the dotted curve (read in the opposite direction) shows the voltage recovery, with time, after the current ceases. The vertical portion of the recovery curve represents the voltage drop due to internal resistance, the further recovery being due to the gradual equalization of concentrations throughout the electrolyte, or in the pores of the electrodes.

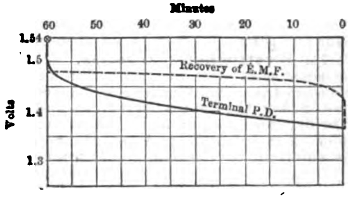

Fig. 1.—Polarization recovery.

9. Local action. In all practical forms of battery, the fundamental reactions are somewhat departed from. Local action takes place, resulting from impurities on one or both the electrodes; this action is of the nature of an elementary short-circuited cell. For example, a zinc electrode always contains impurities such as copper, iron and carbon. Zinc is dissolved, hydrogen gas comes off at the point of impurity, and current flows between the impurity and the point where the zinc enters into solution. This action is reduced by **amalgamating** the surface of the zinc with mercury; this forms a solution of zinc, uniformly covering the surface, and greatly reduces the local action.

10. Electrochemical theory. Two methods may be employed in the theoretical consideration of primary battery phenomena. One, the general thermodynamic method, the other, a mechanical method resulting from the osmotic-pressure theory of solutions. The e.m.f. of a reversible cell may be calculated from the relation

$$E = \frac{JH}{nq_0} + T\frac{dE}{dT} \qquad \text{(volts)} \qquad (2)$$

Where J = mechanical equivalent of heat; H = heat of formation of resultant chemical compound in calories; q_0 = charge in C.G.S. units of 1 g. ion, *i.e.*, 9.654 units; n = valency; T = absolute temperature. The first quantity of the right side of the equation is the controlling one, the second usually having a small value. If a cell has a zero temperature coefficient, the e.m.f. can be directly calculated from the heat of formation of the resultant chemical compound of the reaction. The second term may be either positive or negative. The above equation is deduced on the assumption that the cell is reversible, but the voltage of any cell may be closely approximated by its use.

cup and is in a saturated solution of copper sulphate containing excess crystals. The zinc (usually amalgamated) is in the porous cup, which contains sulphuric acid and zinc sulphate solution. The e.m.f. of the cell depends on the concentration of the zinc sulphate in the porous pot, the maximum initial value being about 1.14 volts. The cell may be set up with zinc sulphate solution only in the porous cup in which case the e.m.f. is approximately 1.07 volts and has a very small temperature coefficient. The chemical reaction is $Zn + CuSO_4 = ZnSO_4 + Cu$. The cell is not adapted to stand on open circuit. When placed out of service the liquids should be poured out and the porous cup should be thoroughly washed in running water until all the zinc sulphate is removed, otherwise the cup will crack on drying.

19. Gravity battery. This cell is the usual modification of the Daniell cell, and is shown in Fig. 3. The porous pot is omitted and gravity is depended upon to keep the heavier copper sulphate solution in the bottom of the cell. The zinc is frequently cast in the form of a "crowfoot" and hangs from the edge of the jar. The copper electrode is made of two or three strips of sheet copper, riveted together and spread out in the bottom of the jar. A rubber-covered wire is fastened to the copper and leads upward out of the cell. Copper-sulphate crystals are placed in the bottom of the jar and zinc sulphate solution is added to cover the zinc. The solution should be poured in carefully, so as not to bring copper sulphate solution in contact with the zinc, as copper would be immediately precipitated on the zinc.

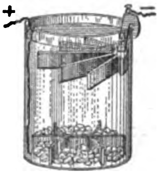

Fig. 3.—Gravity cell.

20. Care of gravity battery. The cell should be kept on closed circuit in order to prevent copper from diffusing upward and precipitating upon the zinc. The edge of the jar should be coated with paraffin to prevent creepage of the zinc sulphate solution. As the top solution becomes saturated with zinc sulphate some of it should be drawn off and carefully replaced with water The copper sulphate solution must not be stirred up. Evaporation may be reduced by covering the solution with a thin layer of mineral oil. If a heavy copper precipitate is present on the zinc, it should be scraped off. A sharp dividing line should be maintained between the two solutions. This can be noted by color difference. At the top should be a light solution, while the copper sulphate is very dark blue. For each ampere hour, the following amounts of materials are theoretically used up or formed—0.042 oz. copper deposited, 0.043 oz. zinc is dissolved, and 0.164 oz. copper sulphate used up. Local action will require at least a 10 per cent. greater amount of zinc and copper sulphate. Note that the increased copper weight should be credited to the cost of upkeep.

21. Bunsen or Grove cell. In the Bunsen cell the zinc plate is in a sulphuric acid solution, while the negative plate is a carbon rod immersed in strong nitric acid, contained in a porous cup. The Grove cell differs from the Bunsen cell only in the use of platinum instead of the carbon. The e.m.f. of this type of cell is about 1.9 to 2 volts and the internal resistance quite low. The cell is adapted for laboratory purposes and can be used for heavy currents. It must not be allowed to stand on open circuit for any considerable time, and must be set up freshly each time it is used.

Vapors of nitric peroxide are given off from the cell and provision must be made for their removal. The chemical reaction of the cell is presented by the equation $Zn + H_2SO_4 + 2HNO_3 = ZnSO_4 + 2H_2O + 2NO_2$.

22. Chromic-acid cell. This cell is in wide use for laboratory purposes. It may be used as a single-fluid cell but the porous-cup form is preferable. The Grenet or plunger type is shown in Fig. 4. Two carbon plates are immersed in a solution of potassium or sodium bichromate, sulphuric acid and water. Potassium permanganate is a fairly satisfactory equivalent to the chromic-acid salt. The zinc plate is between the two carbons when lowered for use. The usual solution is made up as follows: water, 12 lb. concentrated sulphuric acid, 2½ lb. and potassium bichromate, 1 lb. Potassium bichromate gives rise to insoluble crystals of chrome alum and the sodium salt is preferable. Chromic acid, on account of its great solubility is to be preferred over either of the above salts, and the quantity used need be but two-thirds of the weight of either of the salts, required for the same of salammoniac. The e.m.f. is about 1.5 volts but the terminal voltage drops rapidly with high currents. The cell is suitable for open-circuit or closed-circuit work, if large currents are used intermittently and for short periods of time. The continuous current demand on closed circuit must not exceed a few hundredths of an ampere, as otherwise the terminal voltage is too greatly reduced by polarization. The chemical reaction is $Zn+2NH_4Cl+2MnO_2 = ZnCl_2+2NH_3+H_2O+Mn_2O_3$. The dry battery, which is a modification of the Leclanché cell, has largely replaced the latter in practical use.

26. Edison Lalande. The usual form of this cell comprises a plate of compressed copper oxide on either side of which is a zinc plate with ribs. These ribs serve to hold the plate together until it is worn out. The copper-oxide plate is superficially reduced to cover it with a very thin layer of metallic copper for conductivity. The electrolyte is caustic soda solution covered with a layer of mineral oil to prevent evaporation and the formation of sodium carbonate from the carbon dioxide of the air. The construction of these cells is shown in Fig. 8. The chemical reaction is $Zn+2NaOH+CuO = Na_2ZnO_2+H_2O+Cu$. The e.m.f. of the cell is 0.95 volts and the terminal voltage drops to less than two-thirds of this value when furnishing heavy currents. Its internal resistance is low. It is adapted for both closed and open-circuit work and does not depreciate materially, excepting from the using up of the chemicals corresponding to the ampere-hour output. These cells are available in sizes from 100 to 600 amp-hr. On account of the low voltage, the initial cost of a battery of these cells is relatively high.

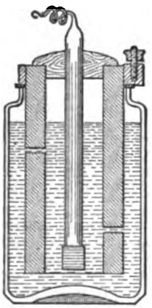

FIG. 7.—Leclanché cell.

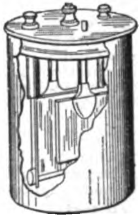

FIG. 8.—Edison-Lalande cell.

27. Carbon cells. A great deal of effort has been expended to develop a cell which would permit the conversion of the chemical energy of coal and the oxygen of the air directly into electric energy. The difficulties at the present time seem insurmountable on account of the high temperature which must obtain in order for the carbon to enter into a suitable reaction, and because the CO_2 necessarily formed, unites with the fused caustic soda electrolyte, which has been proposed. The difficulties in the way of an oxygen electrode are also great.

28. Standard cells. The **Clark cell** comprises an electrode of mercury, containing metallic zinc, an electrolyte of zinc sulphate and a depolarizing electrode of metallic mercury, covered with a paste of difficultly soluble mercurous sulphate. The chemical reaction is $Zn+Hg_2SO_4 = ZnSO_4 +2Hg$. In the **Weston cell**, cadmium is substituted for the zinc. Very elaborate preparation of all the materials used in these cells is imperative, and the reader is referred to the extensive literature on this subject. The variation of the e.m.f. with temperature of the practical forms of these cells is given in Sec. 3. These cells are not adapted for closed-circuit work, although they quickly recover their voltage after an appreciable discharge.

DRY CELLS

29. Definition. The only "dry battery" in commercial use is a modification of the Leclanché cell, in which the sal ammoniac solution is held by capillary action in a porous medium separating the zinc from the opposite electrode also in the pores of the carbon-depolarizer electrode.

39. Service tests. The committee on dry cell tests of the Am. El. Chem. Society (Transactions 1912) has recomended the tests described in Par. 40 to 42.

40. For telephone work. Connect 3 cells in series through a resistance of 20 ohms for a period of 2 min. during each hour until the terminal voltage falls to 0.93 volt per cell at the end of the 2-min. period. The tests are to continue 24 hr. per day and 7 days per week, and the number of days elapsing until the above limiting voltage is reached is to be noted.

41. For gas-engine ignition. Connect 6 cells in series through 16 ohms resistance for two periods of 1 hr. each during each day, 7 days per week. The first discharge may be made during the morning, and the second, late in the afternoon. At the end of each twelfth of the above discharges, shunt the 16-ohm resistance with a 0.5-ohm resistance connected to an ammeter and note the current. The test is considered complete when the current shunted through the ammeter falls below 4 amp., and the total number of hours of actual discharge to this limiting value of 4 amp. is noted.

42. For flash-lamp service. Discharge the battery through a resistance of 4 ohms for each cell connected in series for a period of 5 min. once each day, and determine the total number of minutes of actual discharge, the terminal voltage of the last discharge being limited to 0.75 volt per cell.

STORAGE BATTERIES

43. Definitions. Cells which are reversible to a high degree, *i.e.*, those in which the chemical conditions after discharge are brought back to the original condition simply by causing current to flow in the opposite direction, or "charge," may be used as storage batteries. Storage batteries are sometimes termed **electric accumulators**.

44. Reversibility. In all the practical forms of storage batteries, both the electrode materials and the products of the chemical reaction are relatively insoluble. The form of the electrodes is practically unchanged with use, or at least it changes but slightly. Many of the cells in which the reaction products are soluble and which are ordinarily used as primary batteries can be used as storage batteries. For example, the Daniell or gravity cell and also the Edison-Lalande cell are reversible to a high degree, but have practical disadvantages contributing against their use as storage batteries.

45. Classification. The storage battery which is in widest commercial use, for various purposes, is the lead-sulphuric acid type. The only other type which is of any prominence is the nickel-iron-potash battery, apparently first proposed by Darrieus, then by Jungner and developed in commercial form by Edison. The use of cadmium instead of iron as a negative plate, the battery otherwise being quite similar to the Edison, is due to Hubbell and his battery is in extensive use for miner's lamps.

46. Positive and negative plates. The positive terminal or pole of a battery is that one from which the current flows into the external circuit. In storage battery practice, a positive plate is one which is connected to the positive pole, and the negative plate, the one which is connected to the negative pole. It should be specially noted that this is the reverse of primary-battery terminology. The U. S. Patent Office has attempted to avoid confusion in this regard by insisting on the use of the terms, "**positive-pole plate**" and "**negative-pole plate,**" but this has not come into general use.

47. The e.m.f. or open-circuit voltage of any storage cell depends wholly upon its chemical constituents and not in any way upon the number or total area of its plates. It varies further with the strength of the solution, or electrolyte, and its temperature, and to a minor extent, upon the state of charge of the plates. Upon charge, the terminal voltage of the cell rises, and, upon discharge, it falls, due to the internal resistance and to a number of more or less obscure causes, such as polarization, acid-concentration effects, etc.

48. The capacity of a cell with a definite type and thickness of plate is in proportion to the plate area. The size of a cell is usually stated in terms of its ampere-hour capacity at a standard temperature of 70 deg. fahr., but it is necessary, also, to state the discharge rate, as the capacity of all practical forms of batteries is lower with increasing discharge rates.

49. Battery voltage. The voltage of a battery is that of each cell multiplied by the number of cells connected in series.

55. The variation of voltage is approximated by the following formula, lue to Streintz:

$$E = 1.850 + 0.917(G - g) \qquad \text{(volts)} \qquad (7)$$

n which E = e.m.f. in volts; G = specific gravity of electrolyte, and g = specific gravity of water at the cell temperature.

56. Test or reference electrode. It is often desirable to determine the relative performance of the positive and negative plate groups in a cell and this may be done by taking the voltage between either group and a reference electrode of zinc, spongy lead or, preferably, cadmium.

57. A typical discharge curve for a stationary type of cell is shown in Fig. 9, also the curves for both positive and negative groups with reference to cadmium. Curve (1) shows the cell voltage, curve (2) the voltage of the positive group and cadmium, while curve (3) represents the voltage for the negative group and cadmium. Fig. 10 shows the corresponding curves for charge.

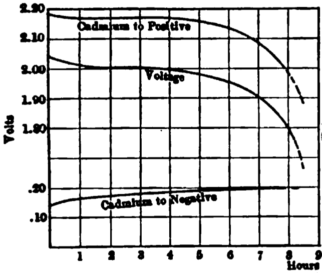

FIG. 9.—Discharge curves.

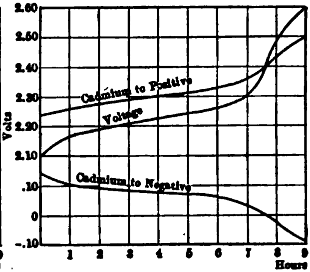

FIG. 10.—Charge curves.

58. Cadmium tests. The cell voltage is the difference between the positive-cadmium and the negative-cadmium voltages. In Fig. 9 the discharge curves are continued in dotted lines and, the greater portion of the final voltage drop occurring with the positives, show that the capacity of the cell, in this instance, is limited by the positive group. This is a desirable condition, as most negatives suffer from overdischarge more than do the positives.

59. Lead battery plates are classified thus: Planté plates (Par. 60) and pasted plates (Par. 62).

60. Planté plates comprise a mass of lead, usually of flat form with a highly developed surface. The increased surface is obtained by casting a cellular structure, or by scoring or cutting a blank of heavy sheet lead. The active material is electrochemically formed as a coherent layer of lead peroxide at the expense of a film of the underlying lead. Such plates are always formed as positives, but Planté negative plates are obtained from the positives by connecting them as negatives in a cell, and charging whereby the active material is reduced to sponge lead.

61. The original Planté process of formation consists of charging the plates alternately in opposite directions; each successive reversal under proper conditions of temperature, strength of electrolyte and current increases the capacity of the plates. This method is extremely wasteful of current and requires a long time; it has been abandoned in favor of accelerated forming processes which consist of making the plate to be formed an anode in an electrolyte of dilute sulphuric acid containing a small amount of nitric, perchloric or other acid which dissolves lead. The current density, straighter in service than other Planté types and that it shows a minimum of buckling. No centre web is employed, an open type of construction being adopted.

70. Centre-web positives. Figs. 12 and 13 show Planté positives made from a sheet-lead blank, the surface being increased by plowing leaves in the first instance, and by "**spinning**" with rotating circular discs in the latter. A section of the latter plate is shown in Fig. 14.

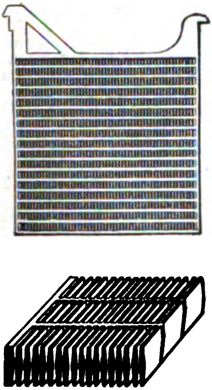

Fig. 11.—Tudor positive and section.

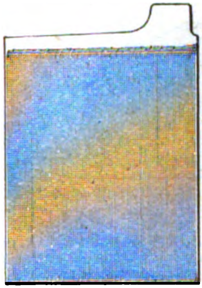

Fig. 12.—Willard "plowed" plate.

71. Manchester positive. Fig. 15 shows a Manchester positive, comprising a casting of lead antimony with a number of round holes symmetrically spaced. Into these holes are inserted spiral coils of corrugated lead ribbon. The plate as a whole is electrochemically formed, but the frame work is but slightly corroded. This makes a very rugged plate. It will not show as good a life in possible number of cycles of charge and discharge as the pure-lead Planté plates, but this is largely counterbalanced by its rigidity. The plate is, however, much more sensitive to overcharge than are the other Planté plates.

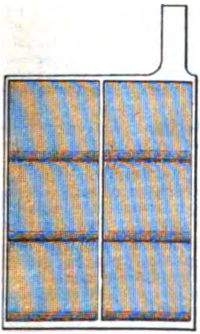

Fig. 13.—Gould "spun" plate.

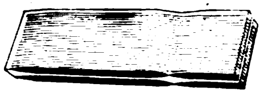

Fig. 14.—Section of Gould "spun" plate.

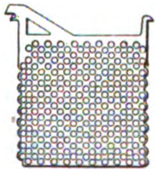

Fig. 15.—Manchester positive.

density of the electrolyte varies with its acid content, and the change in density may be used as a measure of the state of charge of the battery, if the initial and final specific gravities are known.

79. The quantity of electrolyte required for 100 amp-hr. discharge is calculated from the following formula.

$$G_o = \frac{1290 - 10.53d}{D - d} \quad \text{(oz.)} \qquad (8)$$

in which G_o = number of ounces of electrolyte per 100 amp-hr. of discharge; D = per cent. of H_2SO_4 in the electrolyte at the beginning of discharge; and d = per cent. of H_2SO_4 at the end of discharge. For a capacity G other than 100 amp-hr. multiply G_o by $G \div 100$.

When the value of G_o for 100 amp-hr. and either the initial or final density of the electrolyte are known, then that density, which is unknown, can be determined from the following:

$$D = \frac{1290 + d(G_o - 10.53)}{G_o} \qquad (9)$$

and

$$d = \frac{1290 - G_o D}{10.53 - G_o} \qquad (10)$$

80. The change in acid strength is not immediate; it lags behind the values determined in Par. **79** on account of the fact that time is required for the strong acid to diffuse into the plate on discharge, and for the strong acid to diffuse out of the pores of the active material on charge.

81. Separation. It is essential that plates of opposite polarity be kept from coming in contact with each other. This is insured by the use of ribbed perforated sheets of hard rubber, glass spacing tubes or, more frequently, wood **separators.** The wood used is selected for a minimum content of such constituents as would be injurious to the plates and it is usually subjected to a treatment to reduce such constituents still further.

82. Lead burning of joints. The use of solder must be avoided in storage-battery construction. Joints are made by lead burning, by which is meant the melting together of the lead parts by a hydrogen flame. This flame deoxidizes the melted lead, and the two parts readily flux together.

FIG. 20.—Hydrometer.

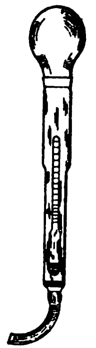

FIG. 21.—Syringe hydrometer.

ELECTROLYTE AND WATER

83. The electrolyte used in lead storage batteries is a solution of sulphuric acid and water. The sulphuric-acid content determines the density of the solution, *i.e.*, its specific gravity (sp. gr.)or the ratio of its weight to that of an equal volume of water.

84. Hydrometer. The specific gravity of electrolyte is practically determined by the use of an hydrometer which comprises a weighted glass bulb with a graduated stem. In strong acid the stem protrudes further above the surface of the solution, and the point at which the top of the meniscus touches the scale is read off directly in degrees of specific gravity.

With stationary types of cells there is usually space enough between plates or at the end of the tank to float a flat bulb hydrometer directly in the acid of the cell. This type of hydrometer is illustrated in Fig. 20.

85. Syringe hydrometer. With vehicle and other types of batteries with small separation between plates, a convenient method to determine the acid density is to employ a syringe hydrometer as illustrated in Fig. 21; the hydrometer floats within the enlarged portion of the glass barrel when acid is sucked into it by means of the rubber bulb.

given				
1100	1.43	1.122	1.00	0.91
1200	1.33	0.900	0.73	0.62
1300	1.35	1.000	0.79	0.43
1400	1.89	1.425	1.05	0.82

91. Freezing point of electrolyte. The freezing point of the electrolyte of fully charged batteries is quite low; however, the electrolyte of partly or fully discharged batteries will freeze at low temperatures. If batteries are to be subjected to such temperatures, it should be seen to that they are fully charged. The freezing point of sulphuric acid solutions is given in the following table:

Sp. gr.	Temp. (deg. Fahr.)	Sp. gr.	Temp. (deg. Fahr.)
1.060	25	1.220	−31
1.080	22	1.240	−51
1.100	18	1.260	−75
1.120	14	1.280	−90
1.140	8	1.300	−95
1.160	2	1.320	−80
1.180	−6		
1.200	−16		

92. New electrolyte. The presence of impurities in a cell is objectionable (Par. 97). In acid used for the first filling of cells they should not exceed the limits cited in Par. 93.

93. Maximum allowable impurities in electrolyte for first filling (initial charge).

Color	Colorless
Suspended matter	Trace
Platinum	Trace
Antimony and arsenic	Trace
Manganese	0.0025 per cent.
Iron	0.005 per cent.
Copper	0.0025 per cent.
Nitrogen in any form	Trace
Chlorine	0.001 per cent.
Organic matter	None

94. Maximum allowable impurities in water used for replacing evaporation. In the operation of a battery, the electrolyte loses water by evaporation, also some water is electrolytically decomposed. Water must be added to the cells, and any impurities it might contain would be cumulative. The maximum limits of impurities in water for storage-battery purposes are given in the following table:

Color	Colorless
Suspended matter	Trace
Total solids	10 parts per 100,000
Calcium and magnesium oxides	4 parts per 100,000
Iron	0.05 parts per 100,000
Ammonia as NH_4	0.8 parts per 100,000
Organic matter	0.1 parts per 100,000
Nitrates as NO_3	1.0 parts per 100,000
Nitrates as NO_2	0.5 parts per 100,000
Chlorine	1.0 parts per 100,000

silver nitrate. If the solution becomes opalescent, the electrolyte should be examined carefully for chlorine content. A great excess of chlorine will be indicated by the test solution becoming curdy.

TESTING

101. Preliminary. Before starting a test on a lead-acid type of storage battery, see that it is fully charged and in good condition. The acid should be pure and its strength adjusted to that which is recommended by the maker as standard for the type. If the battery is new, insure that it is fully developed by taking several preliminary discharges; the capacity of a battery increases very considerably with the first few cycles of charge and discharge. Before starting tests for capacity or efficiency, continue the charge at the normal or 8-hr. current rate for a stationary type of battery, or at the "finishing" rate (usually about one-half of the normal rate) for pasted plate batteries, until neither cell voltage nor acid density show a further increase for four 15-min. intervals, which will indicate that the battery is fully charged.

102. Capacity tests. Since the capacity depends on the rate of discharge, it will be advisable, with stationary types of batteries, to obtain test discharges at several different rates; in particular, those most nearly approximating the desired service conditions. Nearly all the makes of storage batteries will perform the higher discharge rate if they will give full capacity at the normal or 8-hr. rate. In conducting the usual tests, the charges should preferably take place at the normal rate. When the discharge is started, the current should be maintained as steady as possible and should continue until the cell voltage has reached its limiting value. Voltage readings should be taken at stated intervals and the strength of acid, temperatures and possibly also cadmium readings should be taken at the same time. The same readings should be taken on the subsequent charge. It is advisable to plot these readings, as any discrepancies will then be apparent. The ampere-hour capacity of the cell will be the average amperes multiplied by the time of discharge in hours. The watt-hour capacity will be the ampere-hours multiplied by the average voltage of discharge, provided the current is maintained reasonably steady.

103. Characteristic performance. A complete series of tests as outlined in Par. **102**, carefully plotted, will give the battery characteristics. With a set of these curves, the performance of a battery can be quite definitely determined. It is of little value, from an engineering standpoint, to know the internal resistance of a cell, except for highly special applications, as the drop in voltage due to polarization, usually greatly exceeds the resistance drop. The expression of "**virtual internal resistance**," which is an attempt to include polarization effects is also of no value, as it contains no time factor, and the time the discharge is to last is of extreme importance.

104. An approximate way of determining the internal resistance of a cell is to proceed as follows: momentarily interrupt the current and note the instantaneous increase in cell voltage, preferably by the condenser, ballistic galvanometer method. The difference between the terminal voltages with and without the current flow is the resistance drop; dividing this difference by the current will give the approximate value of the internal resistance. Values determined by the wheatstone bridge method with alternating current will be in error on account of the capacity effect which any electrode shows in an electrolyte.

105. Efficiency tests. The efficiency of a storage battery is the ratio of watt-hours of discharge to watt-hours of charge and should be determined as the mean of several charges and discharges, as there is no absolutely definite point to terminate either the charge or discharge. The condition to be met is simply that the battery must have received sufficient charge each time, to insure full capacity on the succeeding discharge. The efficiency should be taken as the ratio of the total watt-hours of discharge to the total watt-hours of charge, for all the charges and discharges. For efficiency tests, the end point of charge should be taken as the point when both positives and negatives are gassing uniformly, the voltage showing the same value for two read-which otherwise would cause internal short-circuits. The separators are kept from floating by pieces of glass called **separator hold-downs.** The cells are set in a layer of sand contained in a wood sand tray thoroughly coated with asphaltum paint, and the sand trays are mounted on glass insulators. The use of porcelain insulators is to be avoided, as the glaze is attacked by acid spray and the insulating properties are lost. Glass sand trays with integral insulating feet are often used instead of the wood trays and insulators. They are not satisfactory with the larger sizes on account of liability to breakage.

110. Lead-lined tank construction. Plates $15\frac{1}{2}$ in. $\times$ $15\frac{1}{2}$ in. and larger are always mounted in lead-lined tanks, the construction being shown in Fig. 25. The wood tanks are preferably of long-leaf yellow pine, with dovetail joints and dowels and without metal fastenings. The tanks should be painted both inside and outside with three coats of acid-resisting paint, and lined with 4-lb. sheet lead, the lining projecting outside the wood tank in order to prevent acid falling onto the tank. Tanks should have liberal mud space to take the accumulation of sediment. The sediment space should exceed one-third of the length of the plate. The tanks should be supported on glass insulators, the oil-filled type with a protecting cover being preferred. Lead footings are placed in the bottom of the tanks, upon which rest the glass support plates. The support plates are about $\frac{3}{8}$ in. thick, and have the upper edges, which support the plate lugs, ground smooth. The plates are lead-burned to bus bars of extruded lead and wood separators with dowels are used to space the plates, as with the glass-jar cells. A few installations of large cells have been made in special acid-proof stoneware tanks, but this construction has not come into general use.

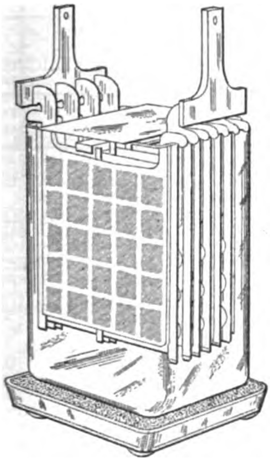

Fig. 24.—Cell in glass jar.

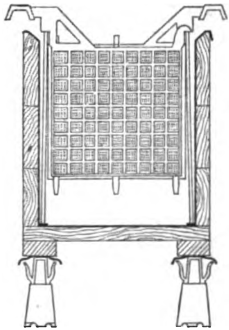

Fig. 25.—Cell in lead-lined tank.

111. Erection. Glass-jar cells are mounted on wood stringers, or two tier racks if space is limited, these being thoroughly coated with acid-resisting paint. The insulators for lead-lined tanks usually rest upon acid-resisting tile, the tiles being brought to a level by supporting them on pillars of sulphur-sand cement. These piers are made by supporting the tile on a ball of stiff cement and pouring melted sulphur, into which sand has been stirred. Another method of insulator support is to use heavy earthenware truncated cones in place of the sulphur piers.

harge at the normal rate, may be as high as 2.65 volts with the cell at 70 eg. Fahr., and as low as 2.45 volts. All commercial lead contains a small ercentage of impurities such as copper, antimony, etc., and these are evenually deposited from the positives, with their proceeding corrosion, onto he negative-plate surfaces. The result of these deposits is generally to educe the final charge voltage. If a positive-plate grid contains antimony, he effect is quite marked. Antimony, artificially introduced into a cell, vill produce this effect.

114. The point of discharge termination is determined arbitrarily, he main condition being that the cell voltage drops with increasing rapidity, oward the end. The capacity decreases with increasing discharge rates, as shown in the curves of Fig. 27, and the initial, average, and final voltages are also indicated. The decrease in capacity, as previously stated, results rom lack of time for acid to diffuse into the active material.

115. Voltage variations on intermittent charges and discharges. Stationary types of lead batteries are capable of charging and discharging at high rates for short intervals, with a relatively small variation of voltage. The curves of Fig. 28 show voltages at the end of charge and discharge for the times indicated on the different curves. These curves are of importance in determining the variation of line voltage with a "floating battery," or that amount of work necessary to be done by a booster generator in series with a battery, in order to maintain a constant line voltage.

116. Variation of capacity with temperature. The rate of diffusion of acid into the pores of the plates varies markedly with temperature, and, in consequence, there is a marked decrease in capacity with lower temperatures. Temperature coefficients for different rates of discharge are as shown in the curve of Fig. 29.

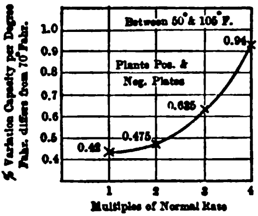

Fig. 29.—Temperature coefficients.

117. Nominal battery ratings. Frequently a stationary battery is referred to as having a kilowatt-hour capacity. By this is meant the 8-hr. or normal ampere-hour capacity multiplied by the number of cells and by the open-circuit voltage per cell which is approximately 2.1 volts.

ELECTRIC VEHICLE BATTERIES

118. Adaptable types. Pasted plates are universally used in vehicle batteries at the present time, although there is no reason why a battery with Planté positives and pasted negatives should not be successful on account of its greater capability to withstand "boosting" charges. By a boosting charge is meant a partial charge at a high current rate, such a charge taking place at the noon hour or other rest period after the battery is partly discharged. The Planté positive, even with a pasted negative, may be charged at enormously high rates without the injurious heating which develops in the Edison battery.

If in a particular service, the capability of a battery to withstand boosting at high rates is of importance, this combination should receive consideration.

The prime reason for the use of pasted plates is their relative lightness, since a reduction in weight of battery results in a reduced current consumption for the vehicle and a reduction in the expense of tire upkeep. For these reasons, battery-plate life is often deliberately sacrificed by using thin plates and a small separation between plates. Small separation makes it necessary to employ strong acid and this reduces the life of the separators as well as the life of the plates. There is already a strong tendency toward the use of thicker separators and a reduced acid strength.

Size of Jar 6.125 in. wide, 4.25 in. long, outside				
Type of plate	Weight per cell (lb.)	Capacity at 6-hr. disch. rate (amp. hr.)	List price per cell	Average life (amp-hr.)
'hick...........	34[illegible]	155	$16.70	77,500
Medium.........	33[illegible]	171	17.75	71,800
'hin............	35	189	19.00	71,000
Extra thin.......	37	204	20.10	61,200

Size of jar 6.125 in. wide, 8 in. long, outside				
Type of plate	Weight per cell (lb.)	Capacity at 6-hr. disch. rate (amp. hr.)	List price per cell	Average life (amp-hr.)
Thick...........	64	309.0	$30.00	154,000
Medium.........	65[illegible]	343.0	32.20	144,000
Thin............	65[illegible]	378.0	34.95	143,000
Extra thin*......	67[illegible]	382.5	35.10	115,000

124. Separators. The plates are insulated from each other by thin ieets of corrugated wood veneer, grooved on one side, the wood used being ther naturally free from such organic substances as would injure the plates, else treated to remove such impurities. These veneers are usually kept vay from the positive plate by inserting a thin sheet of perforated hard ıbber. The smooth side of the veneer is placed against the negative ate. The life of these wood separators is unfavorably influenced by very rong acid also by an excessive amount of overcharge. If batteries are roperly operated, ıe separators will st as long as will ıe plates of a thin- ate battery, that , 12 to 15 months commercial ser- ice and 18 to 24 ıonths in pleasure- ehicle service.

Thick plates will enerally have a mger life than the ood separators, so ıat, in order to ob- ıin the best possible fe of the plates, the ɜparators will re- uire renewal. If ıe separators and the plates are to give approximately equal lives, sufficient pace should be provided in the jars to take all the sediment which will be hrown off in the life of the plates, *i.e.*, high-bridge jars should be used. therwise the space should be ample to take the sediment which will be de- osited during the interval of separator renewals.

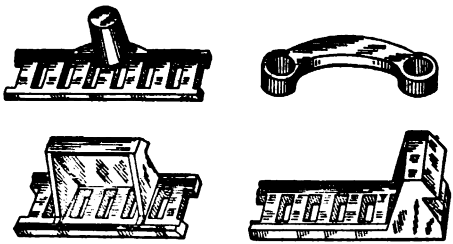

Fig. 33.—Vehicle type straps and connector.

125. The straps to which the plates are burned are of several types, s shown in Fig. 33. The pillar-post strap, used with connector links, is

* Length of standard jar for this size is 7[illegible] in.

discharge is great. In extreme cases, acid of 1.300 sp. gr. at full charge is used, and only sufficient volume employed to give a final acid density of 1.100. A better life of plates and separators will result, however, if a wide enough separation between plates is used to permit a full charge density of 1.260 to 1.280 sp. gr.

128. Crates. The method of assembling vehicle cells into crates is shown in Fig. 34. The crates are of hard wood, painted thoroughly with asphaltum acid-resisting paint or else soaked in hot paraffin oil, then subsequently dipped into melted paraffin. The practice of fastening crate terminals onto the crates is to be thoroughly condemned, as when the crates become acid-soaked, there is current leakage between them, and the positive terminal corrodes seriously. Crate ends are charred from this cause, and the current leakage is of a magnitude not to be neglected.

129. Performance of thin-plate batteries. The variation of capacity of a thin-plate vehicle-type battery in wide commercial use, is shown in

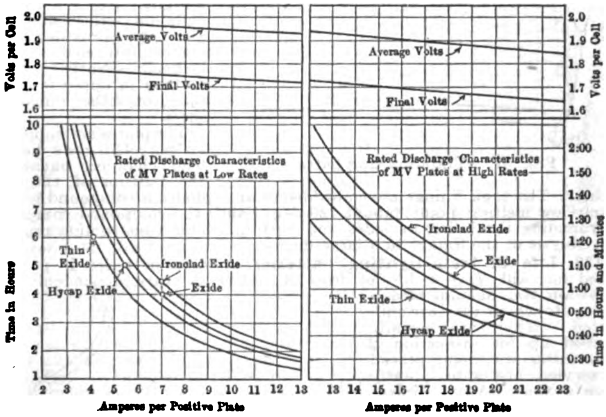

FIG. 36.—Exide plate characteristics.

Fig. 35 and the average and final voltages are also given. The Electric Storage Battery Co. has devised an ingenious chart showing the characteristics of their "Exide" batteries which is reproduced in Fig. 36.

TRAIN-LIGHTING BATTERIES

130. Capacity. A special type of battery has been developed for the lighting of steam railroad trains. The standard battery comprises 16 cells of 300 amp-hr. rated capacity, and this size is used in most cases for coaches, parlor cars, and sleeping cars. For dining cars, 32 cells are frequently used. Batteries of smaller capacity are often used for lighting baggage and postal cars.

131. These batteries are charged either from an outside source at terminal yards, or, especially where the cars run over several different lines, are operated in conjunction with an automatically controlled axle-driven generator. The "head end system," with a steam-driven generator in the baggage car is sometimes used, though it is not so popular as formerly. (See Railway Train Lighting, Sec. 22.)

132. Design. Batteries for train lighting have been standardized, the construction being shown in Fig. 37. The cells are mounted in pairs in [illegible] for the same purpose. Fig. 38 shows a standard battery design for motor starting and lighting.

136. The voltage characteristics of these batteries, as furnished by several manufacturers, is shown in Fig. 39.

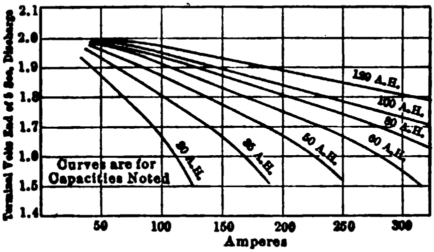

FIG. 39.—Motor starting battery characteristics.

137. Batteries for ignition alone. The current required for ignition rarely exceeds an average value of from ½ to 1 amp. For this reason, batteries for ignition alone usually have thick plate elements, the discharge rates being so low that the full plate thickness is efficiently used. Standard batteries for this service are 4 and 6 volts, that is, two and three cells.

BATTERY ROOMS

138. General rules. It is desirable to install stationary batteries in rooms which have good ventilation and are well lighted. Direct sunlight should not, however, be permitted to fall on the cells; it is well, therefore, to coat windows with an opalescent paint, in order to avoid this possibility and also to cause the illumination of the entire room to be more equally diffused. Where natural illumination is not possible or convenient, a liberal number of electric lamps should be provided. Open flames and fires in stoves must not be permitted, as the cells give off hydrogen and oxygen on overcharge and the mixture of these gases, if sufficiently concentrated, is explosive.

139. Temperature. A battery room should be maintained at as nearly 70 deg. as possible. Higher temperatures than 95 deg. to 100 deg. Fahr., excepting during rare intervals, must be avoided. Low temperatures temporarily reduce the battery capacity, but do no injury.

140. Cleanliness of location. Batteries should not be installed adjacent to an ice plant, or to a stable, as ammonia gas is absorbed with great avidity by the electrolyte and eventually, crystals of ammonium sulphate collecting on the containing tank, may cause the electrolyte to syphon off by capillary action. The capacity of negative plates is reduced by the presence of ammonia. Corrosive gases or vapors from other manufacturing processes should also be avoided. Iron ore dust is also objectionable.

141. Ventilation. If large batteries are to be installed in the immediate vicinity of dwellings, forced ventilation may have to be provided, during the completion of charge, by means of an exhaust fan. The acid vapors may be removed from the exhaust by sucking it through several layers of bronze screen or thin perforated sheets of lead. Exhaust ventilation is much preferable to direct, as air currents are more uniform and there are fewer eddies. The acid spray in the first method does not so readily precipitate upon the tanks and insulators.

142. Protection to iron work and walls. There should be a minimum of exposed piping and iron work in a battery room, especially near the floor.

batteries, the losses of the preceding methods are avoided by the use of automatic regulating boosters (Par. 150) or end cells with end-cell switches (Par. 158).

148. Counter-e.m.f. cells. These are simply cells with unformed plates. When current flows through such cells, they oppose the main battery voltage by approximately 2.8 volts for each counter-e.m.f. cell in series. They are so connected in a circuit that current always flows through them in the same direction, as otherwise they would gradually attain a considerable capacity.

149. Shunt charging booster. This consists of a generator, usually motor-driven, whose field is excited from the line; actually, therefore, the designation is misleading. A variable resistance in series with the field permits the adjustment of the booster voltage to the desired value. These boosters are connected as shown in Figs. 47 and 48.

150. Automatic regulating booster. The charge and discharge of a battery may be made responsive to the variations of any desired means by placing a motor-driven generator in series with the battery, the field of the generator being excited in accordance with such variations. Automatic boosters usually regulate for constant current or for constant voltage. Current regulation is the more frequent application. Regulating boosters are usually driven at practically constant speed. They are used when rapid variations of battery charge and discharge are required.

151. Entz booster. Mailloux proposed the use of two opposing field coils on the booster generator, one a shunt field excited from the line voltage, the other carrying the total current. The Entz modification of this scheme, formerly in wide use, is shown in Fig. 40, in which the coil *A* carries the current from the generator, *B* carries the external load, while the shunt coil *C*, excited at line voltage, carries a practically constant current opposed to *A* and *B*. The coils are so determined that the resultant booster field is zero when both the outside load and the generator load have a certain definite value. Any increase in the outside load then causes a resultant field, and consequently a resultant booster voltage, in the direction forcing the battery to discharge. Any portion of the increased load falling on the generator would tend still further to increase the booster field and result in additional battery discharge. The resultant booster voltage would be in the opposite direction if the outside load decreased and the battery would be forced to charge. Regulation tending toward constant generator current, therefore, results from this scheme. A practical defect of the Entz booster is that, the field being the resultant of two opposing fields, the field structure must carry much more than the normal amount of winding and a highly special machine results.

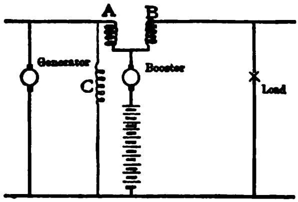

FIG. 40.—Entz booster.

152. Separately-excited booster. The modern boosters have fields of normal dimensions with a single winding excited from a separate machine for this purpose. The excitation schemes in practical use are of two types described below.

153. Carbon-pile regulator. This regulator is shown diagrammatically in Fig. 41 in which two piles of carbon discs are under but a slight compression when the lever arm is in the horizontal position. The lever arm is operated by a solenoid plunger whose coil carries the current to be regulated. The pull of the solenoid is balanced by a spring whose tension is such as to equal the solenoid for normal average current. The bottoms of these two piles are connected, one to the positive and the other to the negative of the battery, and the two tops of the piles connected together. One terminal of the booster field is connected to the junction of the two piles, the other to the middle point of the battery. With the two piles under equal compression, no current flows through the booster field. An increase of current from the main generator causes the solenoid to compress cuits, such as result from hoists, elevator operation, etc., are taken off the opposite side of the booster and are subjected to the battery voltage variation. If the average value of the variable load is less than the difference between the maximum current and the average load, it may be possible to reduce greatly the booster capacity by so connecting it as to realize constant current.

157. Electrical position of booster regulator. Where a portion of the station load is steady and another portion variable, the regulating coil should in general be so placed as to be affected by the variable load only, if this is conveniently possible. This can be done by grouping the constant and the variable loads separately, the coil then being placed between the two groups of circuits. The position indicated will result in closer regulation, since all the practical regulating schemes provide that the current to be regulated shall not depart from its average value by more than a given percentage. This rule holds for both constant current and differential boosters.

158. End-cell switches. An end-cell switch is a device for cutting in or cutting out cells of a series and thereby compensating for battery voltage variation. The contacts of the smaller size switches are usually arranged in the arc of a circle, while with larger sizes the contacts are arranged in a straight row and a heavy laminated copper brush is moved over these contacts by means of a motor-driven worm. In switching from one point to the next, the circuit must not be opened, and the blade must not touch two adjacent contact points, as this would short-circuit a cell having its terminals connected to these points. End-cell switches are therefore provided with an auxiliary contact, either on the moving blade as shown in *B*, Fig. 44, or, in some instances, fixed adjacent to each main contact. The main and auxiliary contacts are joined by a resistance as shown at *C*, but otherwise insulated from each other. The auxiliary contact touches one of the switch points, while the main contact touches the adjacent point. The circuit is, therefore, not interrupted, being completed through the resistance, *C*, which has too low a value to affect the line voltage appreciably. Its resistance, however, is sufficiently great to prevent short-circuiting the cells connected across the two points. The larger sizes of end-cell switches are motor-driven, and are very elaborately designed. The reader is referred to the literature of the various manufacturing companies for full particulars of these switches.

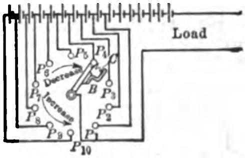

FIG. 44.—End-cell switch.

159. Load-limit devices. It is sometimes desirable to limit the load on the battery. This may be accomplished by providing an adjustable stop to limit the travel of the lever arm of the carbon-pile regulator, and thus limit the amount of current which will flow through the booster field. This, in turn, will limit the amount of battery charge and discharge. An equivalent device for the same purpose can be applied to the Hubbard booster.

160. Average adjuster. It is often desirable to limit the work which a battery does, to taking simply those heavy variations of current which persist for short times, and to allow the main generator to follow the load averaged over relatively long intervals. A device which accomplishes this object is furnished by the Electric Storage Battery Co., and its design is dependent upon the following principle: the armature of a small motor is connected to the adjusting screw which controls the tension of the spring of the carbon pile regulator, through a suitable train of reducing gears. The armature of this motor carries a practically constant current, as it is connected across the line in series with a fixed resistance. The field of the motor is connected across the terminals of the booster. The effect of this arrangement is to permit the battery to absorb momentary fluctuations, while the main generator current follows the load averaged over a relatively longer interval.

OPERATING EQUIPMENT

161. Pilot cells. The specific gravity of the electrolyte of a cell in which the acid level is kept constant by adding water to replace evaporation, is of the power-house. It is necessary to provide a reverse-current circuit-breaker in circuit with the generator.

166. Load-regulating batteries. Batteries may be installed to absorb momentary fluctuations above or below the average load, or any desired percentage of these fluctuations. In this connection it is usual practice to employ an automatic regulating booster (Par. 149) to force the battery to charge and discharge in accordance with the load variations. The number of cells usually installed is equal to the line voltage divided by 2.08, and the size of the battery is generally determined by the condition that frequently recurring discharges should not exceed twice the 1-hr. discharge rate of the battery. Under these conditions, the main battery voltage will not fall below 1.6 volts per cell nor exceed 2.6 volts per cell under regular operating conditions. A limiting voltage of 2.65 volts per cell must, however, be available to complete the regular charge of the battery and to give it the necessary overcharge which occasionally should take place. The booster must, therefore, have a voltage range equal to approximately 0.48 volts times the number of cells, for regulation service. Provision must be made either by increasing the speed of the booster, or else by forcing the booster field to reach the extreme voltage (for booster and generator together) of 2.65 volts per cell in order to give the battery its periodic overcharge. Fig. 46 is a diagram of connections, showing how batteries are applied for this purpose.

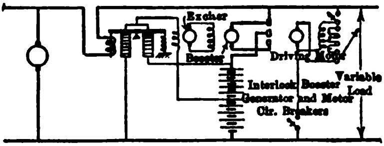

Fig. 46.—Regulating battery.

Regulating battery plants are installed in connection with generators, motor-generator sets or rotary converters, supplying railroad, rolling-mill, elevator and other widely varying loads.

167. Alternating-current regulation. If there is a reversible means of converting alternating to direct current on an alternating-current source of supply, and it is desired to equalize the load variations on the latter, the battery may be made to do this by exciting the booster field in accordance with these variations. The lever of the carbon-pile regulator (Par. 153) would then be subjected to a pull in proportion to the load in watts, or the power component of the load. A solenoid coil carrying the current only will not effect the desired result unless the power-factor remains constant.

Another method of securing equalization of alternating-current variations is to rectify the secondary current from series transformers in the line in such a way that the output of the rectifier is proportional to the power component of the load. The latter may then be the excitation of the c.e.m.f. exciter of the Hubbard booster. The literature of the Gould and Electric Storage Battery Companies should be consulted for details of this method.

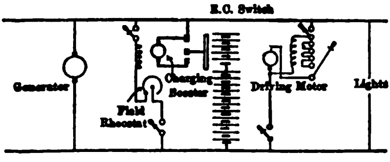

Fig. 47.—Peak load battery.

168. Peak-load batteries. If a battery is to supply a discharge of relatively long duration and at constant voltage, it is usual to effect the voltage regulation by means of an end-cell switch. A diagram of connections for a direct-current two-wire system is shown in Fig. 47. The charging booster is employed for the purpose of adding to the line voltage a sufficient amount to complete the charge of all the cells of the battery. Plants of this nature are used to supply hotel and residence lighting and motor circuits, but are infrequently used for regular operation with large plants, except for emergency reserve.

in regular operating practice, and the end-cell switches are usually installed in pairs for the sake of limiting the amount of current to be carried by a single contact. Provision is not made in the majority of cases for floating the battery on the bus during charge, for the reason that a greater number of end-cell points would be required, and because of the heavy expense of the copper runs to the additional number of end cells. The capacity of a battery for stand-by service is frequently determined by the requirement that it should carry the maximum station peak for a period of 5 or 6 min., and that the usual 150 cells will maintain a voltage of about 115 volts per side during this period.

172. Batteries for telephone exchanges. The batteries of the larger offices are either 11-cell or 22-cell installations, and are floated directly across the power circuit without any special regulating means. The capacity of these batteries is usually such that they will carry the entire station load for a period of 24 hr. or longer. The internal resistance of the batteries is extremely low, owing to the relatively large size of the battery. A low internal battery resistance is especially desirable for telephone service, in order to eliminate the possiblity of "cross talk" (Sec. 21). It is desirable, with these batteries, to select a type that will permit completion of charge at relatively low rates in order to avoid excessive voltages and resultant interference with relay operation and lamp signals.

Planté type batteries are usually used for the purpose on account of their long life. Pure-lead Planté negative plates show high voltages on the completion of overcharge, especially when new, and this fact should receive consideration.

The loads on telephone-office power plants in business districts usually show decided morning and afternoon peaks, and it is usual to operate the charging generator in parallel with the battery during the periods of higher load. The battery alone usually carries the load excepting from, say, 9 A.M. to 4 P.M. in the typical exchange in business districts.

173. Residence and farm lighting plants. A great number of these plants are in service, and they vary in elaboration from a simple battery without voltage regulation (the battery being taken off the lighting service when charging) to

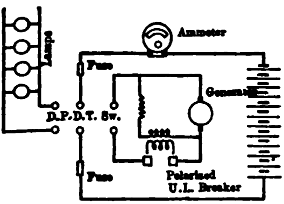

Fig. 49.—Farm lighting plant without voltage regulation.

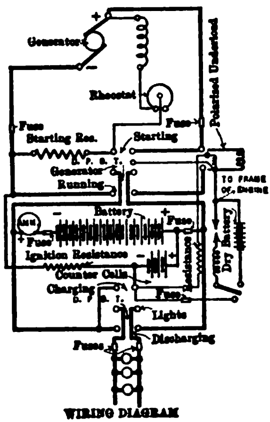

Fig. 50.—Lighting plant with voltage regulation.

the more complete plants previously described. The usual low-voltage plants are 8 and 16 cells, *i.e.*, furnishing 15 and 30 volt lamps. The small plants frequently use vehicle or motor starting and lighting batteries, as these are cheaper for the same capacity and may be readily shipped to a service station for repairs when necessary. The couple-types (Par. 107) of stationary batteries are also frequently used. The regular stationary types will give longer and somewhat more reliable service. Diagrams of connection are given in Figs. 49 and 50, the former without voltage regulation while, in the latter, voltage regulation is effected by counter-e.m.f. cells.

ceive a periodic overcharge at intervals of at least once a week if the attery is called on for heavy service, or once every 2 weeks if the service light. The overcharge is simply a continuation of the regular charge ntil the battery voltage at constant current input has remained constant nd also until the acid density, corrected for temperature, has reached a aximum value as indicated by three successive acid-density determinations, t half-hourly intervals, having the same value.

If any cell or cells are late in gassing or become warm during charge, or if he specific gravity of the electrolyte is markedly lower than in the remaining cells, they should be investigated for short-circuits. Short-circuits will lso be made evident if any cell falls materially behind the others in voltage n discharge. An excessive amount of charge should be avoided, as the resultant gassing will throw off some of the active material, especially from the ositive plates.

182. Removal of separators. If for any reason it is necessary to remove wood separators from a cell, they should be kept covered with water. If llowed to dry out they will shrink, also the resulting concentration of acid n the wood will ruin them. Wood separators which have been in acid for everal months will have so little strength that they cannot be handled without danger of breaking. New separators should be kept damp to prevent heir shrinkage.

183. Evaporation of the electrolyte should be replaced by adding pure water. Keep the level of the electrolyte well above the tops of the plates. Do not add acid to the electrolyte unless it is clearly established hat the removal of possible short-circuits and the subsequent overcharges will not restore the density of the electrolyte. Both water and electrolyte should be pure. It is preferable to add water before an overcharge; as the gassing will serve thoroughly to stir up the acid and equalize any differences in specific gravity between the tops and bottoms of the cells.

184. Operating temperatures. It is best not to allow the temperature of a battery to exceed 100 deg. Fahr.; a temperature above 105 deg. should positively be avoided.

185. It is well to note the color of the plates from time to time and to see that the colors of the plates in different cells are uniform.

186. If the battery is low in capacity, the relative condition of the positive and negative plates should be determined by taking voltage readings between both the positive and negative groups and a cadmium test electrode. This should be done toward the end of the discharge and will determine which of the groups are at fault.

187. If any cell shows low voltage or low acid-density by reason of short-circuits, it should be separately charged after the short-circuits have been removed. In large installations a **milker set** is usually provided for this purpose. This comprises a motor-generator supplying energy at from 3 to 6 volts. Another method is to cut-out the cell on discharge and replace it in the series on charge.

188. The strength of the acid to be used in various types of cells should be that prescribed by the manufacturer. It will depend entirely upon the battery design. The usual practice is to use electrolyte of 1.210 sp. gr. with stationary types of cells, while with vehicle types and with motor-starting and lighting batteries, maximum densities of 1.300 sp. gr. are sometimes used.

189. Be sure that sediment does not accumulate to such an extent as to touch the bottoms of the plates, as this would cause internal short-circuits in the cells. Separators must be kept in place and in good order. The entire battery should be kept clean and free from dirt. Condensed moisture or acid vapors should be wiped off from time to time, and the insulation kept dry. Raw linseed oil should be applied to the wood of lead-lined tanks as occasion demands.

190. Charging rates. The recommendations of the various manufacturers differ widely as to the proper charging current values. The following found necessary thus to interrupt the charging current, the number of ampere-hours of initial charge must be increased.

(e) The initial or developing charge is to be considered complete only when both positives and negatives are gassing uniformly in all the cells, and when there has been no increase in voltage or specific gravity of electrolyte (the latter corrected for temperature) for a period of 5 or 6 hr. The battery should then be open circuited for an hour or so and, subsequently, the current applied again; in this charge, the cells should begin to gas from both positives and negatives within a minute or two.

(f) The battery should not be allowed to discharge until it has been fully developed as above. The color of the positives should be a very deep brown, and the negatives a light lead color.

194. Placing batteries out of commission. If a battery is not to be used for several months it should receive a very thorough charge before allowing it to stand idle. It is desirable, though not absolutely necessary, to give it a freshening charge of an hour or so once a month. If glass-jar batteries are to be left over winter and low temperatures will be met, it may be necessary to remove the acid, see Par. **100**.

If a battery is to remain out of service an indefinitely long time, it will be advisable to remove the acid. Before doing this, it should be given a thorough overcharge. If the plates are to remain in the cells, syphon off the acid and remove the wood separators. Watch cells carefully and when the negatives become hot sprinkle with water. If the plates are to be removed from the cells, keep the positives apart and simply let them dry out. Do not rinse in water. The negative plates must be carefully kept apart, and sprinkled with water as soon as they become hot.

DEPRECIATION AND MAINTENANCE OF LEAD STORAGE BATTERIES

STATIONARY BATTERIES

195. General considerations. As with generating machinery, obsolescence, due principally to changes in service requirements, is the important factor of depreciation. A stationary battery may be maintained indefinitely by replacing worn out parts, but a renewal of tanks or the replacement of a battery room floor is a considerable item of expense. In these events it will frequently be advisable to reconsider the entire installation. Many floating batteries on interurban lines have given ten to twelve years of service with a single renewal of positive plates. The same result has often been obtained with regulating batteries.

196. Actual maintenance costs. A case of five large railway regulating batteries which are called upon daily excepting Sundays, for peak discharges each morning and afternoon, the ampere-hours of discharge aggregating quite approximately the equivalent of one 8-hr. discharge per day, may be cited. A blanket contract to furnish and install all the maintenance material required to maintain the five batteries in efficient operating condition for a second term of 10 years was entered into, the contractor undertaking to do this for approximately 8 per cent. per annum of the initial cost of the installation. The foregoing are among the hardest-worked batteries installed in the United States. Stand-by batteries can be maintained for a period of 10 to 15 years at within 3 per cent. per annum of the cost of installation.

197. Life of plates. Planté positive plates in regulating or line batteries will have lives of from 4 to 6 or more years if they are in hard service, and should last longer in light service. Planté negative plates should outlast two sets of positives within a period of 12 to 14 years. Paste positives in stand-by service show every indication of being good for 10 years of service, negatives being good for a somewhat longer period. The scrap lead of plates, to be replaced, has a considerable value and the cost of plate replacements should be credited with this value. Manufacturers will usually guarantee a minimum life of plates if they know the service conditions.

198. Life of tanks. Glass jars are good until broken and a few jars, especially with the larger sizes, will break from time to time outside of accidental causes. This breakage is usually a consequence of imperfect vercharge of these batteries requires that water be added frequently, if this is not carefully done the insulation of the tanks is injured. Overrge also results in a greater deposition of sediment from positive plates a shortening of their lives.

209. Frequency of cleaning. Train-lighting batteries which are perly charged can be kept in operating condition for 3 years without ng opened up for cleaning. After cleaning the first time such batteries ould be cleaned at intervals of 2 years. With many railroads the actice is to make the first cleaning 2 years after placing in service, with bsequent intervals of 1 year between cleanings.

ALKALINE STORAGE BATTERIES

210. Classification. There are but two practical types of alkaline storage tteries in commercial use: one is the Hubbell, used in the miners' lamps of e Portable Electric Safety Light Co.; the other is the Edison storage battery.

211. The Hubbell battery differs from the Edison in principle, only in sing a negative plate of cadmium instead of the iron of the Edison battery. ubbell apparently was the first to use nickel threads incorporated in the ickel-oxide active material, and this is one of the essential steps in the production of a practicable battery plate with this active material. The nickel xide of the original Edison battery, contained flake graphite to increase the onductivity; the graphite was seriously affected by electrolyte action, and hese plates were short lived. In the present type of Edison battery, flake ickel replaces the graphite of the earlier type. In December, 1914, the first ew of these batteries had completed 5 years of service.

212. Theory of the Edison battery. The active materials of the Edison battery consist of nickel peroxide for the positive plate and finely livided iron for the negative plate. The electrolyte is a 21 per cent. solution of potassium hydrate in water to which is added a small amount of lithium hydrate. To overcome the passivity of iron a certain amount of mercury is incorporated with the iron of the negative plate; a suitable compound is also incorporated with the nickel hydrate which is the salt from which the nickel peroxide is electrolytically formed. The nickel oxide is a relatively poor electrical conductor and, for this reason, layers of flake nickel are added in the mass to increase its conductivity. Catalysis plays a large rôle in the action of the Edison battery. A complete and correct theory of these reactions has probably not yet been given. Essentially, however, it is the following:

$$8OH+3Fe=Fe_3O_4+4H_2O \quad \text{(Negative Plate)} \quad (11)$$

$$8K+6NiO_2=3Ni_2O_4+4K_2O \quad \text{(Positive Plate)} \quad (12)$$

$$8KOH+6NiO_2+3Fe=Fe_3O_4+2Ni_3O_4+8KOH \quad \text{(Both Plates)} \quad (13)$$

or,

$$6NiO_2+3Fe=Fe_3O_4+2Ni_3O_4 \quad (14)$$

The above formula, read from left to right, indicates discharge; read in the reverse direction, it indicates charge.

Both the iron and nickel oxides probably do not exist as such, in the electrolyte, but are hydrated. In the charge of the battery, potassium is not deposited, and there are none but concentration changes in the electrolyte in the pores of the active materials. There is no appreciable change in electrolyte density from the charged to discharged state of the Edison battery. At the latter end of charge a higher oxide of nickel is formed, which is unstable on standing. This oxide decomposes to NiO_2 with time. A freshly charged Edison battery shows a higher voltage on discharge than one which has been standing.

213. Positive-plate construction. The positive plate consists of a nickel-plated steel frame into which are pressed perforated tubes filled with alternate layers of nickel hydrate and metallic nickel in very thin flakes. The tube is formed from a thin sheet of steel, nickel plated and perforated, and has a spirally lapped joint. The active material is tamped into the tubes, nickel hydrate and nickel flake being fed alternately and the tubes when

214. Data, Edison Cel...

Type of cell	B-2	B-4	B-6	A-4	A-5	A-6	A-8	A-10
No. positive plates	2	4	6	4	5	6	8	10
No. negative plates	3	5	7	5	6	7	9	11
Weight (lb. per cell)	4.6	7.4	11.0	13.3	16.8	19.0	27.0	34.0
Capacity (amp.-hr.)	40	80	120	150	187.5	225	300	375
Charge amp. for 7 hr.	7.5	15	22.5	30	37.5	45	60	75
Discharge amp. for 5 hr.	7.5	15	22.5	30	37.5	45	60	75
Avg. volt per cell discharge at above rate	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Amp.-hr. efficiency	82	82	82	82	82	82	82	82
Watt-hr. efficiency	60	60	60	60	60	60	60	60
Watt-hr. per lb. of cell	10.4	13.0	13.7	13.3	13.4	14.1	13.1	13.2

boxes are assembled in the grid and subjected to pressure to weld the joints and to corrugate their surfaces. The iron is precipitated as a chemical compound and the nickel hydrate and this iron compound are converted electrolytically to nickel peroxide and metallic iron respectively, in the forming of plates.

216. The assembly of the cell is shown in Fig. 53. The plates are supported on hard-rubber spacing and insulating pieces. The lugs of the plates are punched and are mounted upon a steel pin with a terminal post. The ends of the pins are threaded and the plates, separated by washers, are held together by steel nuts. The elements are contained in a nickel-plated sheet-steel case, the walls of which are corrugated to add stiffness and also to assist in cooling the cells in action. The cover also is of

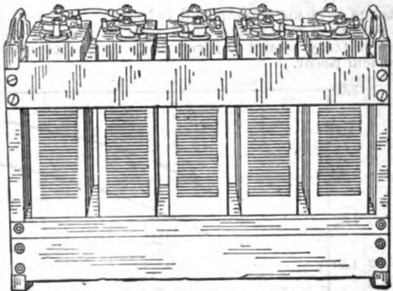

Fig. 54.—Crate mounting.

sheet steel with three openings; two for the terminal bushings, which are provided with stuffing boxes, and the third for the gas vent and for the filling of the cell with water.

The cells are assembled in wood crates as shown in Fig. 54, usually with the bottom left open to secure a circulation of air sufficient to keep the cells cool.

With the Edison battery the discharge rate which has been taken as the normal or standard, is that which would discharge the battery in 5 hr.

The numerals of the type designations indicate the number of positive plates in a cell, and each positive plate of the vehicle size is capable of giving 7.5 amp. for 5 hr.

217. Charge and discharge curves. The characteristic normal charge and discharge curves for an Edison battery are given in Fig. 55. It will be noted that the average voltage on discharge is approximately 1.2 volts; the initial open-circuit voltage is approximately 1.5

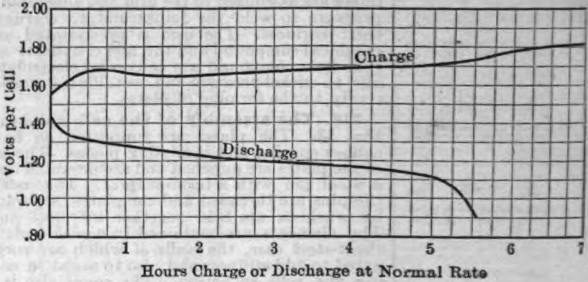

Fig. 55.—Normal charge and discharge curves.

charge. If an Edison cell is known to have been considerably discharged, it is always well to continue the charging current for the full 7-hr. period, as the battery is not injured by overcharge unless the temperature passes a critical point.

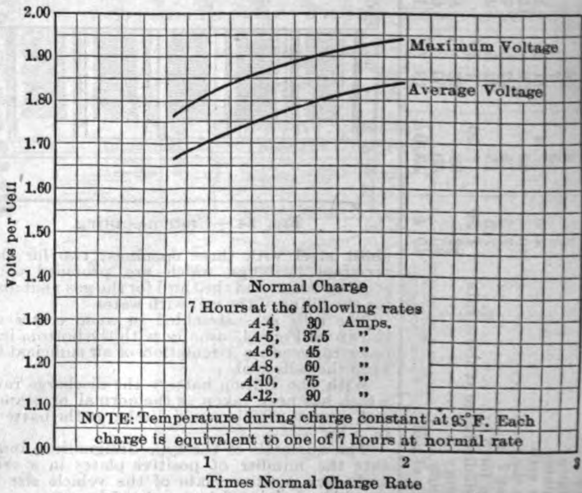

Fig. 56.—Temperature influence on charging voltage.

218. Charging curves. Maximum and average voltages of charge as influenced by charging rate, are shown in Fig. 56. In these curves, the cell is presumed to have a constant temperature of 95 deg. Fahr. and the duration of charge is 7 hr. The voltage on charge decreases considerably with increasing temperatures.

219. Characteristic discharging curves. Characteristic discharge curves for Edison type "*A*" cells are given in Fig. 57. It will be noted that the ampere-hour capacity of an Edison cell does not suffer very greatly with increasing discharge rates, if the terminal voltage be carried low enough. For practical purposes, however, the last portion of the discharge at high rates would have no value because of its great falling off from the open-circuit voltage.

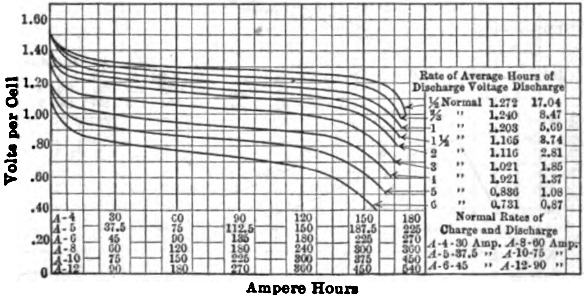

FIG. 57.—Typical discharge curves, type "*A*" cells.

220. Standing discharged. No injury is done to the Edison battery if it is completely discharged and allowed to stand in this condition. This is one of the principal distinguishing features of the Edison battery. The cell, however, loses in capacity by standing as shown in Fig. 58, and is most easily brought back to its condition of full capacity by giving it a very considerable overcharge. The usual practice is to ship the Edison battery in a discharged condition, and it requires several cycles of charge and discharge to bring it to its full capacity.

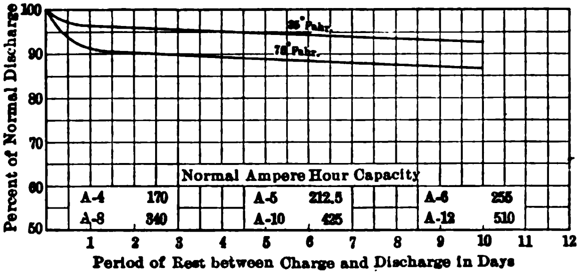

FIG. 58.—Loss of capacity.

221. Overcharge. The Edison battery is not injured by overcharging unless its temperature exceeds 105 to 110 deg. Fahr. High temperatures seriously affect the capacity and life of Edison negative plates, and the manufacturer's guarantee does not hold for overheating from this cause. A continuance of overcharge increases the capacity on the subsequent discharge, but this increase in capacity is obtained at the expense of efficiency. The effect of continued charge is shown in Fig. 59.

222. Effect of temperature. There is a marked falling off in capacity of the Edison battery with low temperature, especially at high discharge suitable neutral or test electrolyte for an Edison battery is a nickel-oxide tube, such as those used in the standard positive plates.

225. Application. The "*B*" type cells are used for ignition and lighting of gasoline motor cars; they are not commercially used for motor starting on account of the high internal resistance. The vehicle-type cells are used for electric vehicle propulsion, storage battery street cars, mining locomotives and industrial trucks; they are not used for load regulation on account of the heavy drop in voltage at high discharge rates, this factor also limiting their use in other power applications.

226. Operation. The life of the Edison battery is guaranteed under certain restrictions as to its operation. The operating instructions of the Edison Storage Battery Co. should be carefully followed if the battery company is to be held to its guarantee. A temperature of 115 deg. Fahr. should not be exceeded under any circumstances, as high temperatures will seriously injure the negative plates.

227. Initial or first charge. Edison batteries are usually shipped in a discharged condition. Before placing them in service they should receive a continued charge at the normal or 5-hr. rate, for a period of 12 hr. or more.

228. Regular charge. If the battery has received a complete discharge, the charge should be started at the normal rate and continued for a period of 7 hr., or until each cell, under normal temperature conditions, has reached a voltage of at least 1.8 volts per cell. The ampere-hours of charge should exceed the ampere-hours of discharge by approximately 40 per cent., and the battery should receive in addition, an overcharge of several hours at the end of each month of service.

229. Replacing evaporation. The electrolyte must be kept well above the plates by adding water whenever necessary, to maintain the level. Always use distilled water for this purpose.

230. The outside of the cells and the trays must be kept clean and dry. Dampness under certain conditions will cause the containers to pit under electrolytic action.

231. Standing idle. If an Edison battery is to be placed out of commission it need not receive any special attention, other than to see that the electrolyte is brought to the proper level. The battery can stand either charged or discharged equally well. To obtain the full capacity, however, after a long period of standing it is necessary to overcharge the battery.

232. Life of Edison battery. A log of a life test as published by the Edison Storage Battery Co. is shown in Fig. 60, the statement is made that the conditions of the test are harder than would normally be met in service. The battery is more durable than the vehicle types of lead battery. It is doubtful if it approaches the durability of the heavy Planté types of lead cells.

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SECTION 21

TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY

BY

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TELEPHONY AND TELEGRAPHY

RADIOTELEGRAPHY

SECTION 21

TELEPHONY AND TELEGRAPHY

BY

FRANK F. FOWLE, S.B.

Consulting Electrical Engineer, Member American Institute of Electri[...] Engineers

DEFINITIONS

1. **The scope of this section** is confined to the needs of electrical eng[...] neers who encounter telephone or telegraph problems only in the sense of a[...] adjunct to a major operation, or subsidiary to the main work in hand. Therefore the section deals exclusively with those applications of telephon[...] and telegraphy which may be termed **private-line systems**, as found in con[...] nection with steam and electric railways, transmission and distribution sys[...] tems, industrial plants, etc.

2. **Telephone systems** may be classified, according to their commerci[...] uses, as follows:

Telephone Systems
- *Public*
  - *Exchange*
  - *Toll*
- *Private*

3. **Public telephone systems** are those operated for commercial profi[...] under some fixed schedule of tariffs or rates. Such systems must serve a[...] who apply, and are usually subject to some form of regulation as to rates an[...] service by the public authorities. Any public system might be broadl[...] defined as a common carrier of intelligence or communication.

4. **Telegraph systems** may be classified, according to their uses, as fo[...] lows:

Telegraph Systems
- *Public*
- *Fire Alarm*
- *Police*
- *Private*

5. **Public telegraph systems** may be defined in general the same [...] public telephone systems, in Par. **3**, with the exception that the mode [...] communication of course is different.

6. **Private telephone and telegraph systems** are those operated [...] auxiliaries to some other form of business or enterprise (Par. **1**), but not d[...] rectly for commercial profit. Private systems are sometimes interconnect[...] with public systems, and in other cases are completely isolated. Any priva[...] system which is operated under especially hazardous conditions, such [...] long parallel exposure under a high-tension transmission line or close pro[...] imity to a single-phase traction system, should be connected to a publ[...] system, if at all, only through elaborate protective apparatus designed [...] reduce to an absolute minimum the probability that dangerous potentials [...] currents will penetrate beyond the protection to any part of the public syste[...]

7. **Private systems may be classified**, according to their uses, as follow[...]

Private Systems
- *Train Dispatching*
- *Load Dispatching*
- *Line Patrol*
- *General communication*
- *Intercommunicating*

systems, or in large transmission and distribution systems, in connection with the centralized control of the distribution system by one or more load dispatchers.

10. Line patrol systems are used in connection with the patrol of transmission lines, to enable patrolmen to communicate quickly with headquarters; they are used also by the U. S. Life-Saving Service.

11. Private systems for general communication have numerous and extensive applications on steam and electric railways, and in connection with central stations, transmission and distribution systems, etc.

12. Intercommunicating systems are designed for isolated local service, usually without attendance, in factories, mills, shops, residences, etc.

STANDARD TELEPHONE INSTRUMENTS

13. Speech is transmitted electrically by means of three supplementary elements, termed the transmitter, the line, and the receiver. The sound waves of the voice impinge upon the diaphragm of the transmitter and cause it to vibrate in substantial synchronism with the impressed disturbance. The diaphragm forms part of an electromechanism which establishes in the line circuit an alternating current of variable frequency, amplitude and wave form, but substantially proportional at any instant to the pitch, intensity and quality, respectively, of the impressed sound. The line current in its passage over the line suffers both loss of intensity, or attenuation, and change of wave shape, or distortion. If not too greatly enfeebled or distorted by its passage over the line, the transmitted energy enters the receiver and is there converted again into sound waves, approaching in pitch, intensity and quality the impressed sound waves at the transmitter. The receiver is an electromechanism whose function is the reverse of that performed by the transmitter.

The alternating line current, in certain instances, is superimposed on a continuous current, the resultant being a pulsating current. The two currents are separable either by means of a transformer, known in telephony as a repeating coil, or by a combination of reactance (choke) coils and condensers.

14. Transmitters of the variable-resistance, granular-carbon type are almost universally employed. This type consists essentially of two parallel circular electrodes, usually of carbon, one of which is attached to the diaphragm, the other being rigidly mounted. Between the electrodes is a loose mass of finely granulated carbon. Vibration of the diaphragm causes simultaneous variations of pressure on the granular carbon, with accompanying changes in total resistance from electrode to electrode; the resistance decreases with increase of pressure, and *vice versa.*

15. High-resistance transmitters, having about 30 to 60 ohms average resistance, are ordinarily employed for both common-battery and local-battery (magneto) sets. High resistance is particularly desirable in common-battery sets, with central energy supply; it also has the advantage, in local-battery sets, of being economical in energy consumption.

16. Low-resistance transmitters, having about 10 to 15 ohms average resistance, are used in special service (local battery) where the transmission requirements are severe, such as railway train dispatching. Special low-resistance transmitters intended to operate from 110-volt direct-current lighting circuits are used in connection with loud-speaking telephones for announcing trains, paging guests in hotels, etc.

17. Solid-back transmitter. Fig. 1 shows a cross-section of what is commonly known as the White or solid-back transmitter. In this, P is the bridge mounted securely at its ends on the front, F. The diaphragm, D, is of aluminium, with its edges enclosed in a soft rubber ring, *e*, and is held in place by two damping springs, *ff*. W is a heavy block of brass, hollowed out to receive the rear electrode, B, which is of carbon secured to the face of a metallic disc, *a*. E is the front electrode, also of carbon, carried on the head of a metal stud, *b*. This electrode is clamped to the diaphragm by means of a

19. Induction coils, when used, form a portion of the transmitting circuit and perform the function of a step-up transformer, in order to transmit to the line impulses or waves of higher potential than those produced in the transmitter circuit. Induction coils are always used with local-battery sets, but not with all makes of common-battery sets (see Fig. 10). It is very important to use the particular type and construction of induction coil which is designed for the transmitter with which it is associated; a different type may operate with fair satisfaction, but not with maximum efficiency.

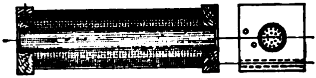


Fig. 3.—Cross-section and end view of induction coil.

The general construction of induction coils is shown in Fig. 3. The core consists of a bundle of small iron wires; some manufacturers employ annealed Norway iron. One manufacturer recommends a ratio of primary to secondary turns, for local-battery sets, of one to four. The secondary is usually wound over the primary. Primary resistances vary from a fraction of an ohm up to about 10 ohms; secondary resistances range from about 20 to 150 ohms. Primary windings range in size from No. 18 to 26 A.W.G. and secondary windings from No. 26 to 36. The diameter of the iron core is usually 0.25 in. minimum.

20. Receivers consist essentially of three elementary parts, a permanent horse-shoe magnet, a sheet-iron diaphragm assembled in front of the magnet poles, and a winding on the polar extremity of each leg of the magnet. The normal tension on the diaphragm varies in synchronism with the current traversing the winding; thus when the winding is energized by voice currents, the diaphragm sets up corresponding voice sounds. Such an instrument is also reversible and may be used as a transmitter of the electromagnetic type; it is not efficient, however, and is used for this purpose only in emergencies, for example when the transmitter battery supply fails, to communicate with the switchboard operator. A modern telephone receiver is shown in Fig. 4. The working parts of this receiver are composed of two bar magnets clamped together by screws passing through an iron tail block, *b*, at one end and through a brass block, *c*, at the end nearest the magnet coils. The magnet unit, in one type, is welded to avoid the presence of joints. The pole pieces are clamped between the magnet ends and the brass block and on their outer ends carry the two coils. The block engages a shoulder in the hard rubber shell and is secured in place by screws, thus holding the working parts securely within the shell. The diaphragm is clamped between the ear piece and the main body of the shell. The terminals of the coils are led to the binding posts, *aa*, to facilitate connecting the receiver in the external circuit. The cord covering is secured to the tail block, *b*, so as to relieve the cord terminals from strain. A type similar in design but differing in that the diaphragm, coils and magnets are all mounted on a separate metallic frame, independently of the enclosing shell, has the advantage that breakage of the shell does not necessarily destroy the adjustment of the instrument.

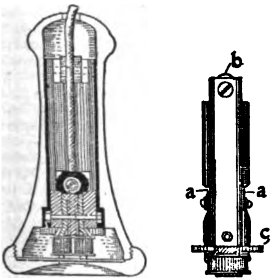


Fig. 4.—Cross-section of receiver and side view of magnets.

Bipolar receivers are also made in the so-called "watch-case" type. This type is attached to a head band and almost universally employed with operators' sets for switchboard service.

type is arranged to revolve in the magnetic field produced by permanent

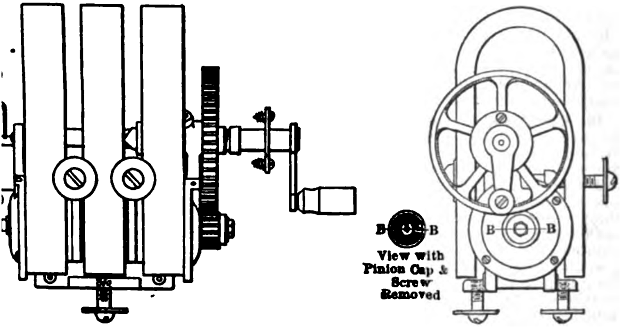


FIG. 6.—Magneto generator.

agnets, being driven through light spur gears increasing the speed in ratio of out 5 to 1. Therefore when the crank is revolved at 200 rev. per min., e frequency will be about 17 cycles per sec.; probably the average freiency is between 10 and 15 cycles.

The **series type**, for series sets (Par. **35**), must be provided with an autoatic short-circuiting device to remove it from circuit when not in use. The unt or **bridging type**, for bridging sets (Par. **34**), must be provided with automatic circuit-opening device to disconnect it from circuit when not in e. These automatic switches are erated by the shaft which carries the nerator handle and large spur gear. g. 7 shows the circuit of a bridging nerator; the shaft *b* is so arranged at it will advance against a coiled ring and engage the spring *c* before tating the spur gear, thus closing the rcuit between the terminals *aa*. In le make of generator, a device is also ovided to separately short-circuit e generator armature when out of e, in order to protect it from lightng or excessive foreign potentials.

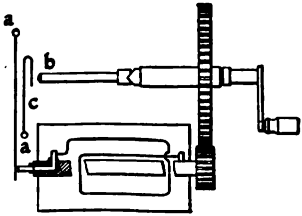


FIG. 7.—Diagram of magneto generator connections.

27. Magneto generator windings d ratings. The output of these nerators, owing to their small size d high internal impedance, is very nited. The lower the internal impedance and the larger the magnetic flux rough the armature, the greater will be the output for a given size and eed. The windings vary in resistance, in different sizes and makes, from out 100 to 500 ohms, with several thousand turns. The best grade of agnet steel (Sec. 4), with maximum retentivity and minimum aging, ould be used. Generators for light service are usually equipped with ree magnets, and are known as the 3-bar type; four bars are used for meium service and five for heavy service. The generated effective e.m.f. at o load and 1,000 r.p.m. (armature speed, giving 16.7 cycles per sec.)

each other, and connected to the instrument terminals through the contacts of the hook switch, the latter being closed only when the receiver is off the hook, as shown in Fig. 9. The ringer and the generator are connected in series with each other, and stand normally connected to the instrument

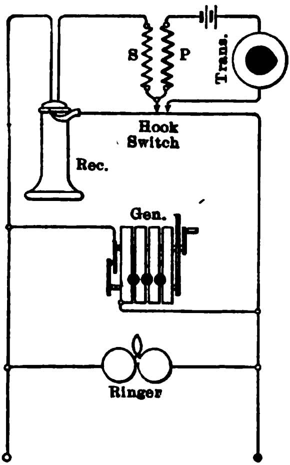


FIG. 8.—Circuit diagram of typical bridging telephone set.

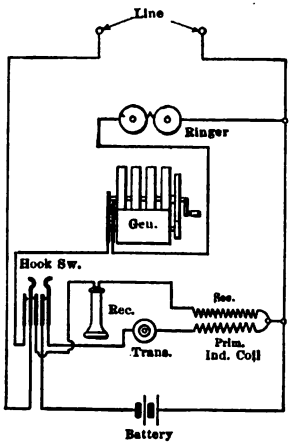


FIG. 9.—Circuit diagram of typical series telephone set (Stromberg-Carlson).

terminals when the receiver is on the hook, but are disconnected when the receiver is in use. The generator is short-circuited except when in action.

38. Common-battery bridging sets are illustrated in Figs. 10 to 13. The simplest type of circuit appears in Fig. 10. The transmitter current is obtained over the line circuit from the central battery at the switchboard.

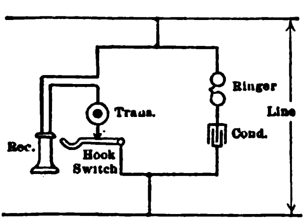


FIG. 10.—Circuit diagram of typical common-battery bridging set without induction coil.

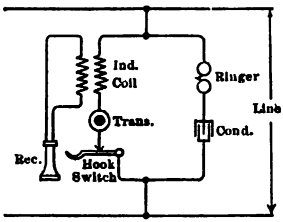


FIG. 11.—Circuit diagram of typical common-battery bridging set with induction coil.

Receivers of the permanent-magnet or polarized type must be properly poled, so that the transmitter current will strengthen their magnets instead of weakening them. Continuous-current receivers (Par. 22) are sometimes used in this type of set.

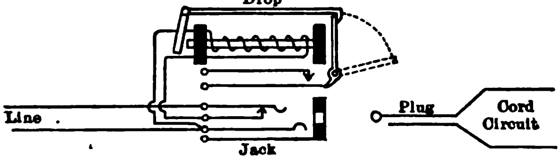


Fig. 14.—Circuit diagram of line jack and drop in non-multiple magneto switchboard.

are made in some cases with a restoring coil which serves to return the shutter to normal position when the operator answers the call by inserting a plug in the answering jack (Par. 43); in other cases the drop and the answering jack

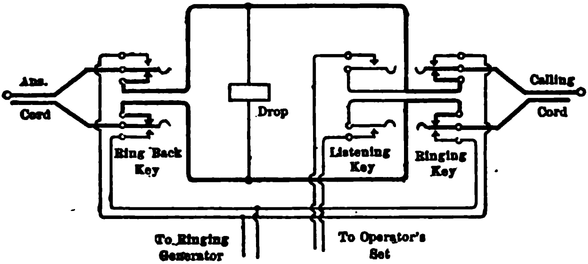


Fig. 15.—Circuit diagram of cord-circuit in non-multiple magneto switchboard; single clearing-out drop.

are mounted together and so arranged that the plug restores the shutter mechanically when the plug enters the jack. The terminus of the line circuit is usually wired as indicated in Fig. 14. Drops are wound of various resistances from 80 ohms to 1,000 or 1,200 ohms; a resistance of 500 to 600 ohms is very commonly used.

43. Switchboard line jacks for non-multiple magneto boards are usually of the type illustrated in Fig. 14. The drop is disconnected from one side of the line by the insertion of the plug in the jack. The night-alarm contacts are shown just below the drop winding.

44. The wiring of a cord circuit with ringing keys, listening key and single supervisory drop is given in Fig. 15. The wires of the through talking circuit are shown in heavy lines. There is some disadvantage in having but one supervisory drop, since it is not possible for the operator to predetermine which line is signalling for attention. This difficulty is overcome in the cord circuit which appears in Fig. 16 (keys not shown), inasmuch as

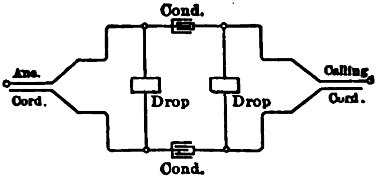


Fig. 16.—Circuit diagram of cord-circuit with double clearing-out drops, for double supervision.

in position between the main frame and the board, for the purpose of enabling any answering jack to be associated with any set of multiple jacks.

50. Switchboard wiring is usually in cable, and the style of cable is commonly referred to as **switchboard cable.** This type of cable is made from various sizes of tinned annealed copper wire (Sec. 4), ranging from No. 18 to 24 A.W.G. The insulation, where the cable is for use in dry places, usually consists of two wrappings of silk and one of cotton; the conductors are twisted into pairs or triples, then a wrapping of paper is applied over all, next a wrapping of thin metal tape (lead, antimony and tin), and finally an outside cotton braid saturated with beeswax. The insulation of the individual wires is sometimes varied, using one silk wrapping and one cotton wrapping, or one silk and two cotton, or two silk and two cotton. These cables are laid up in round, oval or flat cross-sections as desired, in twisted pairs or triples, ranging from 6 pairs to 100 pairs; 5, 10, 15, 20, 25, 30, 40, 50 and 100 pairs are approximately standard sizes. A code color scheme is employed in the cotton covering of individual wires, for the purpose of identifying the pairs and facilitating splices and connections; the manufacturers' bulletins give the codes employed.

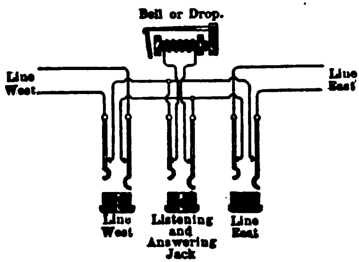


FIG. 18.—Circuit diagram of cut-in station or looping bridge.

Wool-insulated cable is now generally employed in place of pot-head wire (rubber insulated) for connecting underground or aerial cable terminals with the main frame, and in places where there might be trouble with ordinary cotton insulation on account of moisture.

Lead-covered interior cable, insulated with double silk and single cotton saturated with beeswax, is very useful for interior wiring in moist or damp places. It is standard in sizes of 5 to 40 pairs, by steps of 5, and 50, 60, 75, 100, 120, 150 and 200 pairs, of No. 22 A.W.G. tinned annealed copper.

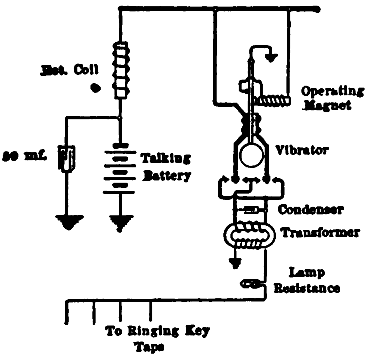


FIG. 19.—Circuits of vibrating pole changer for supplying ringing current from a battery source.

Twisted pairs should be used invariably for all **talking circuits** in order to avoid cross-talk. The length of one complete twist should not exceed 4 or 5 in.

51. Wiring of a through line is shown in Fig. 18. The middle jack is so wired that the operator can listen to determine whether the line is busy before attempting to use it. Code ringing must be employed on a through line connected in this manner. This style of jack wiring is termed a **cut-in station** or **looping bridge.** It can also be arranged with keys instead of jacks, and mounted in a special cabinet if desired.

52. Ringing energy can be obtained in three ways: (a) from a ringing dynamotor (Sec. 9) supplied on the primary side from a lighting or motor circuit, or from a storage battery (in common-battery installations); (b) from a hand generator (Par. 26) mounted in the switchboard; (c) from a one type of cord circuit, complete with ringing and listening keys; this type employs a repeating coil, and is used by the Western Electric Co. in non-multiple boards. The lamp signals are termed supervisory signals,

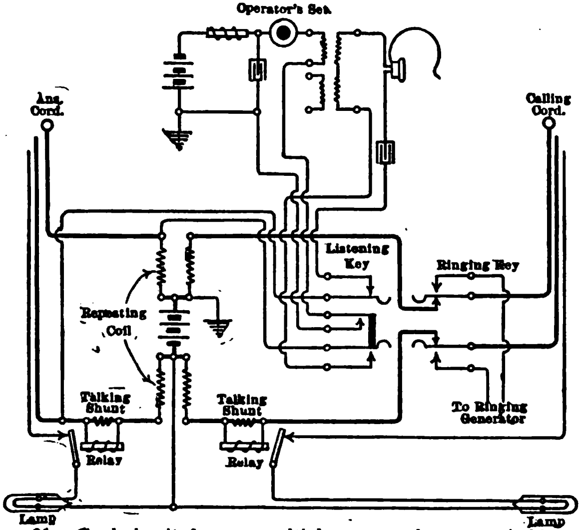


Fig. 21.—Cord circuit for non-multiple common-battery switchboard.

and will be lighted whenever the receiver hook at the line station is depressed. The method of operation is obvious from the figure. Combination cord circuits are those specially wired for the purpose of connecting common-battery lines with local-battery lines.

57. Retardation and repeating coils are quite similar in general construction, but differ in their windings. The principal types of simple impedance or retardation coils are shown in Figs. 22 to 24. Soft Norway iron wire is commonly used in core construction; the **toroidal coil** in Fig. 24 is

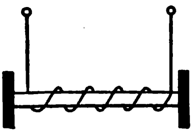


Fig. 22.—Impedance coil with open magnetic circuit.

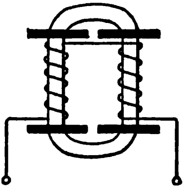


Fig. 23.—Impedance coil with closed magnetic circuit.

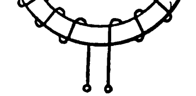


Fig. 24.—Torroidal type of impedance coil.

usually constructed with very fine iron wire covered with a very thin insulation of cellulose or enamel to reduce the eddy-current losses. The desired properties of the iron are high permeability, high resistivity and low hysteresis loss. Enamel insulation for the electrical windings is the most economical frequency, while the impedance coils tend to suppress the corresponding ripples of current in the battery circuit. In large installations, especially with large batteries (of very small internal impedance), the condenser is not required.

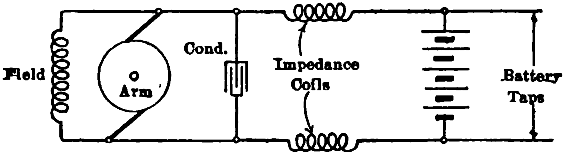


Fig. 26.—Method of suppressing battery noise caused by generator or motor operation.

AUTOMATIC SWITCHBOARDS

64. Fundamental features. There are two general types of automatic systems, the **full automatic** (Par. 65 to 72) and the **semi-automatic** (Par. 73 to 75). The former type performs all switching operations by means of automatic mechanisms under the control of the selector dials or calling devices at the telephone stations; the latter type requires switchboard operators, as in the manual system, but the automatic switching mechanism is under their direction, in the place of using dials at the instruments.

65. Numerous systems have been invented and reduced to commercial practice, including the Strowger, the Lattig-Goodrum, the Lorimer, the Bullard-Rorty and the Clark systems. These systems are all complicated when viewed in their entirety, and cannot be described in the space here permitted. The following description, Par. 66 to 72, covers the **Strowger system** (Automatic Electric Co.) as developed for small installations not exceeding 100 lines.

66. Telephone sets for automatic service are equipped with **calling devices**, one of which is shown attached to a desk stand in Fig. 27. The circuit diagram of this set is given in Fig. 28. The calling device consists of a dial with eleven holes, ten of which numbered with the ten digits, consecutively from 1 to 0. In order to call line No. 73, for example, the person calling first removes the receiver from the hook and then, placing his finger in the seventh hole, pulls the dial around until his finger engages the stop, which causes seven impulses (which are really interruptions of a steady current) to pass over the line to the switchboard; he then places his finger in the third hole and repeats the operation, whereupon the automatic switching mechanisms connect the calling line with line No. 73 and ring the station. When someone answers at station No. 73, the ringing current is automatically cut off and the talking circuits are clear.

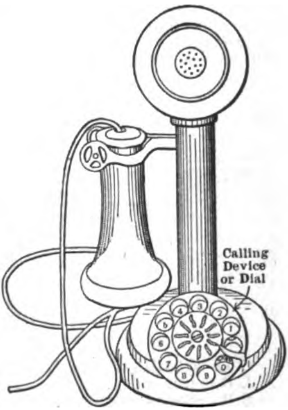


Fig. 27.—Desk stand equipped with calling device or dial for automatic (Strowger) service.

The mechanism of the calling device is shown in Fig. 29. The dial winds a spring which drives an interrupter, consisting of a fibre cam engaging the impulse springs; a tiny ball governor is attached, which insures uniform speed. The line circuit is normally closed (when the receiver is off the hook) and an impulse, so-called, is really a brief interruption of the line current.

switch to the second position, and thus opens the circuit of the vertical magnet and closes the circuit of the rotary magnet. These details are made clearer in Fig. 32.

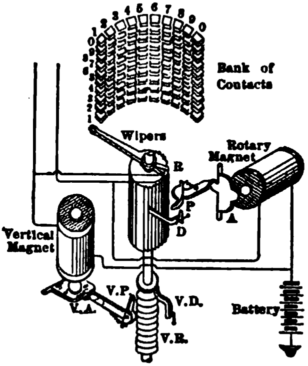
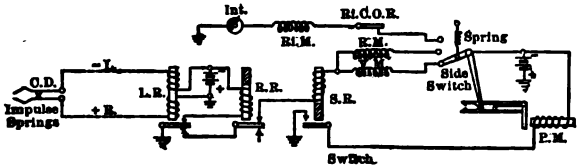


FIG. 31.—Connector switch.

The second set of impulses actuates the rotary magnet and rotates the shaft until the wipers rest on the corresponding set of contacts, which would be the third set in the seventh vertical row, in the case of a call for line No. 73. When the second set of impulses ceases, the private magnet moves the side switch again, and closes the ringing circuit on the called line; ringing continues at short periodic intervals until the receiver at the called station is removed from the hook, upon which the direct current through the back bridge relay operates the same and in turn the ringing cut-off relay. The circuits are then clear for through communication.

When the receiver at the calling station is returned to the hook, the slow-acting release relay (Fig. 32) is de-energized by the line relay and thus re-releases the double-dog (Fig. 30) and the wiper shaft returns to normal, clearing the connection. The off-normal switch serves to keep open the circuit of the release magnet unless the wiper shaft is in action or use.

For the sake of simplicity certain details have been omitted, but the essential principles have been emphasised as fully as space will permit. The busy test, which is not shown, is so arranged that a call for a busy line will not be completed, and the usual busy signal will be communicated to the calling line. For further details see the references below* and the Bibliography (Par. 263).



C.D.—Calling device.
L.R.—Line relay
R.R.—Release relay.
S.R.—Series relay.
INT.—Interrupter (ringing).
Ri.M.—Magnet for ringing-cut-off relay.
Ri.C.O.R.—Ringing-cut-off relay.
P.M.—Private magnet.

FIG. 32.—Details of connector circuit.

70. Mounting. Line switches are usually mounted in groups of 100 each. The necessary connectors for a group of 100 lines are mounted with

* Campbell, W. L. "A Study of Multi-office Automatic Switchboard Telephone Systems;" *Trans.* A. I. E. E., Vol. XXVII, 1908, p. 503–541.
Campbell, W. L. "A Modern Automatic Telephone Apparatus;" *Trans.* A. I. E. E., Vol. XXIX, 1910, p. 55–84.
Smith, A. B. and Campbell, W. L. "Automatic Telephony;" McGraw-Hill Book Co., Inc., New York, 1914.

75. Trunking between automatic and manual switchboards can be readily provided by means of appropriate apparatus, and is extensively employed. For details of such trunking in exchange systems see the Bibliography (Par. 263).

INTERCOMMUNICATING SYSTEMS

76. Intercommunicating systems comprise relatively compact private telephone systems, in most cases without any switchboard or operating attendants, for the purpose of internal communication in factories, industrial plants, stores, offices, hospitals, residences, apartment buildings, etc.

77. Equipment. Each station is equipped with a telephone set and a switching device mounted in a small box or cabinet. For each station there is a telephone line or circuit extending to all other stations, and so arranged that by depressing the appropriate switching key or button in the switching cabinet at any other station, connection can be established with this particular line; at the home station there is also a calling signal or bell (or buzzer), and an answering key arranged to connect the home telephone set with the line. Thus for a 10-line system there will be 10 keys or buttons in each switching cabinet and 10 talking circuits in a small cable multipled to all 10 cabinets; in addition to the 10 line-circuits there is another pair for supplying the talking current (common battery) to each station, and still another pair for supplying ringing current to each station. Direct-current is usually employed for ringing, and dry batteries are used for both ringing and talking.

The keys or buttons are usually so arranged that when depressed as far as possible, the ringing current is sent out on the line; when released, the key automatically returns to an intermediate position, where it is held by a lock or detent, and thereupon the ringing connection is broken and the talking circuit completed. The several keys in any individual switching cabinet are usually so arranged or interlocked, that the depression of one key automatically releases or restores all the others.

78. The operation is very simple. In order to call station No. 7 from station No. 3, the No. 7 button at station No. 3 is depressed as far as possible and held there a moment before releasing it, and meanwhile the bell connected to line No. 7, which is at station No. 7, responds. At station No. 7, the home button is depressed and the receiver taken from the hook, thus establishing communication. The ringing connection on the home button can be omitted, since it is obviously unnecessary.

79. Other equipment combinations can be arranged readily, including master stations for switching, with annunciator; one-way stations for inward calls only; non-selective code-ringing party lines, etc. The manufacturers offer many varieties of equipment for such combinations, which are readily understood from their bulletins.

80. The line capacity of standard equipments varies somewhat among the different manufacturers, but not to any great extent. One manufacturer offers complete units equipped for 6, 12, 22 or 32 stations; another offers sets for 11, 21 or 31 stations; another, 6, 12, 16, 20 or 24 stations, etc. These equipments are usually made in several styles, for desk mounting, wall mounting, or the flush wall type.

PHANTOM CIRCUITS

81. Two types of phantom circuits are in use, one derived by means of repeating coils, the other by bridged impedance coils. Both types are illustrated in theory in Fig. 33, all circuits being metallic.

82. The repeating-coil type of phantom circuit is shown in theory in Fig. 33, at the left of the diagram, where *RC* are repeating coils tapped at the centres of the line-side windings for the derived or phantom circuit.

83. The impedance-coil type of plantom circuit also appears in Fig. 33, at the right, where *IC* are retardation or impedance coils tapped at the centres of their windings for the derived or phantom circuit. This type is especially suitable for station circuits, where it is possible to economise in line wire by connecting the more distant stations to a phantom circuit. In this case grounded signalling cannot be employed. The side circuits should be subtantially alike in all particulars, including length.

90. Morse and Continental Alphabets.*

TELEGRAPH CHARACTERS

	Morse	Continental
A	· —	· —
B	— · · ·	— · · ·
C	· · ·	— · — ·
D	— · ·	— · ·
E	·	·
F	· — ·	· · — ·
G	— — ·	— — ·
H	· · · ·	· · · ·
I	· ·	· ·
J	— · — ·	· — — —
K	— · —	— · —
L	⸺	· — · ·
M	— —	— —
N	— ·	— ·
O	· ·	— — —
P	· · · · ·	· — — ·
Q	· · — ·	— — · —
R	· · ·	· — ·
S	· · ·	· · ·
T	—	—
U	· · —	· · —
V	· · · —	· · · —
W	· — —	· — —
X	· — · ·	— · · —
Y	· · · ·	— · — —
Z	· · · ·	— — · ·
&	· · · ·	
1	· — — ·	· — — — —
2	· · — · ·	· · — — —
3	· · · — ·	· · · — —
4	· · · · —	· · · · —
5	— — —	· · · · ·
6	· · · · · ·	— · · · ·
7	— — · ·	— — · · ·
8	— · · · ·	— — — · ·
9	— · · —	— — — — ·
0	⸺	— — — — —

Short Numerals Generally Used By Continental Operators

1	· —	3	· · · — —	5	·	7	— — · · ·	9	— ·
2	· · —	4	· · · · —	6	— · · · ·	8	— · ·	0	—

		Morse	Continental	Phillips
.	Period	· · — — · ·	· · · · · ·	· · — — · ·
:	Colon	— · — · ·		— · — · ·
:-	Colon Dash			— · — · — · ·
;	Semi-Colon	· — · — ·		· · · · ·
,	Comma	· — · —		· — · —
?	Interrogation	— · · — ·	· · — — · ·	— · · — ·
!	Exclamation	— — — ·	— — · · —	— — — ·
—	Fraction Line	·	— —	·
-	Dash			— · · · — · ·
-	Hyphen		— · · · · —	· · · · · — · ·
'	Apostrophe		· — — — — ·	· · — · · — · ·
£	Pound Sterling			· · · · · · — · ·
/	Shilling		· · ·	· · — —
d	Pence			— · ·
$	Dollars			· · · · — · ·
¢	Cents			· · ·
:"	Colon Followed by Quotation			— · — · · — ·
.	Decimal Point		· — — ·	— · · · · —
¶	Paragraph	— — — — — — ·	— — · —	— — — —
( )	Parenthesis	· — · · —	— · — — · —	· · · · · — ·
[ ]	Brackets			— · · · · — · ·
""	Quotation		· — · · — ·	· · — · — ·
	Quotation within a Quotation			· · — · · — · ·
	End of Quotation		· — · · — ·	· · — · — · — ·
	End of Quotation within Quotation			· · — · · · · ·
	Percent	— — — · · · — — —		· · · · · · ·
	Capitalized Letter			· · · · — · ·
	Italics or Underline	· — · ·	· — · ·	· · — · — · ·

91. The closed-circuit Morse system (Fig. 34) is almost universally employed in this country, except for a few installations of automatic printing systems, some of which employ multiplex or high-speed transmission. The ordinary closed-circuit Morse system, worked simplex, duplex, or quadruplex, is the only one here treated in any detail.

92. The open-circuit Morse system is employed extensively in England and on the Continent, but has never found favor in American

* Appendix "*C*" from McNicol's, "American Telegraph Practice," page 492.

98. The operating currents required in closed-circuit Morse working vary according to the system of working and the sensitiveness of the relays. The usual current with 150-ohm relays, line-circuit closed, is about 0.040 to 0.050 amp.; with 35-ohm relays, 0.060 to 0.075 amp.; for 20-ohm pony relays, about 0.100 amp.; for local sounders, 0.100 to 0.250 amp.

99. The polar duplex is illustrated in theory in Fig. 35, which shows but one terminal of the line, since the other is identical. The polar relay, as its name indicates, is polarised, and responds to currents in one direction but not the other. In order that the armature may be under a slight normal attraction when no signals are passing, it is given a slight bias, or so adjusted that it is nearer one pole-piece, than the other. The polar relay, being differentially wound, is neutral to outgoing currents from the home key, if the artificial and the real line-circuits are electrically balanced. When the distant key is closed the line current in the upper limb of the polar relay becomes (theoretically, with a perfectly insulated line) double that in the lower limb and actuates the local sounder; if the home key is next closed, the relay is not affected. If the home key is closed, while the distant key is normal, the home relay will also be unaffected, as can be seen from consideration of the relative strengths and directions of the currents in the two limbs.

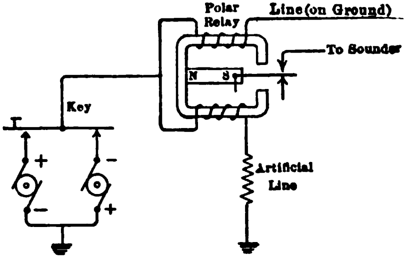


FIG. 35.—Theory of differential polar duplex.

100. The bridge duplex is shown theoretically in Fig. 36, where R_1R_2 are two equal resistances, or equal windings of an impedance coil. The relay is a plain non-polarized type. The compensating resistance should be equal to the internal resistance of the battery, in order not to upset the adjustment of the artificial line.

101. The bridge polar duplex* is similar to Fig. 36, except that the battery and key are displaced by the generators and key in Fig. 35, and a polar relay is required.

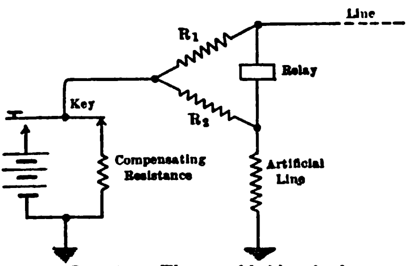


FIG. 36.—Theory of bridge duplex.

102. The bridge quadruplex of the Western Union type developed by Athearn† is shown in theory in Fig. 37. The function of the holding coil *H* on the neutral relay is to hold down the armature of the relay during reversals on the polar side. The extra current condenser *E.C.* has a capacitance of about 0.25 mf. and is in series with a 20-ohm resistor. The impedance coils *U* have a total resistance of 1,000 ohms, or 500 ohms per side. The operating currents are about 0.020 amp. for the polar side and 0.060 for the neutral or common side. This type of quad is very efficient and less subject to interference from inductive disturbances on the line than the differential quad.

* *Telegraph and Telephone Age*, Dec. 1, 1912, p. 802 and Dec. 16, 1912, p. 835.

† *Telegraph and Telephone Age*, Mar. 16, 1911, p. 226: also see issue of Nov. 1, 1910, p. 722.

105. The artificial line must be adjustable, both in resistance and capacitance, in order to establish readily a balance with the real line. When adjusting for a balance the distant battery or generator should be cut out, and a connection made to ground in its place, through an equivalent resistance.

106. Single-line repeaters designed to repeat signals from one Morse circuit to another, with single working, are of various types, including the Milliken, Toye, Weiny-Phillips, Ghegan, Atkinson, Neilson, Horton, d'Humy and others. Only one of these types will be shown; for descriptions of others see the references in Par. 263. Every repeater embraces, for each line, a receiving relay, a transmitter and a holding device; these elements, in duplicate, are common to every type. The principal differences among the various types relate to the form of holding device.

107. The Milliken single-line repeater is shown in Fig. 39, where *RR'* are the main-line relays, *TT'* are the transmitters, and *EM*, *EM'* are the extra magnets or holding devices. When the circuit opens on the west, relay *R* is released, opening the local circuit of transmitter *T* and in turn discon-

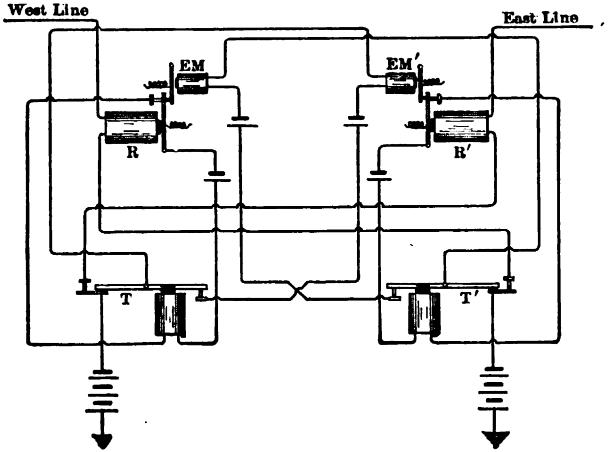


Fig. 39.—Circuits of the Milliken single-line repeater.

necting the battery of the line east; simultaneously the magnet *EM'* is released and its armature falls back on the armature of relay *R'*, holding it closed and thus protecting the transmitter *T'*. The other operations will be evident from this description and the circuits in Fig. 39.

108. Duplex and quadruplex repeaters* are very simple, it being necessary only to place the pole-changer of the east line under control of the polar relay on the west line, and the transmitter (common side) of the east line under control of the neutral relay on the west line, with corresponding connections for working from east to west.

109. Half-set repeaters consist of one relay and one transmitter for connecting a duplexed line with a single line, or one side of a quad with a single line.

110. The phantoplex is a system for superimposing an alternating-current telegraph on an ordinary single, duplex or quadruplex circuit.† It

* "Western Union Bridge Duplex." *Telegraph and Telephone Age;* Jan. 16, 1913, p. 54; Feb. 1, 1913, p. 84.

† McNicol, D. "American Telegraph Practice;" McGraw-Hill Book Co., Inc., New York, 1913; Chap. XIX.

the half-set in Fig. 43. The 2-mf. condensers *cc* perform the same
30-ohm coils *ee* are for the purpose of shunting to ground
pulses passing through the condensers *cc*, which otherw
through the telephone circuit and result in cross-writing b
morse legs.

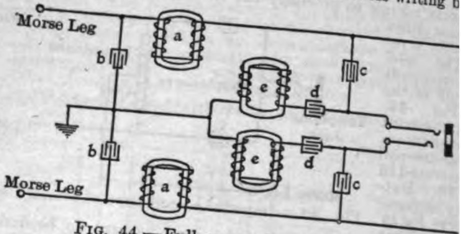


FIG. 44.—Full composite set for metallic circu

118. Duplex working through composite sets require
of a dummy composite set in the artificial line at each term
establish a balance with the sets in the main line. It is also
nect a grounded shunt condenser and serial impedance coil b
changing transmitter and the polar relay, in order to furt
sharpness of the impulses when transmitting morse.

119. Composite ringers. It is not permissible to signal
telephone circuits with the usual 16-cycle ringing current, sin
the morse relays. A high-frequency ringing system is in use
with relatively weak currents and does not interfere wit
morse transmission.*

DISPATCHING AND PATROL SYSTEM

120. Train dispatching systems on steam railroads
operated by Morse telegraph exclusively, but the telephone
superseded the telegraph during the last 6 or 8 years. I
tems on electric interurban railways have been operate
almost without exception since the earliest days of such sys
dispatching system comprises in brief a master sending
station, with means for selectively signalling all other s
circuit, and a plurality of way stations equipped primaril
Dispatching systems vary in detail, but nearly all embrace t
mental features.† Dispatching equipment is manufactu
all of the leading makers of telephone equipment, and the
system are too extensive to reproduce here. Only the l
will be described.

121. The Kellogg selective signalling system for train
shown in theory in Fig. 45. Normally the battery circuits
automatic calling-key s operated by clockwork, there being
for calling each station. The particular key shown will send a
impulses to line represented by 3–1–2–1. The object of the r
and condensers at the dispatcher's station is to make the sign

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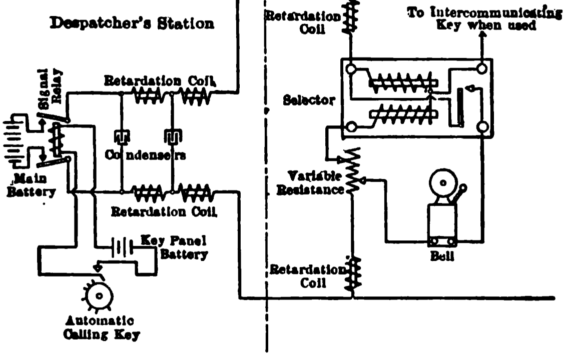
* Kissel, N. C. "The Composite Ringer;" *Telegraph and*
May 1, 1910, p. 318.

† Brown, G. "Some Recent Developments in Railway Tele
Amer. Inst. of Elec. Eng., 1911, Vol. XXX, p. 1007.

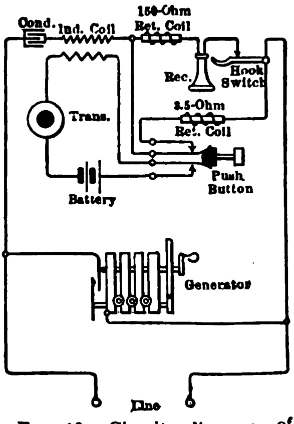
Clapp, M. H. "A Comparison of the Telephone with the
Means of Communication in Steam Railroad Operation;" *Pr*
Mar., 1914.



ɪɢ. 45.—Theoretical circuit of Kellogg selective signalling system using Gill selector, for train dispatching.

fect on voice currents, and also has an adjustable resistance designed to ıualize the line currents in all the selectors to about 0.008 amp. each. A **ill selector** is employed at each station, which is so arranged that a com- nation of impulses, with intermediate ıtervals, will rotate a wheel and at a ırtain point in its travel close a local bell rcuit. The bell may be operated by cal battery or from the main line, and ıe dispatcher receives a signal in his own ıceiver which gives a positive indication ıat the bell is ringing. The dispatcher ın also prolong the ringing as long as he ɜsires, by means of a special key.

122. Way-station dispatching sets ·e usually wired in a special manner ıited to the peculiar needs of such ser- ice. The circuit of the Kellogg booster" set is shown in Fig. 46. This a bridging set arranged with a push- ıtton for closing the transmitter battery rcuit and shunting the receiver when ılking. The adjustable 150-ohm re- ırdation coil is for the purpose of grad- ıg the shunt talking impedance so that l stations on the line will hear equally ell when several are listening simulta- ɜously; the highest impedance should be t the station nearest the dispatcher, nd the lowest impedance at the last ation. Obviously the operator can sten without closing the transmitter cir- ıit, which is a great advantage. When ıe push-button or self-restoring key is epressed, the local battery circuit is osed and the 3.5-ohm adjustable impedance is shunted around the receiver nd the 150-ohm coil, so that the outgoing transmission is materially



Fɪɢ. 46.—Circuit diagram of Kellogg booster set for train dispatching.

units, in response to changes in the system demand. The telephone ipment for such service is not as a whole distinguished by any unusual radical features, and needs no further elaboration. It is quite essential, lectric trunk line operation, to provide ready communication between the n dispatchers and the load dispatcher.

34. Patrol systems may be defined as embracing telephone lines ending along routes covered by patrolmen or inspectors, provided with ans at intervals of ½ mile or so for connecting portable sets and establing temporary communication with headquarters. In the place of table sets, there may be booths or boxes at fixed locations, with telephones rein. Patrol systems are in use along railroad rights of way and along the tes of transmission and distribution lines. In the case of high-tension s, it is desirable where possible to have the telephone line on separate es or supports at some distance away; this not only reduces the induction the telephone line, but also renders it safer and tends to make it more pendable in emergencies, when it is most needed.

FIRE AND POLICE ALARM SYSTEMS

135. Fire alarm systems consist essentially of signal boxes distributed er the area to be protected, a series line circuit looping through the boxes,

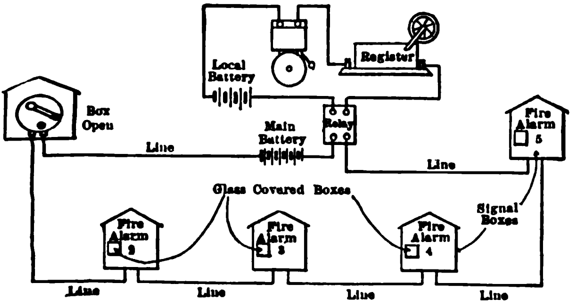


Fig. 47.—Elements of a small fire-alarm system.

and a central station at the engine house or fire headquarters where signals rom the boxes will be registered as received and the alarm given. The simple elements of such a system are shown in Fig. 47. Lack of space prevents more than brief description of the characteristic details; further information should be sought in the references given in the bibliography, Par. 263.

136. The line circuit is normally closed, as shown in Fig. 48. If an alarm is turned in at signal box 12, the circuit will be interrupted once, then after a pause, twice, this signal being repeated each time the wheel revolves; and each time the line relay R becomes de-energised, the bell relay B causes the bell to be struck once.

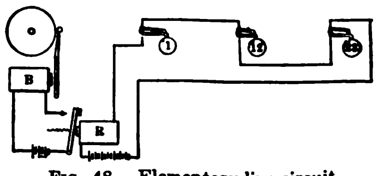


Fig. 48.—Elementary line circuit.

137. Non-interfering box. If two or more alarms should be turned in simultaneously on the same line, they would interfere with each other and

147. Aerial and underground lead-covered paper-insulated cable
(Western Electric Co.)

No. of pairs	No. 22 A.W.G.			No. 19 A.W.G.		
	Thickness of sheath (in.)	Approx. weight per ft. (lb.)	Convenient no. of feet on reel	Thickness of sheath (in.)	Approx. weight per ft. (lb.)	Convenient no. of feet on reel
5	$\frac{1}{16}$	0.530	2500	$\frac{1}{16}$	0.640	2500
10	$\frac{1}{16}$	0.640	2500	$\frac{1}{16}$	0.850	2500
15	$\frac{1}{16}$	0.745	2500	$\frac{1}{16}$	0.970	2500
20	$\frac{1}{16}$	0.849	2500	$\frac{1}{16}$	1.138	2000
25	$\frac{1}{16}$	0.970	2500	$\frac{1}{16}$	1.264	2000
30	$\frac{1}{16}$	1.019	2500	$\frac{1}{16}$	1.390	1500
40	$\frac{1}{16}$	1.189	2000	$\frac{1}{16}$	1.643	1500
50	$\frac{1}{16}$	1.319	2000	$\frac{3}{32}$	1.995	1500
55	$\frac{1}{16}$	1.370	1500	$\frac{3}{32}$	2.130	1200
60	$\frac{1}{16}$	1.449	1500	$\frac{3}{32}$	2.220	1200
75	$\frac{1}{16}$	1.645	1500	$\frac{3}{32}$	2.584	1200
90	$\frac{1}{16}$	1.831	1500	$\frac{3}{32}$	2.810	1200
100	$\frac{3}{32}$	2.120	1500	$\frac{1}{8}$	3.738	1000
110	$\frac{3}{32}$	2.250	1200	$\frac{1}{8}$	3.949	1000
120	$\frac{3}{32}$	2.480	1200	$\frac{1}{8}$	4.221	1000
150	$\frac{3}{32}$	2.740	1200	$\frac{1}{8}$	4.865	1000
180	$\frac{3}{32}$	3.039	1200	$\frac{1}{8}$	5.439	1000
200	$\frac{1}{8}$	4.058	1000	$\frac{1}{8}$	5.808	800
220	$\frac{1}{8}$	4.257	1000	$\frac{1}{8}$	6.168	800
240	$\frac{1}{8}$	4.474	1000	$\frac{1}{8}$	6.594	800
300	$\frac{1}{8}$	5.163	800	$\frac{1}{8}$	7.587	700
330	$\frac{1}{8}$	5.460	800			
360	$\frac{1}{8}$	5.853	800			
400	$\frac{1}{8}$	6.212	700			
440	$\frac{1}{8}$	6.654	700			
480	$\frac{1}{8}$	6.920	700			
500	$\frac{1}{8}$	7.360	500			

These cables have the following constants per mile:

	No. 22	No. 19
Average mutual capacity (mf.)	0.070	0.074
Average grounded capacity (mf.)	0.105	0.111
Insulation resistance (megohm-miles)	500	500

Lead-antimony alloy (Par. 146) is employed for the sheaths. There is but one application of paper insulation; this is so laid on, however, as to provide two thicknesses of paper over each conductor.

148. Aerial lead-covered paper-insulated cable, is made in sizes from 5 to 400 pairs of No. 22 A.W.G. with either double or single wrapping of paper, and pure lead sheaths. Such cable has a mutual capacitance of 0.08 mf. and a grounded capacitance of 0.12 mf. per mile, with a minimum insulation resistance of 500 megohm-miles. On account of the higher capacitance it is somewhat more compact and lighter than No. 22 cable of 0.070 mf. per mile.

149. Composite cable is the term applied to cable which is made up of pairs of more than one gage or diameter, as for example, No. 22, No. 19 and No. 14 A.W.G. Such an arrangement is often economical for trunk cables where several different transmission requirements must be met.

150. Phantom circuits in cable are made possible by twisting together two similar metallic pairs, constituting a "quad," and laying up such quads in reversed helical layers, after the manner of an ordinary cable. This method is not economical in the use of space within the sheath, however, and it is customary to add as many single pairs as space will permit.

151. Electrolysis of lead cable sheaths from stray or foreign currents is covered as a whole by the article in Sec. 16 by Prof. Gans.

158. Ground wires from arresters to earth form a most important link in the system of protection. The conductor should be not smaller than No. 14 A.W.G. and should pass by the nearest accessible route to a substantial ground plate, rod, or coil, or to a water pipe; **gas pipes should never be used** for this purpose. Too much care cannot be given to securing good electrical connection with the earth, with means of a substantial and reliable character.

When a wrought-iron or steel water pipe (service connection) is not available, a fairly efficient earth connection can be made by driving an iron or steel pipe or rod into the ground, in a moist location, to a depth of 5 or 6 ft. See Hayden, J. L. R. "Notes on the Resistance of Gas-pipe Grounds;" *Trans.* A. I. E. E., 1907, Vol. XXVI, p. 1209.

159. Heat coils or sneak-current arresters are, in reality, fuses of special construction, designed to overcome the unreliability of ordinary fuses for very small currents. For example, a heat coil can be constructed to operate on a current of 0.2 amp. in 30 sec., or a variety of other ratings. This device comprises a small winding of fine wire, which develops sufficient heat to melt a small piece of fusible metal and release a spring which grounds the line circuit; the resistance of the winding usually amounts to several ohms, at least. The function of heat coils is to protect telephone apparatus wound with fine wire (relays, drops, etc.), such that injury might result from foreign currents insufficient to blow the fuses. The proper location for the heat coils is between the protectors and the apparatus.

160. Protective or insulating transformers are employed to protect telephone sets, switchboards or terminals connected to lines which are exposed in a hazardous manner to high-tension high-energy transmission lines, such as those erected on the same poles or structures with a transmission circuit. An insulating transformer of this character* made by one of the leading manufacturers is built to withstand a 25,000-volt test between windings for 1 min., and requires a magnetizing current equal to about half the current taken by a 1,000-ohm polarized bell. The transformer is mounted in a weatherproof case for out-door mounting; the casing should always be thoroughly grounded. It should be observed that such transformers introduce additional losses in both transmission and ringing, which should be taken into account in arranging circuit layouts.

161. Special protectors are usually employed with these insulating transformers, located between the line and the transformer. The protector consists of extra long fuses in the line circuit, with spark-gaps bridged to ground; sometimes the fuses are so mounted as to be integral with an air-break disconnecting switch. See Sec. 11.

162. Insulating stools are often used in conjunction with telephones connected to hazardously exposed lines, as in the case of patrol circuits on transmission lines, so that the attendants may be thoroughly insulated from earth while telephoning. An ordinary four-legged hardwood stool, with the legs inserted in inverted porcelain line insulators, will serve very well. **Insulating mats** are sometimes used, in dry interior locations, in place of stools, but in general are not as efficacious.

163. Extra insulation of telephone sets used in connection with hazardously exposed lines is very desirable. Exposed terminals or connections and uninsulated exposed parts should be particularly avoided in selecting equipment for such service. The hook switch should also be very thoroughly insulated.

CROSS-TALK AND INDUCTIVE DISTURBANCES

164. Induction between parallel aerial wires is due to a combination of electrostatic and electromagnetic induction. Such induction is the cause not only of cross-talk between parallel aerial telephone circuits, but also the inductive disturbances in aerial telephone lines situated in parallel exposure to aerial distribution circuits (Sec. 12) or high-tension transmission circuits (Sec. 11). The general means of eliminating such induction is by interchanging or transposing the wires of each circuit at suitable locations, in accordance with a predetermined system. In severe cases it is necessary to resort to further measures of protection. The subject has been treated at

*"Insulating Transformer for Telephone Lines;" *Telephony*, June 5, 1909, Vol. XVII, p. 666.

169. Phantom transpositions make it necessary to modify the details in Fig. 50 quite materially; changes are necessary at one-half the total number of transposition poles and only the "A" poles remain as they were. An 8-mile section, arranged for phantom circuits, is given in Fig. 51. It is also feasible to transpose pairs 5–6 and 15–16 to make a fifth phantom circuit.

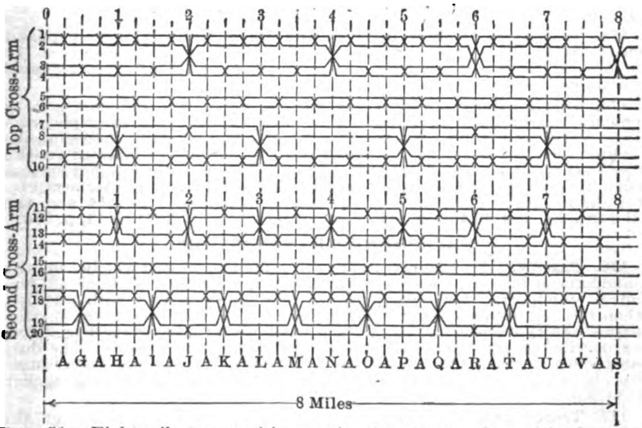


FIG. 51.—Eight-mile transposition section for twenty wires with phantom circuits.

170. Balancing coils, Fig. 52, are sometimes employed to improve the balance of metallic circuits and diminish the intensity of inductive interferences from high-energy circuits. Such coils interfere, however, with phantom, composite or simplex operation, unless installed in the drop side or leg.

171. Drainage coils, Fig. 53, are useful in preventing excessive rise of potential on telephone lines from heavy inductive disturbances caused by parallel high-tension high-energy circuits. The installation of these coils at intervals along the circuit establishes local circuits through earth for the flow of induced currents and thus prevents the cumulative rise of potential which otherwise might occur.

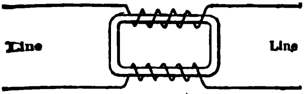


FIG. 52.—Balancing coil for metallic circuit.

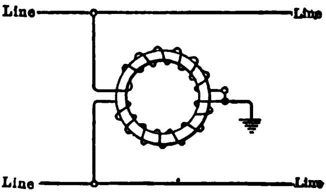


FIG. 53.—Drainage coil for metallic circuit.

172. Inductive disturbances may be minimized by proper arrangement of phase wires, as indicated in the specifications forming part of the report of the Committee on Overhead Line Construction, N. E. L. A., 1911. The phase wires constituting any individual circuit should be grouped as close to each other as feasible. Series circuits should be laid out on the closed-loop system (Sec. 12) and the lamps should be inserted alternately in each side of the loop, to maintain electrostatic balance.

where ϵ is the base of Naperian logarithms, β is the attenuation constant and α is the wave-length constant. In a line of length l, the total attenuation is

$$\epsilon^{-\beta l - j\alpha l} = \epsilon^{-\beta l}(\cos \alpha l - j \sin \alpha l) \qquad (3)$$

The quantity $\epsilon^{-\beta l}$ is the numerical magnitude of the attenuation and the quantity within the bracket is the directive or vector portion; the latter has always a numerical magnitude of unity, and is merely a unit vector expressed in terms of complex imaginary quantities. It follows that when two dissimilar lines give equal transmission,

$$\beta_1 l_1 = \beta_2 l_2 \qquad (4)$$

182. The attentuation constant is given by the expression

$$\beta = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} + (RG - \omega^2LC)]} \qquad (5)$$

where R is the effective resistance in ohms per mile, L is the effective inductance in henries per mile, G is the effective leakage conductance in mhos per mile, C is the effective capacitance in farads per mile, and $\omega = 2\pi f$, where f is the frequency in cycles per sec.

183. The wave-length constant is given by a similar expression, which is

$$\alpha = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} - (RG - \omega^2LC)]} \qquad (6)$$

where the symbols have the same meaning as in the preceding paragraph.

184. The wave length is $\lambda = 2\pi/\alpha$, where λ is the length of one complete wave, α is the wave-length constant and $\pi = 3.1416$. If the line constants are taken per mile, as customary, λ will be in miles.

185. The velocity of propagation is $V = f\lambda$, where V = the velocity, λ is the wave length and f is the frequency. If λ is in mile units, V will be in miles per sec.

186. The KR law, which is strictly applicable only to cables, can be obtained by substituting $L = 0$ and $G = 0$ in Eq. 5. This will give $\beta = \sqrt{RC\omega/2}$. Therefore two dissimilar cables, neglecting the dielectric losses, will give equal transmission when

$$\frac{l_1}{l_2} = \sqrt{\frac{R_2C_2}{R_1C_1}} \qquad (7)$$

where l_1 and l_2 are the respective lengths, R_1 and R_2 the respective resistances per mile and C_1 and C_2 the respective capacitances per mile. The term *KR* law comes from the use of the symbol K for capacitance; it might also be called the *CR* law.

187. The line impedance at the sending end is given by the formula

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (8)$$

The **surge impedance** is equal to $\sqrt{R/G}$. For example the line impedance of 9 A.W.G. open copper metallic circuit at 800 cycles is about 690 ohms; for No. 9 copper clad, of 47 per cent. conductivity, it is about 830 ohms; and for a sample of No. 9 A.W.G. iron it was 1,640 ohms.

188. Wave reflection, or reflection loss, occurs at the junction of dissimilar impedances, such as the junction of open-wire line and cable, or more particularly at the junction of a loaded circuit with a non-loaded circuit.

189. Transmission tests are usually made under talking conditions by comparing one instrument with another, or one line circuit with another, and introducing extra cable in the more efficient circuit until the two are alike in talking volume as nearly as can be determined. The amount of extra cable measures the loss, which is expressed in so-called **cable equivalent.** For this work it is very convenient to have a portable artificial cable.

190. Artificial cable for transmission tests can be made in very compact portable form. A 32-mile artificial cable, equivalent to 32 miles of No. 19 A.W.G. metallic copper cable, 88 ohms loop resistance and 0.054 mf. (at 800 cycles per sec.) mutual electrostatic capacity, is a convenient size; the whole cable is subdivided into two 1-mile, one 2-mile, one 4-mile, one 8-mile and one 16-mile sections.

182. Table of transmission equivalents of ...

Type of circuit			Constants of circuit per mile of loop (2 wires)			Transmission equivalent	
Gage No. A.W.G.	Construction	Physical pairs or phantoms	Resistance (ohms)	Capacity (mf.)	Insulation (megohms)	Miles equivalent to 1 mile of No. 19 A.W.G. standard cable	Reciprocal
19	Dry-core paper cable	Pairs	88	0.060	500	1.00	1.00
22	Dry-core paper cable	Pairs	176	0.083	500	0.60	1.66
22	Dry-core paper cable	Phantoms	88	....	.....	0.68	1.48
22	Dry-core paper cable	Pairs	176	0.070	500	0.65	1.53
22	Dry-core paper cable	Phantoms	88	....	.....	0.74	1.36
19	Dry-core paper cable	Pairs	88	0.074	500	0.90	1.11
19	Dry-core paper cable	Phantoms	44	....	.....	1.01	0.99
16	Dry-core paper cable	Pairs	44	0.074	500	1.28	0.78
16	Dry-core paper cable	Phantoms	22	....	.....	1.43	0.70
14	Dry-core paper cable	Pairs	27	0.074	500	1.61	0.62
14	Dry-core paper cable	Phantoms	13	....	.....	1.82	0.55
13	Dry-core paper cable	Pairs	22	0.074	500	1.82	0.55
13	Dry-core paper cable	Phantoms	11	....	.....	2.04	0.49
10	Dry-core paper cable	Pairs	11	0.074	500	2.55	0.39
10	Dry-core paper cable	Phantoms	5.5	....	.....	2.85	0.35
19	Submarine (impregnated paper)	Pairs	88	....	500	0.53	1.9
3 No. 22	Submarine (rubber)	Pairs	59	....	.....	0.63	1.6
16	Submarine (impregnated paper)	Pairs	44	....	500	0.71	1.4
22	Swbd. cable (cotton and silk)	Pairs	176	....	100	0.45	2.2
19	Swbd. cable (cotton and silk)	Pairs	88	....	100	0.59	1.7
19	Swbd. cable (wool)	Pairs	88	....	100	0.67	1.5

TELEGRAPH TRANSMISSION

199. The theory of telegraph transmission has been developed from a number of standpoints. Herbert* has treated it empirically for English (open-circuit) practice, while Kennelly† has handled it from the purely analytical standpoint, regarding morse impulses as nearly the equivalent of a low uniform frequency (Par. **89**). The author has applied the leakage theory to uniform open-wire lines, for American practice, with results given in Par. **202**. None of these theories is perhaps satisfactory from the standpoint of every type or condition of line met in practice, but collectively they form a fairly reliable guide.

200. The leakage theory as applied to uniform aerial (low-capacitance) lines, derived from the theory of the distribution of continuous currents in the steady state, has been extensively studied by the author,‡ and appears to be applicable to open-wire lines of the closed-circuit type, if there are no considerable lengths of cable in circuit.

201. Commercial operative limits of transmission, with given line resistances and an assumed leakage conductance of 4 micromhos per mile, have been tabulated in Par. **202**, under the further assumptions next stated: single working, 150-ohm main-line relays, 300 ohms total resistance at each terminal, and a ratio of releasing to operating current equal to 0.75; differential polar duplex, 800-ohm polar relays, and a 300 ohm protective resistor at each terminal; differential quadruplex, 400-ohm polar relays, 800-ohm neutral relays, an e.m.f. of 90 volts on the short (polar) side, ratio of long to short voltages equal to 3.5 and a 600-ohm protective resistor at each terminal.

202. Table of commercial operative limits, with closed-circuit single, duplex and quadruplex Morse working

(Based on a leakage conductance of 4 micromhos per mile)

Resistance per mile (ohms)	Maximum permissible length of line§ (miles)		
	Duplex (two sides)	Simplex or single	Quadruplex (four sides)
2	783	597	531
3	658	510	442
4	580	450	386
6	485	376	313
8	425	331	268
10	384	299	236
15	318	248	186
20	278	217	156
25	250	195	135
30	229	179	120
40	200	156	98.7
50	180	140	84.3

203. The KR law of transmission as developed by Herbert (see footnote of Par. **199**) can be stated as follows:

$$W = \frac{A}{KR} \qquad (9)$$

where W is the maximum commercial speed in words per min., K is the total capacitance and R is the total resistance of the line; A is a constant having a value of 10,000,000 for open-wire lines of iron, 12,000,000 for open-

* Herbert, T. E. "Telegraphy;" Whittaker and Co., London, 1906, Chap. XVII.

† Kennelly, A. E. "The Application of Hyperbolic Functions to Electrical Engineering Problems;" The University of London Press, 1912.

‡ Fowle, F. F. "Telegraph Transmission;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 1683 to 1741: A Study of Telegraphic Transmission, *Telephone Engineer*, Vol. IV, Oct., 1910, p. 171, continued to Vol. VI, July, 1911, p. 49.

§ No intermediate stations.

Length in ft.	Circumference (in.)									
	Class A		Class B		Class C		Class D	Class E	Class F	Class G
	Top	6 ft. from butt	Top	6 ft. from butt	Top	6 ft. from butt	Top	Top	Top	Top
20	....	.....	....	.....	....	.....	......	......	15.5	12.5
22	....	.....	....	.....	....	.....	......	15.5	15.5	12.5
25	....	.....	22	32	18.8	30	18.8	17.3	15.5	12.5
30	24	40	22	36	18.8	33	18.8	18.8	18.8	......
35	24	43	22	38	18.8	36	18.8	18.8	18.8	......
40	24	47	22	43	18.8	40	18.8	18.8	18.8	......
50	24	53	22	50	18.8	46	22.0	22.0	18.8	......

Class A poles are used in lines carrying 50 to 80 wires; Class B poles for 40-wire lines; Class C poles for 20-wire lines; Class E for 10-wire lines; Classes F and G for light farmer lines and bracket lines. For properties of timber, see Sec. 4.

210. Pole setting. The depth of poles in the ground should be as follows, for ordinary soil or for solid rock.

Length of pole (ft.)	Depth in the ground		Length of pole (ft.)	Depth in the ground	
	Earth (ft.)	Rock (ft.)		Earth (ft.)	Rock (ft.)
20	4.0	3.0	50	7.0	4.5
25	5.0	3.0	55	7.5	5.0
30	5.5	3.5	60	8.0	5.0
35	6.0	4.0	65	8.5	6.0
40	6.0	4.0	70	9.0	6.0
45	6.5	4.5	75	9.5	6.0

211. Reinforced concrete poles have been used to a very limited extent, largely on an experimental basis. They are not in sufficient use to warrant any considerable description here; see Still, A. "Over-head Electric Power Transmission," New York, 1913. Coombs, R. D and Slocum, C. L. "Reinforced Concrete Poles;" Universal Portland Cement Co., 1910.

212. Preservative treatment of poles to prevent decay, especially below the ground line, is constantly becoming more common. Among the preservatives employed are creosote, carbolineum avenarius, creolin, spirittine, coal

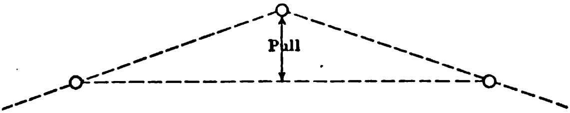


Fig. 55.—Measurement of "pull" on pole-line curve or turn.

tar, zinc chloride and others. There are three methods of treatment, closed-tank process (treating entire pole), open-tank process and brush treatment. The open-tank method, for treating the butts (only) with coal-tar creosote, is recommended as superior to the brush treatment. See publications of the Forest Service, U. S. Dept. of Agriculture, Washington, D. C.

213. Spans. On level straight sections the spans should be about as follows: 40-wire lines, 130 ft.; 20-wire lines, 130 to 150 ft.; 10-wire lines, 150 shown in Figs. 57 and 58; in some cases it is desirable also to guy from the top of pole 1 to the butt of pole 2, and from the top of pole 4 to the butt of pole 3. Back-braces are required on cross-arms on corner poles.

221. Guy strand consists of a galvanized seven-wire strand (or concentric-lay cable) and is usually obtainable in four standard sizes having an ultimate tensile strength of 4,000 lb., 6,000 lb., 10,000 lb. and 16,000 lb., respectively.

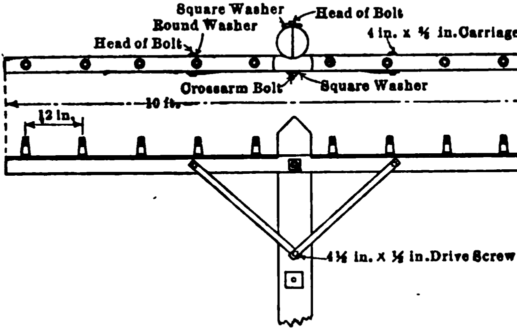
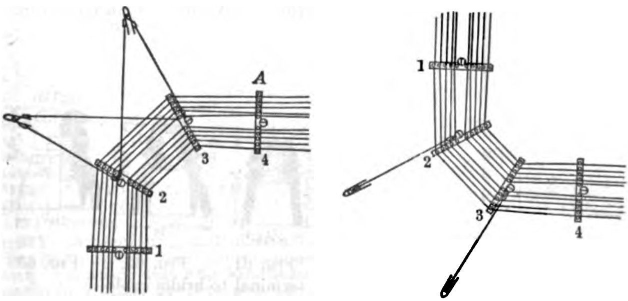


FIG. 56.—Standard pole top and cross arm.

222. Wire used in aerial construction ranges in size from No. 8 B.W.G. (435 lb. per mile) to No. 14 S.W.G. (102 lb. per mile) in hard-drawn copper and from No. 6 B.W.G. (573 lb. per mile) to No. 14 B.W.G. (96 lb. per mile) in galvanized annealed iron and steel. The independent telephone companies employ No. 6 to No. 12 A.W.G. copper, while the Bell companies have



FIGS. 57 and 58.—Methods of guying at a corner.

standardized No. 8 B.W.G. and No. 12 and No. 14 S.W.G. copper. For the properties of wire see Sec. 4.

Insulated open wire is usually covered with two cotton braids saturated with weather-proof compound; this is known as ordinary weather-proof wire. Twisted pairs are insulated with a covering of rubber compound and a braid over each conductor. For weights of insulated wire see Sec. 12 and Sec. 13.

226. Test connectors are usually installed at intervals along a pole line, in order to provide facilities for opening the lines for test without cutting the wires. A pole thus equipped with test connectors is termed a **test pole.** The location of test poles is varied in different installations to suit convenience.

227. Line insulators are ordinarily made of glass, in one of the patterns shown in Figs. 61 to 63. Porcelain is used to a limited extent in place of glass, especially to secure the high insulation necessary on loaded circuits, but is more expensive. Porcelain is used to a much greater extent in Europe than in this country.

228. Sag table for hard-drawn bare copper line wire consisting of No. 12 S.W.G. (0.104 in. diam.) is as follows. The sags are given in inches.

Temp. (deg. fahr.)	Length of span (ft.)								
	75	100	115	130	150	175	200	250	300
−30	1.0	2.0	2.5	3.5	4.5	6.0	8.0	14.0	22.0
−10	1.5	2.5	3.0	4.0	5.0	7.0	9.0	16.0	26.0
+10	1.5	3.0	3.5	4.5	6.0	8.0	11.0	19.0	30.0
30	2.0	3.5	4.0	5.5	7.0	10.0	12.0	21.0	33.0
60	2.5	4.5	5.5	7.0	9.0	12.0	16.0	27.0	43.0
80	3.0	5.5	7.0	8.5	11.5	15.0	19.0	31.0	49.0
100	4.5	7.0	9.0	11.0	14.0	18.0	23.0	36.0	55.0

The sags for No. 14 S.W.G. (0.080 in. diam.) hard-drawn bare copper under like conditions, should be at least 2 in. greater than the above values for No. 12.

229. Transpositions are made by means of special line insulators known as transposition insulators. These insulators are made sometimes in one piece with double grooves, and sometimes in two pieces, with one groove in each.

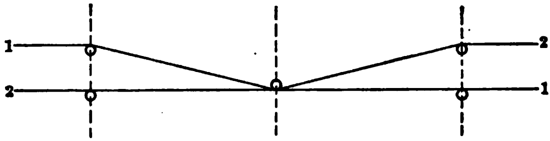


FIG. 64.—Plan view of single-pin transposition.

In modern practice the single-pin transposition is used very extensively (Fig. 64); an alternative method is the use of a two-pin upright iron bracket mounted on the cross-arm so that one wire passes over the arm and one beneath.

230. Phantom transpositions are made by means of upright iron brackets attached to the cross-arms; these brackets may support either transposition insulators or standard insulators, as designed.

231. Stresses in pole lines and wire spans are covered in Sec. 11 and Sec. 12.* In territories subject to sleet storms, the maximum stresses occur with combined sleet and wind loads. The maximum load sometimes assumed in calculating pole and wire stresses is that due to an ice coating ⅜ in. thick combined with a wind velocity of 50 miles per hr. Sleet frequently accumulates to a greater thickness, however; assumptions of 0.5 in. to 0.75 in. have been made in some cases.

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* Also see Report of Committee on Overhead Line Construction; N. E. L. A., 1911, 1912, 1913 and 1914.

Thomas, P. H. "Sag Calculations for Suspended Wires;" *Trans.* A. I. E. E., Vol. XXX, 1911, p. 2229.

Still, A. "Overhead Electric Power Transmission;" McGraw-Hill Book Company, Inc., New York, 1913.

239. Cable rings (galvanized) attached to the messenger are now extensively employed for supporting the cable. Rings should be spaced from 15 to 20 in. apart.

240. Continuous cable lengths in aerial construction are limited by the amount of cable which can be pulled into place in one operation without injury. Except with very small cables, the continuous lengths do not ordinarily exceed 1,000 to 1,200 ft.

241. Cable splices. A straight splice is shown in Fig. 66. The conductors are twisted together in pig-tail fashion and folded back so that a

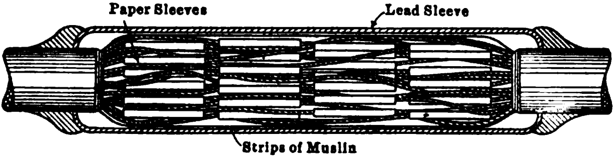

FIG. 66.—Cable splice.

paper tube or sleeve may be slipped over the joint to insulate it. These individual joints are staggered as shown in Fig. 66 and the whole is covered with a lead sleeve made water-tight by means of wiped joints. A number of forms of patented construction for such joints are also on the market.

242. Twisted pairs in rings, the latter supported from a messenger (perhaps carrying a cable also), constitute a form of construction now extensively used in reaching drops from a cable terminal or box.

243. The messenger should be bonded to the cable and grounded as a means of protection against foreign currents and lightning.

244. Grounds may be made by means of a coil of messenger or guy strand buried in coke, at a depth of 5 to 6 ft. in the ground, or by means of an iron pipe (about 6 to 8 ft. long and 1.5 in. diam.) driven into the ground. The first method is preferable. See Par. **158.**

245. Underground conduit construction consists of a system of ducts laid from 2 to 4 ft. below ground, with intercepting manholes at intervals of 300 to 700 ft. (Fig. 68).

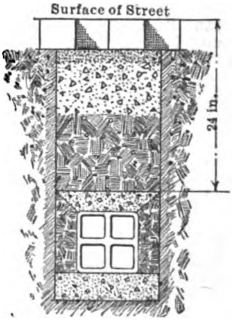

FIG. 67.—Section of four-duct underground conduit, showing cover.

246. Ducts are made of vitrified clay tile, creosoted wood, concrete, impregnated fibre, or iron pipe. The material most used is vitrified tile; this is made in both single duct and multiple duct, the latter including two-duct, three-duct, four-duct, six-duct, and nine-duct combinations in one piece The length of a single piece of duct is from 1.5 ft. to 3 ft., and the duct opening about 2¼, 3¼ or 3½ in. in diameter.

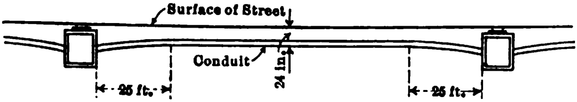

FIG. 68.—Section of underground conduit showing method of grading for drainage of ducts.

247. Standard conduit construction consists of some one of the above mentioned materials laid in a properly graded trench on a bed of Portland cement concrete and covered with an envelope on the top and sides, of the

258. The location of a ground usually requires the use of the Varley loop test or the Murray loop test, next described.

259. The Varley loop test, Fig. 70, is frequently employed. When the bridge is balanced,

$$R_x = \frac{R_1R_0 - R_2R}{R_1 + R_2} \qquad \text{(ohms)} \qquad (10)$$

$$R_0 = R_x + R_y + R_z \qquad \text{(ohms)} \qquad (11)$$

Equation (10) expresses the resistance of the grounded conductor from the bridge to the fault and (11) expresses the loop resistance of both conductors. Assuming the conductors to be uniform, it is a simple matter to calculate the distance to the fault. If desired, the resistance R can be connected in series with the other conductor, and in that case the formula given above (Eq.

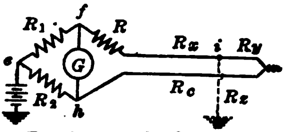

FIG. 70.—Varley loop test.

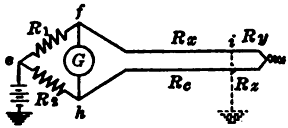

FIG. 71.—Murray loop test.

10) no longer holds true, and instead becomes, $R_x = R_1(R + R_0)/(R_1 + R_2)$. This test is especially useful because it is not affected by the resistance of the fault.

260. The Murray loop test, Fig. 71, is quite similar to the Varley test. The resistance of the defective conductor from the bridge to the fault is given by this formula, assuming the bridge to be balanced.

$$R_x = \frac{R_1R_0}{R_1 + R_2} \qquad \text{(ohms)} \qquad (12)$$

261. Insulation resistance comes under the class of high-resistance measurements (Sec. 3). A simple method in extensive use for measuring insulation resistance is the so-called **voltmeter method,** Fig. 72. The insulation resistance in megohm-miles is

$$R = lr_v\left(\frac{E}{V} - 1\right)10^{-6} \qquad (13)$$

where E = potential in volts of the battery; V = voltmeter reading when connected to line: r_v = voltmeter resistance in ohms; l = length of line in miles. See discussion of this method, and a modification of it, by the author in the *Electrical World*, Feb. 6, 1904 and Mar. 9, 1912. The reciprocal of insulation resistance is termed leakance, and is a conductance expressible in mhos or micromhos.

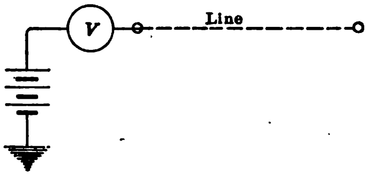

FIG. 72.—Voltmeter test for insulation resistance.

262. Quantitative measurements of telephone or telegraph circuits to determine resistance, inductance, reactance, capacitance and leakance, either to continuous or alternating currents, are covered as a whole in Sec. 3.

BIBLIOGRAPHY

263. General literature on telephony and telegraphy. The following treatises, text-books, periodicals and society transactions are given for the convenience of those who desire more detailed or specialized information.

MCMEEN, S. G. AND MILLER, K. B.—"Telephony." American School of Correspondence, Chicago, 1912.

MILLER, K. B.—"American Telephone Practice." McGraw-Hill Book Co., Inc., New York, 1905.

forth until the energy is consumed either in the form of heat in the circuit itself, or through radiation of electrical waves. The number of times the charge surges back and forth before it is dissipated and the discharge across the spark gap ceases depends on the equivalent resistance of the various sources of energy loss in the circuit.

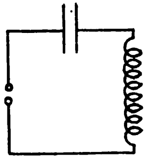

FIG. 73.—Closed oscillatory circuit.

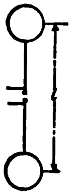

FIG. 74.—Hertzian oscillator.

265. Damped oscillations. Gradually decreasing oscillations of this kind are called damped oscillations and obey the law that each succeeding amplitude is a given fraction of the one before it. The constant difference between the natural logarithms of the successive amplitudes is known as the **logarithmic decrement.**

266. Spark. In the simplest form of sending set, the spark is placed directly in the antenna (see Figs. 74 and 78), but in order to use any except the smallest power (since the antenna capacity is in all ordinary cases small), a high voltage must be applied to the antenna. This necessitates the use of a long spark, which in turn introduces a high resistance into the antenna circuit, thus limiting the antenna current obtainable.

267. Coupled circuits. In order to get rid of this objectionable spark resistance, it is customary to excite the antenna circuit by means of a step-up transformer either inductively connected (Fig. 75) or directly connected (Fig. 76), the antenna circuit and the closed circuit containing the spark-gap

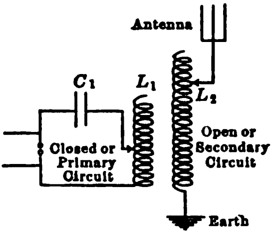

FIG. 75.—Inductive coupling.

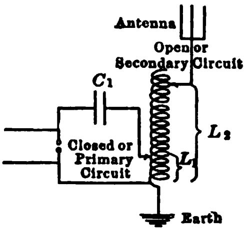

FIG. 76.—Direct coupling.

being tuned to resonance. Two circuits are in resonance, or the electric charges oscillate with the same frequency, when the product of the inductance and capacity in one circuit is equal to the product of the inductance and capacity in the other. A certain portion of the energy oscillating in the antenna is returned and is lost in the spark circuit; that is, the presence of the spark circuit is equivalent to a definite resistance introduced in the antenna. The amount of this equivalent resistance can be regulated by varying the mutual inductance between the antenna and spark circuit.

The fact that the spark length and the capacity in the spark circuit can be varied, provided the conditions of resonance are maintained, makes the double-circuit sending system far more flexible and capable of producing much higher currents in the antenna than the simple system shown in Fig. 78. The only disadvantage of the double-circuit system is that in general parallel wires separated by spreaders and supported by two masts. Fig. 80 is an umbrella antenna. This consists of a system of wires supported on a single tower and held in position by insulated guys. Another type is the platform antenna which is the one used in the high-power Naval station at Arlington, Va. In this, the antenna is supported by three towers and may consist either of a system of wires supported on spreaders, or simply of a triangular network of wires between the towers. All of these forms of antenna in practical use are subject to various modifications which cannot be entered into here. The effective height of the antenna is measured to the geometric centre of capacity of the wire system, if the ground is perfect (salt water) and there are no elevated masses of metal (steel supporting towers) close to the antenna. In land stations the actual effective height is from 50 to 90 per cent. of the measured height. That the height may be made as great as possible, it is desirable to increase the capacity of the upper portion, and to diminish the capacity of the leading-down wires, keeping them bunched together and using only enough to supply proper conductivity.

271. The amount of energy which can be introduced into an antenna (Eq. 14) is proportional to its capacity, the square of its maximum voltage, and the number of times it is charged per sec.; *i.e.*, the spark frequency. The voltage is limited by the insulation and on shipboard should not exceed 70,000 volts maximum. The fact that the energy for a given voltage is proportional to the spark frequency shows the great advantage of making the latter large, and explains why 60-cycle apparatus will not deliver a large amount of energy.

272. Antenna capacity required per kilowatt of antenna energy

Maximum antenna potential	1,000 sparks per sec.	120 sparks per sec.
50,000 (volts)	0.0008 (mf. per kw.)	0.0067 (mf. per kw.)
71,000	0.0004	0.0033
100,000	0.0002	0.0017

273. Energy in antenna of 0.001 microfarad capacity at 50,000 volts maximum potential*

Sparks per second	Kilowatts	Antenna current†
120	0.15	5.0 amp.
240	0.30	7.1 amp.
500	0.625	10.2 amp.
1,000	1.25	14.3 amp.

274. Capacity required per kw. at 1,000 sparks per sec. and various voltages

Volts, (max.)	Mf. per kw.	Volts, (max.)	Mf. per kw.
14,500	0.010	25,000	0.003
17,700	0.006	31,400	0.002
22,400	0.004		

275. Wave length. If no inductance coil is introduced into the antenna, it oscillates with a period corresponding to the distributed inductance and capacity of the antenna wires, and the wave length produced is called the fundamental wave length of the antenna. If it is desired to increase this wave length, inductance coils are placed in series between the antenna and the earth, and if it is desired to decrease it, a condenser is placed between the antenna and the earth. In the case of the excitation of the antenna by the closed circuit, it is of course necessary to have a certain amount of inductance in the antenna for the purpose of coupling.

276. Radiation resistance. The process of radiation withdraws energy from the antenna and it is customary to speak of radiation resistance,

* *Journal* of the Washington Academy; 1911, Vol. I, p. 5.

† Antenna resistance assumed to be 6 ohms.

coupled. The coupling is defined as $K = M/\sqrt{L_1L_2}$. In the case of close coupling, owing to the mutual reactions between the circuits, oscillations of two wave lengths are produced in each circuit, even though the two circuits singly are tuned to resonance with each other. As the coupling is loosened, the two wave lengths approach each other and eventually merge. It was formerly customary to employ close coupling, but modern practice finds that the greatest range is attained with a coupling loose enough to cause the antenna to radiate waves of a single frequency.

280. Types of spark gap. For small sets the simple **sphere gap** such as commonly seen on induction coils is sometimes used, but for larger powers either a **rotary gap** or the so-called **quenched gap** is commonly employed.

281. The rotary gap (Fig. 81) usually consists of two stationary electrodes with a rotating disc provided with projecting metal spokes or knobs which form the movable electrodes. The disc is usually attached to the shaft of the alternator and insulated from it, and is so adjusted that the maximum potential in the circuit is reached just before the movable electrodes come opposite the stationary electrodes. This ensures the regular passage of the spark, and the rapid motion produces sufficient cooling to prevent the formation of an arc. When used with a 500-cycle alternator, a pure musical note of 1,000 vibrations per sec. is produced in the receiving telephones. This high-pitched musical note is particularly advantageous in telephonic reception, being easily read through the atmospheric disturbances.

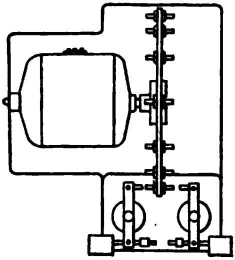

Fig. 81.—Rotary spark gap.

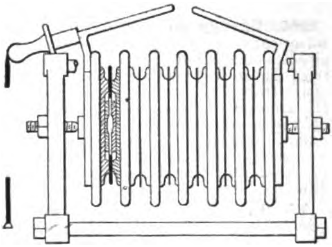

Fig. 82.—Quenched spark gap.

282. The quenched gap (Fig. 82) consists of a number of plates insulated from each other and separated by spaces of a fraction of a millimeter. It is in reality a number of gaps in series. On account of the spark being divided up into many parts in close proximity to large surfaces of metal, the cooling is very rapid. This, in addition to the rapid flow of energy from the closed circuit into the antenna, causes the spark to go out after four or five complete oscillations, and before a sufficient time has elapsed for any of the energy transferred to the antenna to return to the closed circuit. By adjusting the mutual inductance between the two circuits it is possible to make this quenching take place at the exact moment when practically all the energy is in the antenna. The fact that no energy can flow back into the closed circuit does away with the complicated reactions of ordinary double-circuit sending, and ensures that the radiated oscillations shall be of only one wave length. This gap is slightly more efficient in transferring energy to the antenna than the rotary gap.

283. Antenna ground connections. The outward and inward movement of the lines of electric force during the oscillations in the antenna give rise to earth currents. These earth currents are most intense in the immediate neighborhood of the antenna, and if the earth is a poor conductor a large waste of energy ensues. To guard against this loss, a radiating network of wire is placed beneath and around the antenna. In the case of a flat-top antenna, the radius of this wire net should not be less than the length of the horizontal portion of the antenna. In addition, if ground water is generally employed in the better types of apparatus are various kinds of rectifying contacts and vacuum detectors.

289. Contact rectifiers. The rectifiers most frequently consist of a contact between a fine wire and some variety of mineral. Among the minerals frequently used are iron pyrites, galena, silicon, and molybdenite. In other forms, two crystals are used in contact, such as zinkite with chalcopyrite or bornite, or silicon with metallic arsenic.

The exact nature of the action of the contact rectifiers is not known. They behave in general like high resistance thermoelements (though it is certain that they are not thermoelements in the ordinary sense), the rectified current pulses produced by each wave-train being very approximately proportional to the square of the oscillatory current passing through the detector.

For detecting the direct-current pulses, **head telephones** of from 1,000 to 3,000 ohms resistance are ordinarily used. These are placed in shunt across the stopping condenser K (Fig. 83) of from 0.01 to 0.02 mf., which permits the oscillatory currents to pass freely through it but stores up the direct-current pulses and discharges them through the telephone. If the spark at the sending station is regular, the sound produced in the telephone is a pure musical note. As a rough method of measuring the strength of signal, a resistance box is frequently placed across the telephones and the resistance reduced until the signals just remain audible. The relative strength of the telephone current at various times can thus be determined from the law of shunts. For laboratory purposes a galvanometer is frequently used in place of the telephones.

TRANSMISSION OF WAVES FROM THE SENDING TO THE RECEIVING ANTENNAS

290. Day transmission.—The radiation from a radiotelegraphic antenna may be conceived to consist of lines of electrostatic force with their ends terminating in positive and negative electric charges at the earth's surface somewhat as shown in Fig. 87. At moderate distances the strength of the electric field is represented by Eq. 16. For distances of more than 100 miles, over sea water, and for still shorter distances over land, an absorption of energy appears which modifies the results of Eq. 16. This absorption is due in part, at least, to the resistance of the earth to the passage of the positive and negative electric charges at the base of the electrical wave. At great distances the bottom of the wave is so much retarded that the wave front becomes bent forward. When brought into this position the electric field can be divided into two components, one at right angles to the earth's surface and the other parallel to it. The latter produces oscillatory earth currents which, while they withdraw energy rapidly from the wave, make possible the reception of signals by means of long horizontal antennas, only a few feet above the ground. Experiments by the U. S. Navy Department extending up to a distance of 2,000 miles have given results for flat-top antennas which may be represented by the following empirical formula*

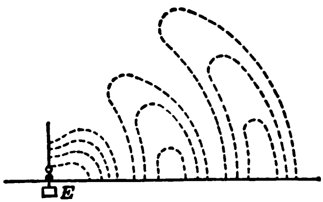

FIG. 87.—Earthed electric waves.

$$I_R = 377 \frac{h_1 h_2 I_s}{\lambda d R \sqrt{1 + \frac{\delta_1}{\delta_2}}} \epsilon^{-\frac{0.0015 d}{\sqrt{\lambda}}} \quad \text{(amp.)} \qquad (20)$$

where I_R represents the current in the receiving antenna, I_s the current in the sending antenna, R the receiving resistance, d the distance, λ the wave length, and $h_1 h_2$ the height to the centre of capacity of the sending and

* Austin L. W. Bulletin Bureau of Standards, Vol. VII, p. 362 (reprint 159), 1911, and Vol XI, p. 69 (Reprint 226), 1914.

fluctuations. At times night signals between two stations will be no stronger than those observed in the day time, while at other times sending sets of very moderate power and efficiency have been known to transmit signals several thousand miles. During the colder months of the year, night transmission can be depended upon to be considerably superior to day, with a fair degree of regularity. The cause of the increased night range is not definitely known. It has been thought by some authorities that it is due to a clearing up of the absorption supposed to exist in the upper atmosphere caused by the shorter light waves, and possibly cathode rays from the sun. Another explanation is that the absorption is fairly constant and that the increased received energy is due to reflection from the upper conducting layers of the atmosphere. This last view is supported by certain interference phenomena which cannot be entered into here, and by the fact that the abnormally strong night signals appear to pass over land almost as freely as over salt water, although the absorption in the day time is many times greater over land. That the normal energy is at times augmented in long-range night communication is shown by the fact that in many cases the received signals are stronger than would be expected from the geometric diminution of intensity with the distance, leaving absorption entirely out of account. It must also not be forgotten in this particular that observations show that the day condition is the stable one while the longer ranges covered at night show the irregularities which might be expected to come from irregular conditions of reflection.

UNDAMPED OSCILLATIONS

295. Advantages of undamped oscillations. It has already been said (Par. 264) that the oscillations produced from the electric spark form damped wave trains with intervals between in which no energy is given off. If, instead of supplying energy merely at the beginning of the wave train, a constant source of supply can be obtained, the oscillations will continue indefinitely and with equal amplitude. The use of such undamped oscillations in radio communication has a number of advantages; first, if the energy is divided among a great number of waves of equal amplitude, instead of being concentrated in a few wave trains, the maximum voltages required for a given amount of power are very much less than in the case of damped waves, and consequently the insulation of the apparatus is much less difficult, ard much larger amounts of energy can be sent out from moderate sized antennas. Second, undamped oscillations allow a greater sharpness of tuning and enable a looseness of coupling to be used at the receiving station between the antenna and secondary which greatly reduces the danger of interference and disturbance from atmospheric discharges. Third, and most important of all, observations indicate that undamped oscillations in passing over the surface of the earth fall off in intensity less rapidly at great distances than the damped oscillations from the spark.

296. Production of undamped oscillations. The most obvious way of producing undamped oscillations is by means of high frequency generators. Three types of such machines have been built; the Fessenden-Alexanderson, the Goldschmidt, and the Arco. The first has been used successfully with small powers, and the last two have been constructed with a capacity of more than 100 kw. and are in successful use in communication between Germany and America. For descriptions of these machines the reader is referred to Zenneck's "Lehrbuch der drahtlosen Telegraphie."

THE ELECTRIC ARC WAVE GENERATOR

297. The arc method of producing oscillations was discovered by Elihu Thomson in 1892 and has been developed by V. Poulsen, R. A. Fessenden and others. In this method a circuit containing suitable inductance and capacity is placed around the arc as shown in Fig. 88. Choke coils and resistance are placed in the main dynamo circuit to control the voltage and to prevent the oscillations from running back into the dynamo. When the shunt condenser circuit is closed around the arc a part of the current flows into the condenser thus robbing the arc of a portion of its current. But since the arc has the characteristic that the potential across the arc increases as the current decreases, this decrease in current increases the potential difference and the condenser continues to charge. At the next instant, however, the condenser commences to discharge, increasing the direct arc current until it is entirely discharged. Then the process repeats itself. For the

301. The Fessenden heterodyne. In the heterodyne method of receiving, an ordinary receiving set is used, as shown in Fig. 91. The heterodyne proper is a piece of auxiliary apparatus consisting of a small arc circuit coupled to the antenna and so tuned to the incoming waves as to produce beat tones in the detector and its telephone. By slightly shifting the frequency of the heterodyne any desired tone can be produced in the receiver proper which makes it particularly efficient in working through interference and atmospheric disturbances. It has also the property of increasing somewhat the sensitiveness of the detector. The heterodyne is also used with spark oscillations but in this case a musical note is not generally obtained.

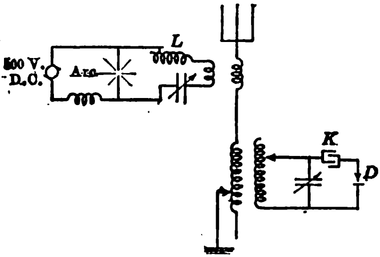

Fig. 91.—Heterodyne circuit.

302. Vacuum detectors. Hot-filament vacuum detectors were first invented by Prof. Fleming. The modern oscillating types, of which the DeForest ultra audion, the von Lieben and the Marconi tubes are examples, all operate on the same principle, differing only in arrangement of electrodes, voltage employed, etc. The DeForest ultra-audion is shown diagrammatically in Fig. 92. It consists of a highly evacuated glass bulb containing a filament F heated to incandescence by a storage battery of 6 volts, A, an intermediate grid electrode G, and a plate electrode P. The secondary receiving circuit LC is connected through a small variable stopping condenser C′ of a few ten-thousandths microfarad to P and G. The incoming oscillations produce disturbances in the electron flow in the tube which are heard as audible sounds in the telephone T. When the condenser C is small and the inductance L large, instability is automatically set up in the electron flow and continuous oscillations take place in the secondary circuit. The strength of these oscillations is increased by a variable bridging condenser C″. Then, as in the case of the heterodyne, if the local oscillations are slightly detuned from the incoming continuous oscillations, musical beat tones are produced which are heard in the telephone and by means of which the incoming signals may be read. The presence of the oscillations in the local circuit may be ascertained by touching with the finger any metallic portion of the circuit between the inductance of the secondary circuit and the stopping condenser. If oscillations are present a sound is heard in the telephones. For receiving spark signals the ultra-audion may be used either oscillating or non-oscillating. In both cases it is far more sensitive than the crystal detectors, especially when oscillating. In this case however the muscial tone of the spark is not clear.

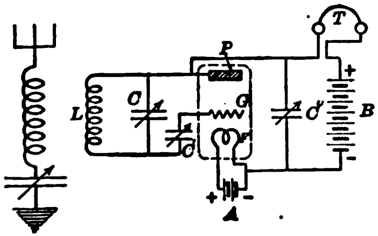

Fig. 92.—Deforrest ultra audion vacuum detectors.

The Audion Ampliphone. The audion ampliphone consists of two or three audions connected in cascade through small transformers by which the strength of signal in any detector may be increased from 20 to 150 times.

THE WIRELESS TELEPHONE

303. General principles. As long as continuous oscillations either from the high frequency machine or from the electric arc are of the same intensity,

308. The theories* of the directive radiation of the bent antenna have been much discussed and the different authorities are not yet in entire agreement on the subject. Low horizontal antennas several hundred feet long and only a few feet above the earth have been tried by a number of experimenters and have recently been brought into prominence by the work of F. Kiebitz.† These antennas usually have the receiving apparatus in the middle while the ends are either free or connected to earth through condensers (Fig. 95). They receive remarkably well in the direction of their length, while at right angles to this direction the energy received is very feeble. Dr. Kiebitz has also had some success in using these antennas for sending, but at the present writing it seems doubtful whether they will in practice be made to take the place of the elevated forms already described.

309. The directive antennas of Bellini and Tosi differ from those already mentioned. They are based on the fact that a nearly closed oscillating system (Fig. 96) radiates and receives more powerfully in its plane than at right angles. These inventors have very ingeniously made use of two such antennas at right angles to each other (Fig. 97). Each of the antennas contains a primary of a double transformer, the coils lying at right angles to each other. Inside the primaries a single secondary can be rotated so as to receive different amounts of energy from the two primaries. By noting the position of the secondary at which the signals are strongest, the direction of the sending station can be determined within two or three degrees. The same system of antennas can be used for sending if the rotating coil be connected to a suitable spark gap and condenser. By placing the moving coil in the proper position signals can be sent out in any plane desired.

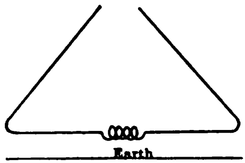

FIG. 96.—Directive antenna (nearly closed type).

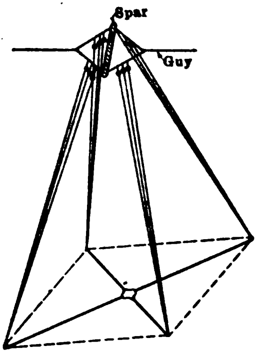

FIG. 97.—Bellini Tosi directive antenna.

The Bellini-Tosi system has proved itself valuable in permitting ships to determine the direction of sending stations erected along the coast for the purpose of aiding navigation in time of fog. According to the international regulations, stations used for this purpose must operate with small power and very short wave lengths so as not to interfere with other radiotelegraphic work.

310. Telefunken compass. Another system intended to assist in navigation has been developed by the Telefunken Company of Berlin and is called the Telefunken Compass. In this, the directive stations are fixed shore stations and the receiving is done on an ordinary ship's antenna. The sending station has a set of thirty-two bent antennas (Fig. 98) extending radially from it. The sending circuit is connected to each of these in turn by means of a rotating contact. When contact is made with the antenna sending in a certain definite direction, say due North, a special signal differing from the others is produced and sent out also from a non-directive antenna. The mariner desiring to know his direction from the sending station starts a

* Fleming, J. "Electric Wave Telegraphy," p. 651.
Zenneck, J. "Lehrbuch der drahtlosen Telegrahpie," p. 427.

† Kiebitz, F. "Jahrbuch der drahtlosen Telegraphie," Vol. V, p. 360, 1912 and Vol. VI, p. 1, 1912.

milliwattmeter which indicates by a maximum deflection when the wave meter is brought into resonance with the high-frequency circuit under examination. The variable capacity in the wave meter usually consists of a semicircular plate air condenser which is varied until the point of resonance is obtained. Fig. 100 shows a so-called **resonance curve** giving the relation between the hot-wire milliwattmeter deflection and the degrees on the condenser. As was mentioned in Par. **267**, when the wave meter is in resonance with the circuit under examination the product of the inductance and capacity in the wave meter circuit is equal to the product of the inductance and capacity in the other. The wave lengths corresponding to various wave meter readings are either engraved on the condenser scale or given in a table.

313. Formula for wave length. Since the time of oscillation of the charge is

$$T = 2\pi\sqrt{LC} \qquad \text{(sec.)} \qquad (21)$$

and $v = n\lambda$ and $T = 1/n$, then the wave length is

$$\lambda = v2\pi\sqrt{LC} \quad \text{or}$$
$$\lambda = 1.885\sqrt{LC} \times 10^9 \qquad \text{(meters)} \qquad (22)$$

where v is the velocity of light, L the inductance and C the capacity, all expressed in electromagnetic units. In place of the milliammeter a thermoelement and galvanometer or some other indicating device is sometimes used to indicate the current strength in the wave meter.

In order that the wave meter may be used for exciting receiving and other circuits at definite wave lengths, it is often connected to a buzzer circuit shown in Fig. 101. When the current from the cell s flowing through the inductance of the wave meter is broken at the vibrator of the buzzer B, the induced electromotive force charges the condenser of the wave meter. This charge oscillates back and forth through the inductance and condenser until the energy is dissipated in heat or radiation. As there is little resistance in the wave meter circuit the oscillations produced in this way are very feebly damped. If greater damping is desired, fine-wire resistance is introduced into the circuit at r. In order to eliminate the disturbing effects of the buzzer spark, a condenser K, of a few tenths of a microfarad, is placed around the coil of the buzzer. As the intensity of the oscillatory current in the wave meter depends on the magnitude of the direct current through the buzzer, this last should be of low resistance, about two or three ohms. Where great steadiness of high frequency current is desired for measurement purposes, the small high-pitch buzzers manufactured by the Eriksson Telephone Co., have proved especially satisfactory.

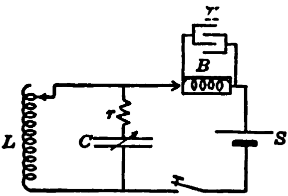

Fig. 101.—Buzzer-driven wave meter.

314. Measurement of logarithmic decrement. This measurement is of great importance since it makes possible the determination of the equivalent resistance of the circuits under consideration, and also gives information concerning the lengths of the wave trains. The value of the sum of the decrements of two circuits may be obtained from their resonance curve (Fig. 100).

According to the theory of coupled circuits,*

$$\delta_1 + \delta_2 = \pi\frac{C_m - C}{C_m}\sqrt{\frac{I^2}{I_m^2 - I^2}} \qquad (23$$

where δ_1 is the decrement of the unknown circuit, δ_2 that of the wave meter, C_m the reading of the wave meter condenser for resonance, and C any other condenser setting. I_m is the corresponding current in the wave meter for resonance and I for the setting C. If great accuracy in the determination is not desired, the formula becomes much simplified if instead of plotting a com-

* Fleming, J. "Principles of Electric Wave Telegraphy," p. 212.

Spark length (in cm.)	Spark voltage	Spark length (in cm.)	Spark voltage
0.1	4,700	1	31,300
0.2	8,100	1.5	40,300
0.3	11,400	2	47,400
0.4	14,500	2.5	53,000
0.5	17,500	3	57,500
0.6	20,400	3.5	61,100
0.7	23,250	4	64,200
0.8	26,100	4.5	67,200
0.9	28,800	5	69,800

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International regulations are agreed to by the leading governments of the world and **Federal regulations** of the U. S. A., are published as a bulletin of the Radio service, Department of Commerce, July, 1914.

SECTION 22

MISCELLANEOUS APPLICATIONS OF ELECTRICITY

CONTENTS

(*Numbers refer to Paragraphs*)

(a) Use a dry coat, a dry rope, a dry stick or board, or any other *dry non-conductor* to move either the victim or the wire, so as to break the electrical contact. Beware of using metal or any moist material. The victim's loose clothing, if dry, may be used to pull him away; do not touch the soles or heels of his shoes while he remains in contact—the nails are dangerous.

(b) If the body must be touched by your hands, be sure to cover them with rubber gloves, mackintosh, rubber sheeting or dry cloth; or stand on a dry board or on some other dry insulating surface. If possible, use only *one* hand.

If the victim is conducting the current to ground, and is convulsively clutching the live conductor, it may be easier to shut off the current by lifting him than by laying him on the ground and trying to break his grasp.

(c) Open the nearest switch, if that is the quickest way to break the circuit.

(d) If necessary to cut a live wire, use an ax or a hatchet with a dry wooden handle, or properly insulated pliers.

II.—SEND FOR THE NEAREST DOCTOR

This should be done without a moment's delay, as soon as the accident occurs, and while the victim is being removed from the conductor.

III.—ATTEND INSTANTLY TO VICTIM'S BREATHING

(a) As soon as the victim is clear of the live conductor, quickly feel with your finger in his mouth and throat and remove any foreign body (tobacco, false teeth, etc.). Then begin artificial respiration at once. Do not stop to loosen the patient's clothing; *every moment of delay is serious.*

(b) Lay the subject on his belly, with arms extended as straight forward as possible, and with face to one side, so that the nose and mouth are free for breathing (see Fig. 1). Let an assistant draw forward the subject's tongue.

Fig. 1.—Inspiration; pressure off.

If possible, avoid so laying the subject that any burned places are pressed upon.

Do not permit bystanders to crowd about and shut off fresh air.

(c) Kneel straddling the subject's thighs and facing his head; put the palms of your hands on the loins (on the muscles of the small of the back), with thumbs nearly touching each other, and with fingers spread over the lowest ribs (see Fig. 1).

Fig. 2.—Expiration; pressure on.

(d) With arms held straight, swing forward slowly so that the weight of your body is gradually brought to bear upon the subject (see Fig. 2). This operation, which should take from two to three seconds, *must not be violent*—internal organs may be injured. The lower part of the chest and also the abdomen are thus compressed, and air is forced out of the lungs.

(e) Now *immediately* swing backward so as to remove the pressure, but leave your hands in place, thus returning to the position shown in Fig. 1

and the reversing mechanism. It is so constructed that inspiration ceases when the entering gas encounters sufficient resistance to cause the mechanism to reverse and expiration to begin. This reversal is intended to result from the resistance due to completely filled organs of respiration.

Records of cases in which the pulmotor has been used are not convincing that it is superior to or even the peer of the Schaefer method, properly applied. It is claimed that two factors interfere with its successful use. In the first place, as the reversal of respiratory flow is controlled automatically, there is no assurance that inspiration may not be changed to expiration too soon, as the result of obstructions in the air passages which act upon the reversing mechanism before a complete ventilation has taken place. It is possible to overcome this defect by manually controlling the operating mechanism and thus extending the inspiration to the proper limit. The second factor is observed in connection with expiration by suction. The finer bronchioles are provided with no cartilages to stiffen them, and when air is sucked from the trachea and from the larger bronchi, these bronchioles are likely to close before air can be drawn through them from the alveoli. Furthermore, during the process of suction, the walls of the bronchioles and alveoli may collapse and stick together, rendering the subsequent inspiration more difficult, and further decreasing the ventilation. The escape of air into the stomach has been observed to cause movements of the thorax which closely simulate respiration, while actually no air enters or leaves the bronchial tree.

9. Pharyngeal insufflation* is a method of mechanically applied artificial respiration which has been recommended by the Commission on Resuscitation as a satisfactory supplement to the prone-pressure (Schaefer) method in cases of suspended respiration. Inspiratory air enters through a tube inserted in the pharynx, and so constructed as to conform to the human anatomy in order to prevent the escape of air through the mouth and nasal passages. An oxygen tank or a pair of foot bellows supplies the necessary pressure, and reversals of respiration are controlled by the operation of a respiratory valve, which can be conveniently held and operated with one hand. This valve is essentially a three-way cock which, when the valve is in one position, will furnish communication between the source of pressure and the pharyngeal tube, and when in another position, will allow a free expiration to the atmosphere while the pressure lead is shut. In case a specially constructed pharyngeal tube is not available, it is possible to use a close-fitting mask, provided with a tube for connection to the valve. Air is prevented from entering the stomach by placing a heavy weight upon the abdomen; this may be reinforced by a belt, though a belt alone should not be depended upon. A weight upon the abdomen may likewise render good service to a failing circulation by increase of blood pressure. In cases where it is found impracticable to use weights, the air may be drained from the stomach through a tube which furnishes communication between the stomach and the outside air. This stomach tube passes through the pharyngeal tube, but interferes in no way with the process of insufflation. This machine is light and can be constructed at relatively small expense.

10. Current tolerance of the human body. It was announced many years ago by Tesla, Elihu Thompson and D'Arsonval, that alternating currents of high frequency produced little sensation when passed through the human body, compared with alternating currents of low frequency and equal strength. Tests have been made to determine the "tolerance current" of various individuals at several frequencies. The tolerance current was arbitrarily assumed as the limiting current strength which the subject could take through his arms and body, without marked discomfort or distress.

It was found that for each individual, there is a marked increase of current strength which may be tolerated, as the frequency is increased from 11,000 to 100,000 cycles per sec. A man can tolerate only about 30 milliamperes at 11,000 cycles per sec. but can tolerate nearly half an ampere at 100,000 cycles per sec.† Although the tolerance current was found to increase

* See *Journal of American Medical Association*, 1913, Vol. LX, p. 1407.

† Kennelly, A. E. and Alexanderson, E. F. W. "The Physiological Tolerance of Alternating-current Strengths;" *Electrical World*, 1910, Vol. LVI, page 154.

Diff. in temp.	Ratio	Diff. in temp.	Ratio	Diff. in temp.	Ratio
Deg. Fahr.	K_1	Deg. Fahr.	K_1	Deg. Fahr.	K_1
10	1.15	160	1.61	310	2.34
20	1.18	170	1.65	320	2.40
30	1.20	180	1.68	330	2.47
40	1.23	190	1.73	340	2.54
50	1.25	200	1.78	350	2.60
60	1.27	210	1.82	360	2.68
70	1.32	220	1.86	370	2.77
80	1.35	230	1.90	380	2.84
90	1.38	240	1.95	390	2.93
100	1.40	250	2.00	400	3.02
110	1.44	260	2.05	410	3.10
120	1.47	270	2.10	420	3.20
130	1.50	280	2.16	430	3.30
140	1.54	290	2.21	440	3.40
150	1.57	300	2.27	450	3.50

17. Convection. Heat transfer from a body by convection is a form of conduction in which the heat is absorbed and carried away by the surrounding medium, which is in motion. Convected heat is mainly influenced by the following conditions: (a) the velocity of the passing air; (b) the extent of the friction between the body and the air, due to the surface condition; (c) the temperature difference between the air and the heated surface; (d) the location of the heated surface, whether at the top, bottom or side of the body.

18. Conduction of heat is simply the transference of heat through matter without visible molecular motion. Conduction of heat is comparable to the transmission of electric current through a conductor, under the following assumptions: (a) that the temperature difference is similar to the difference of potential; (b) that thermal resistance is similar to electric resistance. With these assumptions, the thermal resistance may be expressed as follows:

$$\frac{L}{\lambda_t A} \tag{3}$$

Where L is the length of path, A is the cross-section and λ_t the thermal conductivity. For a table of thermal conductivities of various substances, see Sec. 4. The flow of heat which a given temperature difference will establish through a given thermal resistance equals the difference in temperature divided by the thermal resistance.

19. Resistors. One of the essential qualifications necessary in heating apparatus is that the operation of the electric heater be as rapid as possible. In this manner the losses are reduced and appliances of the highest efficiency and lowest operating cost are obtained. New resistance materials available in recent years have aided this development materially, in the respect that the alloys can be rated much higher, and thus answer the requirements of good, high-duty resistors.

These requirements may be stated as follows: (a) no oxidation; (b) high melting point; (c) high specific resistance; (d) low temperature coefficient of resistance; (e) no deterioration or aging due to repeated heating and cooling; (f) uniformity of cross-section; (g) freedom from impurities.

20. The resistors most widely used at the present time by manufacturers of heating devices, are comprised of nickel-chromium alloys (Sec. 4). These not only satisfy the requirements of withstanding oxidation and high specific resistance, but can be operated safely at high temperatures and without danger of burning out the unit. The German silver resistors become brittle after repeated heating and cooling. Copper-nickel is still used for low-temperature work. The materials of nickel steel oxidize in the open air, and are only used when protected by special cements or enamels.

26. Heat Given off by the Human Body

	Authority	B.t.u. per hr.		Authority	B.t.u per hr.
Infant	Rubner	63	Child 6 years	Barrel	240
Adult at rest	Rubner	380	Man 29 years of age in atmosphere whose temp. is 31 deg. Fahr.	Barrel	610
Adult at medium hard work	Rubner	470	Same, temp. 68 deg. Fahr	Barrel	440
Adult at medium hard work	Rubner	550	Man, 59 years	Barrel	510
Adult in old age	Rubner	360	Woman, 32 years	Barrel	480

Petten Kofer states that the mean heat radiated from an adult at 70 deg. Fahr. is 400 B.t.u. per hr., and 200 B.t.u. from a child.

27. Advantages of electric heating. The general advantages gained by electric heating are as follows: (a) the elimination of explosion and fire risk; (b) the absence of smoke and fumes; (c) the ease of variation, exact duplication and control of temperature; (d) the localisation of heat where desired. These advantages result in a reduction of insurance rates, better working conditions, and a superior product.

28. Cost of operating heating devices. The cost depends entirely on two variables each of which has a wide range; first, the unit cost of energy, which is determined by local conditions; second, the efficiency of the apparatus, which depends upon its design.

The following results are given as the comparative charges for gas and electric cooking:

	Elec. per kw-hr.	Gas per 1,000 cu. ft.
R. Borlase Matthews; Oct. 6, 1911; *Elec. Rev.*, London	$0.033	$1.00
W. R. Cooper; Inst. of Elec. Eng., Nov. 26, 1908	0.03	1.00
Heating Committee; Ass'n. of Edison Illum. Co. (Sept., '07)	0.025	1.00
James I. Ayer; N. E. L. A. Report, May, 1904	0.0227	1.00

29. A general rule for cooking is to allow one-third kw-hr. per person per meal. The following table shows the result of comparative experiments on the cost of electric cooking for three persons extending over a period of three months, by W. R. Cooper, Institution of Electrical Engineers, September 25, 1908.

Period 1901	Kw-hr.	
	For one month	Per day
March 22–April 22	67.04	2.24
May 1–May 31	63.55	2.19
June 1–June 30	66.31	2.21

30. Equipment of Hotel Moserboben.* Boiler for soups and meats, a potato steamer and table range. Boiler—3 heats, 3 kw. capacity, 15 gal., boil water in 30 min. Potato steamer—1 kw. capacity, 10 gal., water jacket, 5 qt. water, boil water in 10 min. Table Range—4 plates, 12 in. diam., each 1.5 kw., 4 plates 8½ in. diam., each 1 kw., total 11.2 kw. Large range—8 plates—2 roasting ovens, 3 kw. each, total 16.2 kw.

* Electric Cooking and Heating in Hotels, *Electrician*, July 19, 1907.

	cu. in.	bread	min.	Energy used
Gas	6400	8	58	31 cu. ft. gas
Electricity	6137	9	52	0.92 kw-hr.

The United States Navy has adopted electric heating devices for cooking and baking on war-ships, finding that they are cheaper to operate, occupy less space, are cleaner, and give better results.

34. Industrial heating. In industrial trades, due to the large consumption of electricity, manufacturers can obtain a very favorable rate for electricity. In many industries it has been found cheaper to operate an isolated plant, using a dual system of exhaust steam and electric heating. The exhaust steam is used for low-temperature heating and electricity for high temperatures. In these isolated plants the cost per kw-hr. depends upon the load factor and the uses of exhaust steam, and varies from a minimum of less than 1 cent to approximately 2½ cents.

The following trades are using electrically heated devices on a large scale to advantage: hatting, laundry, newspaper, printing and publishing, candy, clothing, buttons and celluloid, paper-box, shoes, furniture, handkerchiefs, gloves, tin-can manufacturing, branding and many leather goods industries.

In many cases, even where the electricity charges are high, it has been proven that the total cost of production is cheaper by using electrically heated devices as compared with gas. The better working conditions, absence of exhaust gases, and control of temperature, have raised the efficiency of the workman and the machine, resulting in fewer products scrapped, and also, including rejected and accepted products, more articles produced per day.

35. Laundry Appliances

	Watts
Flat irons, 6 & 7 lb.	500
Flat irons, 9 lb.	600
Sleeve and yoke ironer	1,300
Combined hand ironer	
Sleeve ironers—10 in.	1,080
Sleeve ironers—15 in.	1,620
Wrist band ironer	500
Band ironer, 4½ in. shoe	520
Band ironer, 6 in. shoe	680
Body ironers–12 in. roll	1,140
Body ironers–24 in. roll	2,260
Drop board ironer–12 in.	2,050
Drop board ironer–18 in.	3,080
C–C ironers	1,650 to 3,860
Collar & cuff press	1,600
2-loop conv. D.R. (68½ in.×100 in.×82½ in.)	13,000
6-loop conv. D.R. (122½ in.×100 in.×82½ in.)	23,500
Dry rooms for cu. ft.	40
(From Troy Laundry Machine Co.)	

36. Tailoring Appliances

	Watts
Narrow iron—15 lb.	700
Wide iron	800
Machine iron	770

*Gray, Harold. "Electric Heating as applied to Cooking Appliances," *Electrical Review*, London, Feb. 10, 1911.

Linotype pots	600
Monotype pots	1300
Matrix beds	2500
1-qt. glue pots	300
4-qt. glue pots	500
Back rounders	200
Press heads—embossing	
Matrix scorchers	
Glue cookers—25 gal	1000
Sweating plate—14 in. × 14 in.	1200
Sweating plate—18 in. × 25 in.	3200
Wax kettle—20 in. dia., 17 in. Deep	3710
Wax stripping table—28 in. × 34 in.	6100
Composition kettle	4000
Finisher's tool heater	550
Palette-elect. heads—3 in. × 10 in.	235
Bench lever stamp	1650
Felt burners	110

43. Shoe Machinery

	Watts
Shoe warmer	60
Relasting irons	50
Stamping machine	500
Shoe ironing tools	200
Treeing machines	......

ELECTRIC WELDING

BY OTIS ALLEN KENYON

Consulting Electrical Engineer, Associate, American Institute of Electrical Engineers

44. There are three distinct processes of electric welding. (a) the incandescent process; (b) the carbon arc process; (c) the metallic arc process.

THOMPSON PROCESS

45. Temperature distribution. In making welds it is important that the temperature distribution over the face of the joint should be as uniform as possible. Alternating current assists in meeting these requirements as, on account of skin effect, the current density is greater near the surface than at the center, which tends to maintain an even temperature throughout the joint in spite of the radiation from the surface. On account of the necessity for uniform temperature distribution, it is impracticable to butt weld two pieces of different areas, as the smaller one will become much hotter than the large one. For this same reason it is also impractical to butt-weld large surfaces, as the current will not distribute itself uniformly over the section.

46. The incandescent process (known as the Thompson process) is primarily suited for manufacturing process where more or less standard welds are made. The principle of this process consists in connecting the joint to be welded in a low-potential alternating-current circuit and applying a definite mechanical pressure to the joint while the metal is at the welding temperature. The heating energy may be taken from any alternating-current system. The welding machine itself consists of suitable clamps for holding the pieces to be joined, and a means of applying pressure. The clamps, together with the joint, close the secondary circuit of a transformer, and these terminals are usually water cooled. Fig. 3 gives the average

48. Power and Energy Absorbed in Electric Welding.—Professor Thomson's Process

Iron and steel					Brass					Copper			
Area sq. in.	Watts in primary of welders	Time sec.	H.p. applied to generator	Kilo ft.-lb.	Area sq. in.	Watts in primary of welder	Time sec.	H.p. applied to generator	Kilo ft.-lb.	Area sq. in.	Watts in primary of welders	Time sec.	H.p. applie to gen ator
0.5	8,550	33	14.4	260	0.25	7,500	17	12.6	117	0.125	6,000	8	10.0
1.0	16,700	45	28.0	692	0.50	13,500	22	22.6	281	0.25	14,000	11	23.4
1.5	23,500	55	39.4	1,191	0.75	19,000	29	31.8	508	0.375	19,000	13	31.8
2.0	29,000	65	48.6	1,738	1.00	25,000	33	42.0	760	0.500	25,000	16	42.0
2.5	34,000	70	57.0	2,194	1.25	31,000	38	52.0	1087	0.625	31,000	18	51.9
3.0	39,000	78	65.4	2,804	1.50	36,000	42	60.3	1390	0.75	36,500	21	61.2
3.5	44,000	85	73.7	3,447	1.75	40,000	45	67.0	1659	0.875	43,000	22	72.9
4.0	50,000	90	83.8	4,148	2.00	44,000	48	73.7	1947	1.000	49,000	23	82.1

NOTE.—The stock should be clamped in the machine so as to fulfil the following relations: Iron and steel: l = $l = 3d$; copper: $l = 4d$, wherein l is the distance between the inside face of the clamps and d the diameter of the welded.

CARBON-ARC PROCESS

49. Characteristics of Carbon Welding Arc
(C. B. Auel, Amer., Mach., Mar. 16, 1911)

Arc length. (in.)	E.m.f. across arc and carbon (volts)	Current (amp.)	Length carbo
6	101	300	1×6.5
5	98	350	
4	93	400	
3	86	605	
2	80	750	

57. The arc can also be used for filling blow holes in castings. The casting must first be heated to a dull red color in order to prevent the production of harmful stresses, then the arc is applied either by connecting one side of the circuit to the casting, or by deflecting against the casting, with a magnet, an arc formed between two carbons, the metal used to fill the holes being introduced in the arc.

METALLIC-ARC PROCESS

58. The metallic-arc (Slavianoff) process was developed to avoid the introduction of carbon into the weld. In this process there is substituted for the carbon electrode an iron or steel pencil, which is melted by the arc and serves to fill the space between the pieces to be welded. The composition of the welding pencil is an important factor in determining the success of a weld. At present it is impossible to give specific information on this subject because those who have investigated it do not choose to reveal their results. However, the practice of those most successful, seems to be the employment of a commercially pure iron to which small percentages of other metals have been added, according to the character of the metal to be welded.

59. Refractory-flux coating. This process did not come into commercial use until the value of refractory-flux coatings on the welding pencil was discovered by Kjellberg in Sweden. In accordance with Kjellberg's invention the electrode or welding pencil is dipped in a paste containing suitable fluxing materials and a refractory base, and this mixture is then allowed to dry upon the electrode. The composition of welding fluxes is even more important than that of the pencils. Indeed in many cases it is possible to use commercially pure iron pencils and to insert the alloying metals in the flux. The composition of fluxes, like that of welding pencils, is jealously guarded by those who have investigated the subject.

The **advantages** of the refractory coating are: First, it applies the flux to the weld at a rate which adjusts itself perfectly to that of the melting of the welding pencil. Second, when welding overhead, it forms a tiny crucible which holds a small quantity of molten iron on the end of the pencil and allows the "pinch effect" (Sec. 19) of the current to squeeze the molten iron upward and into the weld.

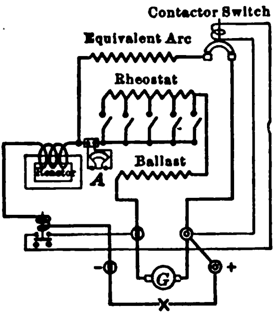

FIG. 7.—Metallic-arc controller for constant-potential generator. (The Elec. Weld. Co.)

60. Equipment. The metallic arc is short, varying from less than 0.125 in. to 0.187 in. and requires a pressure between 15 and 30 volts. The current depends upon the character of the work, varying from 50 amp. for light work to 170 amp. for very heavy work. The arc being short and of low voltage is very sensitive to changes in length; therefore it is desirable to design a welding circuit for a constant-current characteristic. In practice constant-potential generators of from 60 to 100 volts or more are used, the difference between the arc voltage and generator voltage being absorbed in rheostats. A single arc may be operated from a constant-current generator and the rheostats eliminated. However, if the generator is to furnish energy over a wide range of currents, rheostats must be provided for shunting the windings. Very recently there has been developed a constant-current machine, equipped with relays, which permits the operation of several arcs in series. This machine, as at present designed, meets the requirements of metallic-electrode welding and allows the adjustment of current from 60 amp. to 160 amp. without the use of heavy-current rheostats. When a constant-potential generator is used for welding (Fig. 7), any number of welders up to the capacity of the machine may draw energy from it. However, on account of the necessity of maintaining a suitable arc, it is necessary to connect a **ballast resistance** in series with each arc, In comparing arc-welding costs with oxy-acetlyene-welding costs, the cost of electric energy is balanced against that of oxygen and acetylene.

63. Advantages. The extreme localization of heat in the metallic-arc process is an enormous advantage, especially where large masses of metal are concerned, as it minimizes stresses due to expansion and contraction with the practical result that preheating need not be resorted to nor must the joints be more open at one end than at the other to allow for expansion, as is the case with hot-flame and carbon-arc processes. Another advantage of the metallic arc is that the operator uses only one hand for welding, leaving the other free to manipulate a glass screen. This he holds before his face when the arc is on, and lowers each time the arc breaks in order that he may examine the work and closely control its quality.

64. Strength of weld. Experience shows that with a metallic arc, welds can be made in which the strength of the joint is the same as that of the metal itself and even greater. However, on account of inferior work that has been done by unskilled welders, engineers are inclined to avoid arc welding except in cases where it can be subjected to test before putting it into service. If some method of inspection could be developed whereby the quality of a finished joint could be determined without damaging it, welding would undoubtedly displace riveting in a great many structures, and thus an enormous saving in labor and materials be accomplished.

65. Porosity test. Wherever the character of a joint is suitable, its porousness may be tested by applying kerosene to one side. Kerosene will penetrate a porous joint that is so tight that water under high pressure could not penetrate it. In this way the soundness of welds may be tested and a really unsound weld will reveal itself under a few minutes' application of kerosene.

66. Literature. The May, 1913, *Bulletin* of the New York Public Library gives a list of works relating to electric welding, covering the period between 1786 and 1912, inclusive, comprising several hundred articles and books in English and foreign languages, as well as references to the most important patents.

ELECTRICAL EQUIPMENT FOR GAS AUTOMOBILES

BY JOHN C. BOGLE

Engineer, McMeen and Miller; Associate, Amer. Inst. Elec. Engineers

BATTERIES

67. Type adaptable to requirements. It is standard practice to employ the pasted-plate lead cell for gas-car service. The advantageous features of this type of cell are: economy of space and reduction of weight, together with a low internal resistance and the possibilities of discharge at a high rate for a short interval. The last-mentioned advantage obtains in the case of battery systems which include provisions for electric starting.

The battery should be of rigid construction, capable of withstanding the severe vibration to which it will be subjected in service. The outer box should be of excellent workmanship. It has been thought desirable, in some cases, to fill the space between the outer box and the inner jar with some yielding plastic or compound. Jars are constructed of hard rubber having relatively high tensile strength and some flexibility.

Plates are designed for least possible internal resistance and for maximum product of life and capacity. Separators of wood or hard rubber are usually inserted between adjacent plates; these should be perforated or otherwise so constructed that they will interpose no appreciable increase in internal resistance.

68. Methods employed in charging. If the battery system serves merely for ignition and car lighting, it is usual practice to charge the cells independent of the car equipment. If the car equipment includes electric starting devices, the battery will receive its charge from a direct-current generator in the car. Charging on removal from the car must be attended with precautions observed in connection with any battery (see Sec. 20). In addition, however, separate precautions should be observed in case the battery is to be left out of service for any considerable length of time. Under

74. Battery discharge rate during cranking. From the curve of Fig. 10,* it will be seen that if a battery is discharged at the 20-min. rate, an amp-hr. capacity will be realised with an approximate value only 30 per cent. of that obtained at the normal 8-hr. discharge rate. This means that a battery with a normal rating of 120 amp-hr. will furnish only 36 amp-hr. if allowed to discharge completely in 20 min., and the current will be in the neighborhood of 110 amp. if maintained uniform throughout this period. Compare this figure with the result of a test, shown in Par. 76.

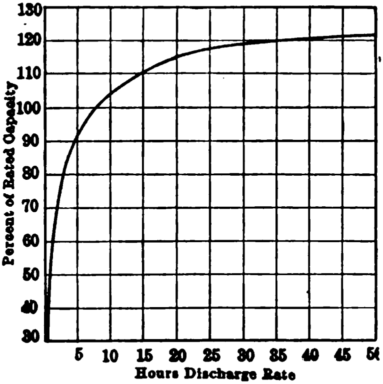

Fig. 10.—Variation of amp-hr. capacity with different discharge rates.

75. The ampere "draw" during the cranking period depends upon the operative voltage, the engine dimensions, the degree of compression, the number of cylinders, the friction, and upon certain exigencies such, for example, as obstruction in any part of the starting mechanism. The "draw" with 6-volt systems will usually be about 80 amp. for the lighter cars, and will not greatly exceed 140 amp. for the heaviest. Some 6-cylinder pleasure cars draw as high currents at starting as large 4-cylinder trucks. The proper value of ampere draw can only be determined accurately as the result of exhaustive tests, which take into consideration all possible rigors to which the equipment may be subjected in service.

76. Typical starting-test data.† Commercial starter turning dead engine of Model 36-B, Buick. A 6-volt, 120-amp-hr. (on 10-amp. discharge rate) battery was used. Car had been run about 2,000 miles, and engine was warm at time of test.

Time	Volts per cell	Ampere draw	Rev. per min.	Specific gravity
3:00 P.M.	2.00	95	120	1300
3:05 P.M.	1.99	91	116	1295
3:10 P M.	1.96	95	116	1280
3:15 P.M.	1.93	97	116	1280
3:20 P.M.	1.88	102	112	1275
3:25 P.M.	1.84	103	112	1270
3:30 P.M.	1.80	105	112	1265
3:35 P.M.	1.72	110	112	1255
3:38 P.M.	1.52	110	100	1250
3:39 P.M		Stopped		

77. Battery requirements for starting service. A rough rule for battery requirements may be stated, namely: that the capacity of the battery in ampere-hours shall be numerically equal to the ampere draw necessary to turn the engine after it has once been started. This figure is suggestive of the S. A. E. rating for batteries (Par. 72).

78. The momentary discharge rate at the instant of starting is dependent on the **breakaway torque** of the engine, which consists chiefly of

* *The Automobile*, Feb. 6, 1913; page 421.
† Vesta Accumulator Co., April, 1914.

One of the first automatic controllers was the so-called speed governor. This was in reality a centrifugally operated clutch connecting the generator element with the engine driving it, and so arranged that at the higher speeds the fly-balls would relieve the frictional adhesion between parallel surfaces, and the slippage, thus automatically adjusted, would maintain a constant generator speed and potential. The speed governor is in disfavor at the time of this writing (March, 1915), due to its rapid depreciation in service.

Another class of charging controllers includes those employing a vibratory contact, connected as a recurrent shunt on the generator field rheostat; in other systems, the vibrator has been used to shunt the magnetic circuit or to oppose to the main field flux the counter magnetomotive force of a differential winding; any of these methods operates by varying the effective flux threading the armature.

The present tendency seems to be toward a reduction of the number of moving parts. There are several starters on the market which limit the charging current either by a differential field compounding or a correctly

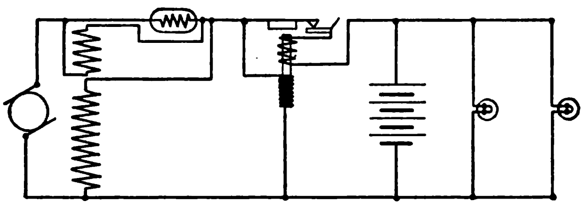

FIG. 11.—Typical charging controller and automatic cut-out.

gaged armature reaction. A starter of this class is illustrated in Fig. 11. Here a ballast coil or series resistance of iron wire is inserted in one of the leads from the generator. The shunt field is connected outside the ballast coil, and a differential field is shunted across the ballast coil. The effect of the differential compounding is to limit the field strength and the charging current.

83. Constant charging current vs. constant potential. If constant charging current is maintained, the generator voltage will have to increase slowly as the charge progresses, in order to overcome the rising e.m.f. of the battery. The resultant variation of generator voltage is objectionable, however, because it shortens the life of the lamps; it is not considered practicable to employ a lamp regulator such as may be found in train-lighting systems (Par. 298), because of the added complexity.

If constant generator voltage is maintained, the battery charge will be a tapering one, since the battery e.m.f. ranges from 1.7 volts per cell at complete discharge to 2.2 volts per cell at full charge. Necessarily the charging current will be excessive when the battery is exhausted; the discharge may be excessive at times, also, and the combined effects are likely to shorten the life of the cells.

84. Grounded and ungrounded systems. The wiring of electric apparatus on gas cars should be as simple as possible in order not to confuse the operator who is presumed to be unversed in electric circuits. To carry this idea further, some manufacturers utilize the metal framework of the car as a ground return. Though the simplicity of this arrangement presents an obvious advantage, the difficulty of maintaining a multiplicity of ground connections militates against such practice in the judgement of some manufacturers who prefer the use of the two-wire system.

85. Single-unit, two-unit, and three-unit systems. As in all rapidly developing arts, competition allows no standardization of operating method. In order that each system may have distinctive design, the manufacturers of starters approach a common objective from widely differing directions. One point of differentiation lies in the number of rotational unit equipped with two commutators; these commutators are connected in series for charging and in parallel when the machine is operating as a motor.

The wiring connections of a typical single-unit system are shown in Fig. 13.

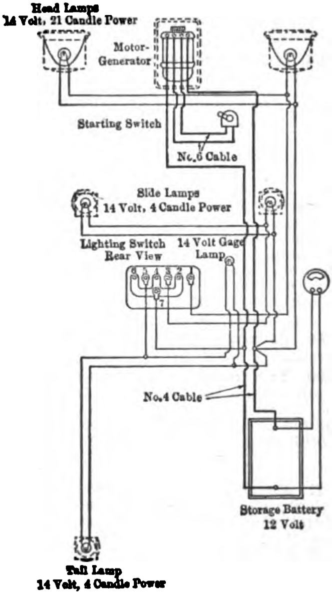

FIG. 13.—Single-unit, two-wire, 12-volt system.

The mechanical construction of the several units should be such as to demand little or no attention from the operator. Easy access should be afforded for repairs.

LIGHTING

86. Reflectors are of many shapes, and perform the same function as the backing of any ordinary headlight. It is essential for efficient use that they focus properly, and that the beam have proper alignment with the direction of car motion. Some lamps are provided with a mechanism by which the bulb may be either advanced or retracted until the proper focus is obtained. Proper alignment is secured by focusing the ray to a pencil beam and then aligning the lamp by resetting the props. A focusing lamp is shown in Fig. 14.

In some cities a "glare ordinance" restricts the use of blinding rays from head lamps. This difficulty has been overcome by the use of translucent screens, by an auxiliary lamp of smaller size located in the same reflector, by interposed obstructions to the beam, and by backing the bulb with a small shroud of low reflecting power.

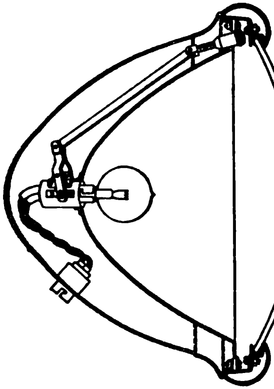

FIG. 14.—Focusing lamp.

87. Wiring for lighting systems must be installed with a view toward permanence of insulation and contact. Oil will depreciate rubber insulation, hence automobile wire is cloth-covered. If a grounded or a one-wire system is used, care must be taken to secure a perfect and lasting ground on the metal frame of the car. It should be remembered that the carrying capacity of wire for a given candle-power must be considerably higher than is found in standard 110-volt systems of distribution. Simplicity in the arrangement of leads is essential, for repairs are likely to be made by operators absolutely uninformed regarding the simplest electrical circuits.

Lamps are usually controlled from a multi-point switch located within easy reach of the operator. Ordinances of certain cities demand that the

The spark variation may be accomplished manually, or, by means of a governing apparatus, the process may be made automatic. This relieves the operator of the care and attention bestowed on the spark lever, and, in addition, accurately determines the proper position of the spark for all engine speeds.

93. Low-tension (make-and-break) system. The spark may be made within the cylinder by the action of a spring which breaks the contact made by a device driven from a cam mechanism which is positively connected to the engine. The circuit leading to the terminals of this contact include either a battery or a low-tension magneto in series with a simple reactance. The sparking action is simply the inductive kick of the reactance coil when a steady current temporarily flowing through it is suddenly broken. The size of the spark depends upon the value of current built up in the reactance during the time of contact; this current value varies with the engine speed. At high engine speeds a reduced intensity of spark is thus realized, and a heavier spark is obtained at the lower speeds, which is desirable. The timing of ignition is secured by the adjustment of the cam or cams. Fig. 15 shows the arrangement of a low-tension system of ignition, offering a choice of magneto or battery and coil at the will of the operator. In the former case, the magneto, as here shown, embodies all the reactance necessary. An arrangement of this nature provides an auxiliary source of energy, whereby, if starting with ignition supplied from a magneto is insufficient at the low cranking speed, ignition may temporarily be supplied from the battery.

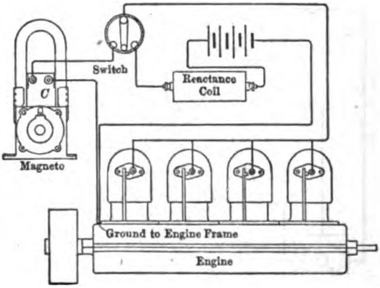

Fig. 15.—Low-tension (make-and-break) system.

94. Multiple-vibrator system. Where more than one cylinder is used it is possible, by supplying duplicate ignition units (a separate unit for each cylinder), to secure firing which is approximately synchronous. In Fig. 16 may be seen four separate induction coils, each supplied with its own vibrator. The primary circuit of each one of these coils is completed by a contact maker, which at the proper time (here indicated by the position of a cam), closes the primary circuit of the coil corresponding to the cylinder which is to be fired, and, by the action of a vibrator, causes a spark in that cylinder. Synchronized ignition for four or more cylinders with this method, can be only approximate at best. It is impossible so to attune the vibrators that they will respond equally to the action of the timer. The time lag, mentioned in Par. 91, may vary for each of the several cylinder equipments. The effect of this is improperly timed firing, and the smoothness and economy of the engine as a whole is greatly reduced. It is due to these difficulties that multiple-vibrator ignition is losing in favor, and is being rapidly replaced by several other systems.

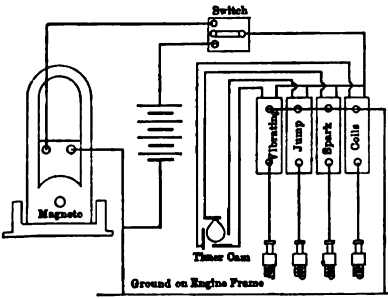

Fig. 16.—Multiple-vibrator system.

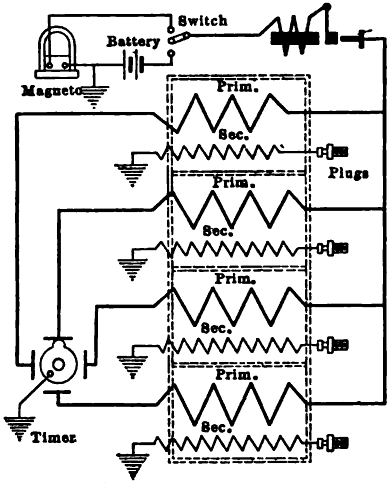

FIG. 17.—Connections of master vibrator.

convert a multiple-vibrator system into one more nearly synchronous. Essentially it consists of a single vibrator connected in that primary lead from the battery which is common to all coils. In addition, certain features of refinement have been added which ordinarily do not appear in the separate vibrators of the multiple-vibrator systems. In Fig. 17 a master vibrator is shown connected to a four-coil ignition arrangement. A master vibrator can be installed in any accessible place in the car and may be connected, with few changes, to an existing multiple-vibrator system; however, all vibrators on the individual coils must be short-circuited. The source of energy, as in the multiple-vibrator system, may be either a battery or a low-tension magneto.

96. Single coil with distributor. In many of the modern types of car, ignition is accomplished by means of a single coil whose secondary is connected successively to the spark plugs of all cylinders by means of a device which is known as a **distributor**. The required energy may be supplied from a high-tension magneto or a battery and coil.

The high-tension magneto may be of several designs, each maker claiming certain advantages for his own method. In one type (Fig. 18), current is first generated at a low voltage, and then led out to the primary of a coil. From the secondary of this coil, high-tension current is brought back to the distributor which is mounted on the magneto and connected with the magneto shaft through suitable gearing. The primary circuit is normally closed through the armature of the magneto and the coil. This circuit is opened by a contact breaker, also located on the magneto. Leads extend from the distributor to the spark plugs of the various cylinders. Another type of high-tension magneto contains the induction coil as an integral part of the armature. The armature thus carries

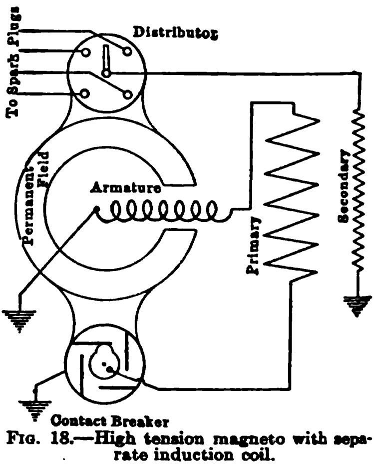

FIG. 18.—High tension magneto with separate induction coil.

two coils, one of few turns and one of many turns. The former or primary winding includes in its circuit the contact breaker, and the secondary winding is led to the distributor which is located on the magneto. High-tension magnetos are coupled positively to the engine in order that the proper relation may be preserved between magneto and engine.

Where a battery is used with the single-coil distributor system, it is usual practice to employ what is known as a **single-spark contact maker and breaker**. Such a device is shown diagramatically in Fig. 19. It will be seen that in this system the circuit is closed for a certain definite percentage of each revolution of the timer. As the engine speed increases, this duration of contact will be preceptibly shortened, consequently the primary current will build up to a smaller value, and when this current is broken, the resultant spark will be smaller, even though the speed of break is reasonably constant for all speeds. A refinement which has been added to this system, is an automatic regulator for securing the same length of break at all except the very slowest speeds. It is argued in favor of this kind of battery ignition, that a quick break, properly timed, results in a rapid combustion of the gas and the greatest pressure upon the piston at the beginning of the power stroke.

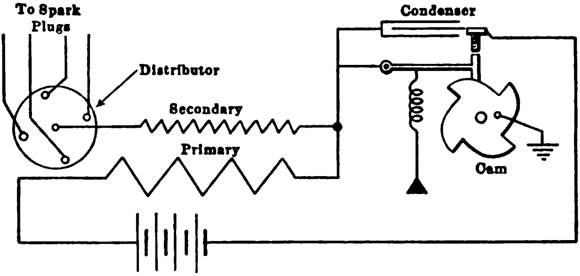

FIG. 19.—Single-spark system of battery ignition.

97. Battery versus magneto. Prior to the advent of recent improvements in battery starting and lighting systems, the magneto system of ignition was decidedly in public favor. But the very rapid adoption of battery starting and lighting systems has resulted in considerable controversy over the relative merits of battery and magneto ignition systems. The most important advantage claimed for the magneto was reliability; it also consumes but a small portion of the engine output, never becomes exhausted and never requires recharging as batteries do. The last-named advantages disappear in large degree when the magneto system is compared with the modern battery ignition systems in which the batteries are under charge almost continuously while the engine is in operation. It is also claimed that the magneto is less likely to suffer complete failure than a battery which may become short-circuited and give out completely. On the other hand, battery ignition produces greater spark intensity at the lower engine speeds than the magneto system, and certain experts have claimed that this feature makes the battery system decidedly superior. Another advantage which is claimed for battery ignition is the increased range of spark adjustment (Par. 92).

THAWING WATER PIPES

BY H. B. GEAR, A.B., M.E.

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98. Advantages of electrical method. The thawing of frozen water pipes by the use of electrical energy has become quite common in the northern

100. Another method of thawing pipes, using a small amount of energy, is shown in Fig. 21. With this scheme a piece of rubber-covered wire is thrust into the end of the pipe and a current of about 20 amp. slowly melts the ice. A disc of insulating material centres the wire and prevents it from making contact with the pipe. This method is only applicable where the pipe is straight and where the end is accessible.

101. Power capacity required. In thawing ordinary house services which are not over 1¼ in. in diameter, it has been found that a transformer capacity of about 30 kw. is ample to start water flowing in from 15 to 30 min. Where standard transformers are used, the connection shown in Fig. 22 has been quite generally employed; this affords about 55 volts and from 350 to 500 amp. Standard transformers may be safely overloaded 50 per cent or more for 15 min. during the cold weather in which this kind of work is done.

The thawing of a 6-in. (15.24 cm.) main, 1,700 ft. (518 m.) in length in the East River at New York required the use of 750 kw. for 36 hr. In this case the pipe was laid in the bed of the river and was surrounded by salt water having a temperature of about 30 deg. Fahr. It was very difficult to raise the temperature sufficiently to thaw the ice inside, as the heat was carried away so rapidly by the moving water around the pipe. The accompanying table gives data on the amount of current and the length of time required to thaw frozen water pipes by electricity. ("Proceedings of American Water Works Association," 1912. *Eng. and Cont'g*, Feb. 12, 1913.)

Size pipe (iron)*, in.	Length, ft.	Volts	Amperes	Time required to thaw, min.
¾	40	50	300	8
¾	100	55	135	10
¾	250	50	400	20
1	250	50	500	20
				Hours
1	700	55	175	5
4	1,300	55	260	3
10	800	62	400	2

* To thaw out lead pipe, the current must be increased 50 per cent.

MARINE APPLICATIONS OF ELECTRICITY

BY H. A. HORNOR, B.A.

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MERCHANT MARINE PRACTICE

102. Rules for installations. In general the electrical construction on merchant vessels must comply with the requirements of the classification society under the rules of which the vessel is constructed. Such societies are established in all the large maritime countries. The American Bureau of Shipping and Lloyd's Register of British and Foreign Shipping are the societies under which most of the merchant vessels of this country are built. In addition, the Navigation Laws of the U. S., and the Pilot Rules, issued by the Department of Commerce, must be carefully followed. For certain inland vessels, especially those plying to and from New York City, the National Board of Fire Underwriters specify and inspect the installation. To cover detail requirements and special operating features the vessel owner also provides a general specification both for use in obtaining a price as well as for an instrument of guarantee. These rules and specifications give a wide latitude to the engineer, and in many cases the finished installation more than covers the requirements. This is due to rapid advance in the art.

103. Lighting circuits. The distribution of energy is the same as in a two-wire system on land. Feeders are led from the switchboard to distribution cabinets, and branch leads are thence distributed to groups of

111. Searchlights. This apparatus, because of the comparatively large current consumed, is considered as furnishing part of the power load. The searchlight is served through a separate switch on the main switchboard, and the arc voltage is adjusted by an external variable resistance. Provision is made on the switchboard whereby the voltage of the searchlight feeder may be observed by use of the generator voltmeter. The searchlight may be managed from the pilot house by either direct hand control or remote electric control. In order to insure against the ill effects of radio-telegraph induction it is necessary that exposed leads to searchlights be either encased in pipe or wrapped with wire. In both cases the outer steel covering must be well grounded to the hull of the vessel. Searchlights are useful in picking up buoys in harbor channels and, in some trades, are very necessary for loading and unloading at night. For freight vessels or for passenger and freight vessels of 4,000 tons carrying capacity or over, the searchlight should not be less than 18 in. in diameter.

112. Electric radiators. For certain service, such as the coastwise traffic of the Pacific coast, electric air heaters find a suitable application. Where the temperature varies but a few degrees, as in this instance, passenger steamers can thus be comfortably heated without exceeding proper temperatures. For attractiveness some vessels carry luminous radiators in the staterooms and lounging rooms, and tubular air heaters in the passageways and in the rooms less frequented. These appliances must be designed to undergo hard service, must be properly fused, arranged for mounting on bulkheads, and should be sufficiently guarded to prevent inflammable materials from being cast upon them.

113. Engine telegraph system. For the maneuvering directions between the pilot house and bridge and the engine room, mechanical signals are employed. This system consists generally of transmitters, located one in the pilot house and one on the bridge, connected by low-brass wire and triple-link chain passing over brass pulleys to a receiver in the engine room. A reply system assures that the signal has been properly received. Occasionally an electrical attachment is made from the engine-room receiver to the reversing shaft of the engine whereby a false signal may be immediately made known. The transmitter dials are electrically illuminated. Various models to suit the propelling machinery are manufactured.

114. Miscellaneous mechanical telegraph and bell pulls. Other telegraphs for the purpose of docking the ship, steering, indicating the rudder angle, and for adjusting the mooring lines, are exactly similar to the engine telegraph instruments except that the dial orders are suitably changed. As an emergency precaution mechanical bell-pulls are installed near the engine telegraphs, connecting with a gong and a jingle bell in the engine room. As an auxiliary to any means for operating the main steam-whistle valve, mechanical pulls are located on the bridge and in the pilot house.

115. Telephone speaking tubes and call-bell system. The law requires that for vessels in which the distance from the pilot house to the engine room is greater than 150 ft. a telephone must be installed in addition to, or in place of, the voice tube. For shorter distances speaking tubes are used giving communication between important places in the vessel. It is compulsory to install either a speaking tube or a telephone between the wireless room and the bridge. Other points of communication are merely for convenience and differ with the desires of the owner. In both passenger and freight vessels, annunciators are located in the main pantry and push buttons are installed in all staterooms, messrooms, saloons, etc. In living quarters remote from the bridge and not provided with watchmen on continuous duty, alarm gongs are installed; these are actuated by a push button located in the pilot house. This is a requirement of law.

116. Fire-alarm system. All vessels are not equipped with such a system, and the systems that have hitherto been installed have not proven altogether satisfactory. Such systems usually consist of electrical contacts which are closed by the melting of a fuse of soft metal, and merely indicate the presence of fire. Two systems are on the market to-day which more nearly approach satisfactory service. In one of these not only is warning of the exact location of the fire given, but live steam is admitted to the origin of the fire by means of a direct lead of pipe.

117. Submarine signals. Large cast-brass bells, rung either by electric, air or wave power, are submerged beneath the lightships that beacon the be run in parallel, others preferring that each feeder be provided with a double-throw switch and that separate bus bars be provided for each generator. This is more a question of operation than one of engineering, but with the conditions as described in Par. 121 it would seem more desirable to keep the generators on separate bus bars, should no electrician be carried.

124. Conduit and moulding. The special requirement for any marine installation is that the conductors be so protected that grounds will seldom occur and that the water-tightness of the vessel will not be impaired. All of the above cited rules require a heavy insulation of rubber and furthermore require that the completed installation must show approximately one megohn of insulation resistance. Beyond these rules the owner usually specifies the highest quality of wire upon the market. As it is customary to use enamel-lined conduits, double-braided wire is installed in conduits and single-braided wire in mouldings. In a combined conduit and moulding installation, conduits are run on exposed decks, in cargo holds, machinery spaces, galleys, pantrys, crew's quarters, etc. Water-tight junction boxes for branch connections and steam-tight fixtures are used on such lines. In the living quarters, mouldings matching the woodwork are provided, all connections being carefully made and laid in the moulding. When conductors pass through steel beams or bulkheads the hole is bushed with hard rubber. When conduits pass through water-tight decks or bulkheads a brass stuffing tube is fitted at the bulkhead; this tube is packed with red lead and flax, forming a water-tight joint.

125. Flexible cables and conduit. Flexible cables with or without a lead covering are sometimes used in lieu of mouldings. The flexible cables are strapped on the structure, have the advantage of being readily overhauled, and, if the insulation is properly selected, reduce the amount of inflammable material.

126. Steel braided armored cables. There is at present on the American market a design of steel-armored cable similar to that used for some time past in foreign countries. This material supersedes both conduits and mouldings, as the lead-covered steel-armored cable is perfectly water-tight and sufficiently protected for exposed spaces; the armored cable without a lead sheath is applicable for living spaces where it may be safely run behind panel work or in decorative mouldings. As mentioned above, this type of installation besides having the important characteristic of reducing grounds to a minimum also makes a perfectly safe installation for heavy wireless telegraph outfits. The only change necessary in fittings is that stuffing tubes must be added to the water-tight branch junction boxes.

NAVAL PRACTICE

127. Lighting system. All governments strive to obtain for their naval vessels the very latest and best developments of the art. This desire precludes standardisation to any great extent. The methods of distributing light, the type of lighting fixtures, and the problems of illumination are all being carefully studied; advances in the art are rapidly adopted. In general the fixtures are heavier than in ordinary practice, and the materials, as specified, are more closely inspected. In the United States Navy, the standard lamp is rated at 123 volts, and metallic-filament lamps are now in service. Arc lamps are no longer used, having been superseded by the 250-watt tungsten lamp.

128. Motor system. Motors and their controlling equipments are elaborately specified, tested and inspected by the United States Government. Copies of these specifications as well as all apparatus and material furnished the United States Government may be procured upon application to the Navy Bureau concerned. Within recent years the motor load on a battleship has very greatly increased both in capacity and importance. This augmentation has caused some governments to increase the generator voltage to 220, still retaining direct current. Such auxiliaries as the anchor windlass, requiring 300 rated horse-power, and the steering gear which requires approximately a like amount, illustrate the above statement.

AVERY, W. G.—"Marine Electric Generating Plant, Distribution and Interior Communication." *International Marine Engineering*, Vol. XVI, p. 265, 1911.

HORNOR, H. A.—"The Electrical Equipment of the Modern Battleship." *The Journal of the Franklin Institute* of Pa., 1913.

APPLICATIONS OF ELECTRICITY IN THE UNITED STATES ARMY

BY EDWARD D. ARDERY

Captain, Corps of Engineers, United States Army

134. General applications. Aside from the usual applications to illumination and the operation of machinery, electrical energy is employed in the Army for communication, operation of searchlights, maneuvering seacoast guns, operating ammunition hoists, blasting, exploding mines and firing guns.

135. Energy supply. A central generating plant would be the most economical arrangement, but might be paralysed by a single well-directed shot. To provide for such an emergency, a reserve supply is necessary. Where reserve energy supply is not already provided for in other ways at seacoast forts, it is current practice to install 25-kw. gasoline generating sets in or near the batteries. Commercial supply also is used when available. On account of the development of the gasoline sets, the use of storage batteries in fortifications is being discontinued; these batteries were formerly required for supplying the telautographs, but are now employed only in connection with the telephone systems.

136. General specifications for power plants in fortifications. The National Coast-Defense Board, in 1906, recommended: (a) that the electrical energy used for fortification and defense purposes be furnished by an adequate steam-driven, direct-current central power plant, all machinery to conform in type to approved commercial standards; (b) that each battery or group of batteries be equipped with gas-driven or oil-driven direct-current generators, installed as a reserve to the central plant; (c) that the energy supply of searchlights be provided by self-contained units unless the searchlights are in close proximity to the central plant; (d) that the torpedo casemates be supplied with energy from independent sources for submarine-mine purposes; this arrangement should constitute an integral part of the submarine-mine defense; (e) that alternating current energy, when essential, should be obtained from the direct-current distribution system, using for the purpose a suitable converter; if, however, it is found more economical, this energy may be obtained from a separate alternator; (f) that the central-station output, when not needed for fortification service, may be used for garrison purposes, provided that the latter load does not require too large an increase in the size and number of units; (g) that, should the garrison service require an alternating-current distribution system, the energy should be supplied from the central plant, either through a suitable converter or from alternators installed for this special purpose in the central station; (h) that uniformity of types and accessories should be adhered to as closely as possible.

137. Protection of distribution. Considerations of economy, efficiency, and protection against hostile fire require that the greater part of the electrical communications be either subterranean or submarine. Conductors are sometimes laid underground in trenches roofed with plank for protection. Such conductors should be lead-covered and armored, the armor being served with a jute yarn in some cases. Lead-covered, unarmored cable, without jute on the lead covering, is suitable for conduit construction.

138. Wiring specifications. The wiring rules formulated by a Board on Standardisation of Wiring for Seacoast Batteries are as follows: (a) conduits should not be employed for local distribution in emplacements where their use can be avoided; (b) all wires leading out from the emplacepart in the transmission of information, orders, etc. The telegraph is of less importance, and is used in the same manner as in commercial practice.

145. Buzzer. This apparatus consists of an interrupter and an induction coil supplied with energy from a few dry cells. In operation the buzzer is used as a transmitter for the purpose of signaling; the frequency of the current is such as to produce a high note in a telephone receiver at the far end of the signaling circuit. Leaks, bad connections, and high resistances, any one of which would cripple a system employing Morse instruments, merely affect the loudness of the signals in the receiver. Each transmitting station is equipped with a telegraph key and a telephone transmitter, and may be used either for telegraph or telephone communication.

146. Wireless telegraphy (radio) is readily adaptable to military purposes, and for ordinary distances can take the place of the telegraph, making it particularly useful in field operations. In Alaska, on account of the frozen soil, satisfactory grounds are sometimes difficult to obtain. The Signal Corps has developed portable radio sets that may be transported on mules, on a wagon, or on an aeroplane. High frequency, quenched-spark circuits are used. Both silicon and perikon detectors are employed. The generator of the pack set is driven by hand, but a storage battery can be used. The wagon set is larger and of higher efficiency than the pack set. For aeroplanes the generator is operated by a friction drive from the engine. In the absence of a ground connection, a counterpoise is used. Receiving is rendered difficult on account of the noise of the engine.

147. Handling of guns. For enabling seacoast guns to be traversed by power, motors are attached to some of the gun carriages. When, at drill, the guns on disappearing carriages are tripped into battery without being subsequently fired, the retracting to the loading position may be done by motors. Retracting motors can also be arranged to elevate or depress the muzzle of the guns when being aimed.

148. Firing of seacoast guns may be accomplished electrically or by pulling a lanyard. To guard against accidents in electrical firing, there are usually three breaks in the circuit. Two are closed automatically: one when the breech-block is properly locked, and the second when the gun has moved properly into battery; the third is a contact which is manually closed at the firing pistol or switch when all is in readiness. Energy may be supplied from dry cells or an electric exploder.

149. Ammunition hoists are used for raising projectiles from the magazine level to the loading-platform level of some of the larger guns; these hoists consist of endless sprocket chains, with carrier arms attached, operated by electric motors. To avoid accidents, the motors cannot normally be reversed, but the projectiles can be lowered by hand. The powder charges may be handled on similar hoists.

150. The velocity of a projectile is measured by firing it through two targets *t*, Fig. 23, separated by a known distance. An electric circuit is broken at each target, and the elapsed time between breaks is determined with a Le Boulengé Chronograph (*b*, *d*, *r*). The velocity of gun recoil can be similarly determined.

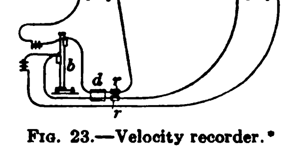

Fig. 23.—Velocity recorder.*

151. Targets. The face of the self-scoring target for rifle practice is divided into segments of armor plate, which the rifle bullet cannot penetrate. Held against the backs of these sections by springs are one or more spindles. A bullet striking a segment causes the spindle or spindles abutting against that segment to jump backward, closing an electrical contact; this causes a number representing the value of the hit to appear in a corresponding place on a miniature-target annunciator at the firing point. Dry cells furnish the energy required for operation. Each segment has a separate circuit, but with a common return.

152. Electrical caps, or fuses (Fig. 24) contain fulminate of mercury, with a platinum bridge, *p*, imbedded in the fulminate; heating the bridge by passage of an electric current through it causes the ignition. Caps stored

* Lissak, O. M. "Ordnance and Gunnery;" New York, Wiley and Sons, 1908.

lery School, 1912.

ELECTRICITY AND PLANT GROWTH

By JOHN E. NEWMAN

General Manager, The Agricultural Electric Discharge Co., Ltd.

155. General. In the eighteenth century a Scotchman subjected myrtles to the discharge from a frictional machine and reported that they were benefitted. Since his time there have been many experiments, but they may all be divided into two main classes, as follows: (a) those aiming to influence the plant by changes in the atmospheric electrification; and (b) those in which currents are passed through the soil about the plants. The records of these experiments show that, generally speaking, where artificial discharges of electricity to the air over the plants take place, favorable results have been recorded; where the method has been that of passing currents through the soil, the results are contradictory.

156. The first systematic experiments on any important scale are those of the late Prof. Lemstrom, of Helsingfors University, Finland, who carried out experiments on a field scale in Finland, France, Germany and in England (at Durham University). In the course of his trials, he experimented with almost all the common vegetables and cereals as well as with strawberries and raspberries. His method was to suspend a network of fine iron wires, spaced about 4 ft. apart, 16 in. above the plants to be electrified. These wires were provided with points like barbed wire, and had to be raised as the plants grew. While the results showed a definite increase, from 20 per cent. to 45 per cent. in the case of most crops, the method is impracticable for work on a large scale. The close network of wires about 1 ft. above the crop and the numerous posts necessary, seriously interfere with the ordinary cultivation of the ground and make horse or steam cultivation impossible. Nor can an influence machine be considered practical from an engineering standpoint.

157. In the Evesham experiments, commenced in 1906 (and still being carried on) by the writer, in cooperation with Mr. R. Bomford and Sir Oliver Lodge, the following arrangements were adopted and have been followed essentially in subsequent installations in different parts of the world, including the plant now being worked by the Department of Agriculture at Washington. Over the area to be electrified is erected a wire network consisting of thin galvanised steel or bronze wire run at an average height of 15 ft. above ground (this being assumed as that clearance which would allow a loaded harvesting wagon to pass underneath), the wires being 10 ft. apart and carried as span wires between stout telegraph wire, on insulators mounted on posts planted 71 yd. apart in parallel rows 102 yd. apart. Thus 21 poles will do for 20 acres, or roughly a pole to an acre.

158. The potential at which the network is charged varies from 50,000 to 75,000 volts. This corresponds to the potential at which the network is actually charged by an average thunderstorm, and at this pressure the discharge on a quiet day is distinctly audible. What we have is practically a leaky condenser, with the air as the dielectric; and this condenser must be kept charged.

159. Source of energy. The current to charge the network is provided by an induction coil, the negative high-tension pole of which is earthed and the positive high-tension pole connected to the network through from 3 to 5 **Lodge valves** in series. The valves will allow positive electricity to pass through them in one direction only, and negative electricity to pass through them only in the other direction. Any value of direct-current voltage up to 250 may be employed, or alternating current may be used, with some decrease in efficiency.

160. A motor-driven mercury gas break, able to run about 1,000 hr. without being cleaned out, is used; it is equipped, when necessary, with an automatic hydrogen generator.

161. The power absorbed by the coil when charging a network of 25 acres is about 300 to 500 watts, and the small break motor and ventilating fan motor absorb another 100 watts.

162. The best length and time of application of the current is

where V is the true wind velocity and v is the actual velocity of the cup centres in the anemometer. See *Electrical World*, Vol. LVI, Oct. 27, 1910, pp. 995 to 1000. As a rule, the measured or indicated velocity is the one implied in discussions of velocity and pressure.

167. Wind movement is recorded in miles, and is virtually the integration of the instantaneous velocities for a given period or the total distance a given particle of air would move in that time. Tables of wind movement per day or per month have been prepared and published for various localities; many of these can be found in the government publications. Such information is very essential to any careful study or forecast of the probable performance of a windmill in any specific locality.

Wind pressure and its relation to wind velocity is a subject which has received much study by many investigators. The Weather Bureau formula is

$$P = 0.004\left(\frac{B}{30}\right)V^2 \qquad \text{(lb. per sq. ft.)} \qquad (6)$$

where B is the barometer reading in inches of mercury and V is the indicated velocity in miles per hr.

168. Available work in air currents. The total aerostatic head of a moving gas, at any given point, is the sum of the pressure head and the velocity head. Since the aerostatic gradient changes but slightly between areas of high and low pressure, it is sensibly constant in passing any given locality. Therefore the total available work stored in the moving gas is represented by the velocity head, or energy of momentum.

169. Windmill characteristics are shown in Figs. 26 and 27, plotted from the test data on a 16-ft. aermotor (steel mill) taken from Par. 172. It is obvious from Fig. 26 that both the speed and the load torque increase

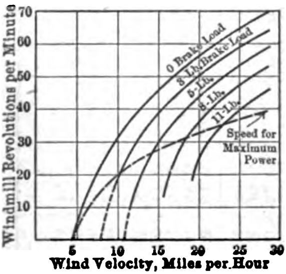

FIG. 26.—Speed curves of 16-ft. Aermotor.

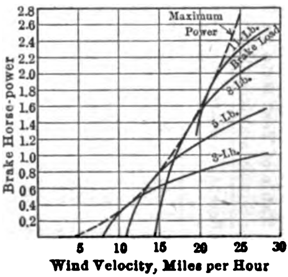

FIG. 27.—Power curves of 16-ft. Aermotor.

with the wind velocity, for maximum output; this is made even clearer by the maximum power curve in Fig. 27. Maximum output therefore requires that the load on the mill, under variable wind velocities, shall have the characteristic of increasing torque with rising speed, in a certain definite manner for any given mill.

170. Efficiency. The 12-ft. aermotor (Par. 172) in a 9-mile wind, at maximum power, had an efficiency of 26 per cent.; this value was computed from the basis of the total wind area of the wheel (12-ft. circle). In a 14-mile wind the efficiency was 23 per cent. Maximum efficiency always occurs with maximum power or output.

171. Windmill governors. Practically all forms of vertical mills are equipped with a form of device which throws them partially or wholly out of the wind, when the wind velocity exceeds a certain value. The effect is to prevent excessive or dangerous speeds in high winds or gales.

led him to the conclusion that steel wheels are superior to wooden wheels, also that curved sails are superior to flat sails. Furthermore, a relatively small number of large sails will give higher efficiency than a large number of small sails, of equal total area. Steel mills are commonly employed except along the seacoast or in very damp climates, where corrosion is likely to give more than ordinary trouble.

174. Example of useful work performed in a given period. Based on the records of mean wind movement at Dodge, Kansas, from 1889 to 1893, Murphy estimated (Water Supply and Irrigation Paper No. 42, Part II, page 118) that steel mills (aermotor) would give the following performances.

Size of mill	Horse-power-hours per month		
	Mean	Maximum (April)	Minimum (November)
12-foot........	338	461	245
16-foot........	488	671	351

175. Height of tower. The mill should always be placed well above surrounding objects such as trees or buildings, at least 30 ft. On account of competition, the tower weights are kept as low as possible and for this reason steel towers sometimes lack stiffness; wooden towers are usually less objectionable in this respect. It is almost always economical to place the mill at an elevation of 50 ft. or more above the ground, not only to avoid obstacles to free wind movement, but also because wind velocities are known to increase somewhat with the elevation.

176. Generators for windmill electric plants are referred to in Sec. 8, Par. **186** and **189**. A shunt-wound machine, with variable-speed drive, requires an automatic regulator for maintaining constant voltage. The differential type of winding, applied to a machine for charging storage batteries, tends inherently to regulate for constant output with variable-speed drive.

177. Automatic battery switch. In order to connect the generator to the storage battery when the speed and the terminal voltage are sufficiently high, and to disconnect the generator when the speed and the voltage fall too low for charging, an automatic switch is employed whose functions are controlled by the terminal voltage of the generator.

178. Storage-battery reserve. The necessary reserve capacity in the storage battery, for any given installation, can be determined only by a careful study of the records of wind movement at the place in question. If the periods of calm occur frequently and last for any considerable time, it will pay to consider a gasolene engine for stand-by instead of the extra battery capacity required.

179. Data on Cost and Capacity of Windmill Electric Plants
(A. V. Abbott)

Diam. of wheel (ft.)	Horse-power in 16-mile wind	Total cost of installation	Required capacity of battery (amp-hr.)	Watt-hours delivered per day from battery*
12	0.21	$249	5	280
16	0.41	415	10	551
20	0.79	606	32	1,762
30	2.40	1,344	103	5,640
40	4.42	2,000	190	10,390
50	6.88	3,190	294	16,170
60	10.00	4,179	427	23,500

* Assumed dynamo efficiency, 50 per cent.; battery efficiency, 45 per cent.; assumed daily charge, 8 hr.; wind velocity, 16 miles per hr., for 8 hr. per day.

becomes a dark blue mobile liquid with highly magnetic properties. The chemical formula is O_3 and the molecular weight 48; the critical pressure is 125 atmospheres and the critical temperature, −103 deg. cent. It is an endothermic compound and the heat of formation is nearly 33,380 g-cal. per mole. At ordinary temperatures it is relatively stable but it decomposes in contact with organic, or in general, oxidisable matter, and spontaneously at 260 deg. cent. It is practically insoluble in water, 1.5 to 10 mg. per liter being the limits of solution at temperatures of from 2 deg. to 28 deg. cent., according to Maufang.

184. Formation. Ozone may be formed in various ways, which are: (a) by chemical action; (b) by electrolysis; (c) by the electrostatic field; (d) by ultraviolet rays; (e) by the radioactive elements; (f) by incandescent solids: (g) and by the evaporation of water. Only the production by the electrostatic field has been developed commercially. The theory of this method is not fully understood but it is probable that ionisation by collision takes place, with consequent dissociation of the oxygen which on recombination furnishes aggregates of ions consisting of molecules with an attached extra atom. Within working limits, in commercial ozone generators, the production is roughly proportionate to the electrostatic intensity above a certain critical value, and with alternating currents, to the frequency employed.

185. Chemical analysis. Treadwell and Anneler, in 1905, checked all previous results and finally established the correctness of the method of chemical analysis which is now in general use. This depends on the following reactions:

$$2KI + O_3 + H_2O = 2KOH + I_2 + O_2 \qquad (7)$$

$$2Na_2S_2O_3 + I_2 + 2KOH + H_2SO_4 = Na_2S_4O_6 + 2NaI + K_2SO_4 + 2H_2O \qquad (8)$$

In practice these reduce to the following volumetric equation:

$$1{,}000 \text{ c.c. } N/10\,Na_2S_2O_3 = O_3/20 = 48/20 = 2.4 \text{ gm. } O_3 \qquad (9)$$

The sample of ozonized air of measured volume is drawn through a neutral solution of KI and titrated with $Na_2S_2O_3$ or it may be collected in a calibrated flask and shaken with the neutral KI solution. The mixture of KI and I_2 is acidified with an equivalent of H_2SO_4 before the titration. It is customary to denote the amount of ozone in terms of gm. per cu. m. of air and to reduce the readings to spt.

186. Ozone generators have been made in various forms. The essential principle in all cases is the juxtaposition of two or more discharging surfaces so as to form a condenser with an air gap which may or may not be furnished with a dielectric element. The discharging surfaces may be smooth or armed with points, and if smooth they may be flat or curved. Ozonators without dielectrics generally possess rotating electrodes, so that they are in relative motion in order to avert sparking which favors the formation of nitrogen oxides and the destruction of ozone already formed. The great majority of successful ozone generators have smooth electrodes and dielectrics, and are divisible into two types, the cylindrical and the plate.

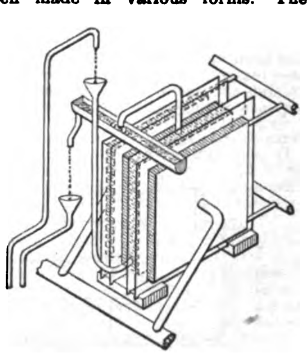

Fig. 28.—Plate ozonator.

187. A typical form of plate ozonizer is shown in Figs. 28 and 29. The two outer plates are pierced at the centre, and the ozonized air is aspirated through tubes inserted in the holes. The air enters at the peripheries of the plates and passes through the field to the centre. Cooling is effected by means of flat rectangular water boxes in contact with the two outer plates, and with a similar box in contact with and between the two inner plates. The two outer boxes are earthed; the inner box is insulated and forms and removed by allowing the water to fall through the air a distance sufficient to ensure against wasteful electrical leakage. The whole structure is commonly contained in a glass retaining case into which suitable dry air is introduced. The advantage of this type of ozonator is that as the field is produced between the two glass plates, the labor necessary to keep the machine clean is nominal. The disadvantages are as follows: difficulty of assembling and taking apart, high potential required, complexity of the cooling system, large space occupied and danger of shut down of the whole system through the failure of one unit.

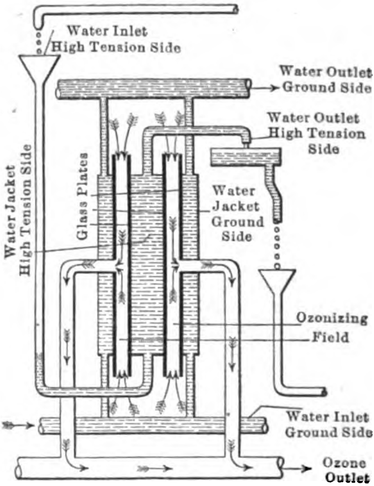

FIG. 29.—Plate ozonator.

188. Operating voltages. Commercial ozonators are commonly operated on voltages ranging from 5,000 to 20,000 and at frequencies of from 50 to 500 cycles per sec., and are used in connection with transformers. Special high-frequency generators are generally furnished in all but the smallest installations, for the capacity of an ozone generator is almost proportional to the frequency employed.

189. Refrigeration of air supply. An essential to successful and economical ozonizing is dry dense air and consequently most installations, excepting very small ones, include a means for refrigerating the air. It has been found in practice that air cooled to about zero Centigrade possesses the requisite dryness, and that further cooling is uneconomical because, though the yield of the ozonator is increased, this is secured only at the expense of relatively greater cost for refrigeration.

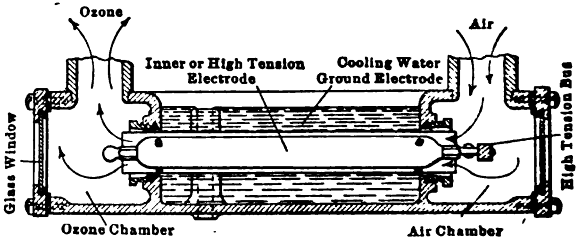

FIG. 30.—Tubular ozonator.

190. Tubular ozonizers. A representative tubular unit is shown in Figs. 30 and 31. This consists of a cast-iron frame with two closed bulkheads connected together by the ozone tubes in much the same way as in a water in water which forms the ground element, while the inner high-potential elements are connected to the circuit by means of suitable contacts on a bus bar which is carried into the air header through insulating bushings. The air is introduced into the rear header and passes through the tubes to the front, whence it passes into the ozone collecting pipe. This machine requires cleaning from time to time, but the operation is simple and quickly performed. The door of the ozone header is removed, the inner electrodes are drawn out and the tubes are cleaned with a swab.

The advantages of the tubular ozonizer are compactness, relatively low voltage (about one-half that of the plate machine), readiness with which it may be assembled and taken apart, simplicity of the cooling system, and facility with which one or more units may be inserted or taken out.

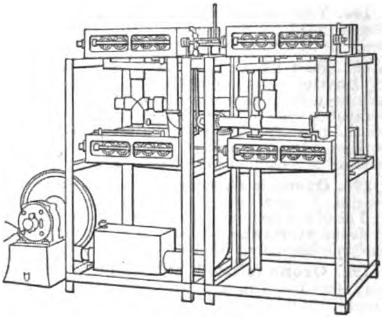

Fig. 31.—Tubular ozonator.

191. Concentrations and yields. For most industrial purposes the concentration should be in the neighborhood of from 1 to 3 g. per cubic meter of air, although in some special cases it may be as high as 5 g. It is rarely found expedient to operate at greater concentrations. The average yield is about 50 g. per kw-hr., and although much higher yields are claimed from time to time for certain types of generators, these have not been attained in commercial operation.

192. Oxidizing effect of ozone. The applications of ozone are dependent upon the fact that it is a powerful oxidizing agent, and that it oxidizes most substances at temperatures far below those at which they are capable of combining with ordinary oxygen.

193. Ventilation. Ozone is used in ventilation chiefly on account of its power of destroying organic odors. It has been shown that it is capable of oxidizing the odors arising from various animal and industrial activities, for instance those of valerianic acid, butyric acid, skatol, indol, decayed foods, fish, tanners' scrap, manure, etc. The causes of distress in vitiated air are heat moisture and crowd odors. It is not believed that the organic excreta causing the latter are poisonous, although admittedly objectionable. Prof. Bass recently has conducted experiments on school children, which have established the fact that the addition of about one part of ozone in a million parts of air determines the difference between tolerable and intolerable conditions, when the air supply is very small.

194. Bactericidal power. It was at one time supposed that on account of the very great bactericidal power of ozone it would prove valuable in disinfecting the air of dwellings and factories, but it has been shown that in breathable concentrations it has little effect on the dry bacteria in the air; this, however, is immaterial, as it is now generally conceded that the dried bacteria in the air are not concerned in its vitiation nor in disease transmission. In suitable concentrations ozone may be used for disinfecting and deodorizing rooms that have become contaminated or infected.

195. Water purifications. The purification of potable water constitutes the most important application of ozone, in point of magnitude, up to the present time. The advantages of the method are the non-poisonous nature of the reagent; its insolubility which ensures against an excess remaining in the water; and the fact that besides rendering the water sterile, it removes all taste and odor which might be due to organic defilement.

moving charged particle, its effective mass should increase with its velocity, but only appreciably when its velocity approaches that of light; a particle moving with the velocity of light would have an infinite mass. This prediction of theory is borne out by experimental results. The ratio of charge to mass for particles whose velocities do not exceed 3×10^9 cm. per sec. is found to be 1.77×10^7 in absolute c.g.s. electromagnetic units. Thus the mass of a single β particle is 10^{-27} grams. The β particle is the smallest known mass.

205. The α rays. These are formed of positively charged atoms of helium, carrying a charge double that of the elementary charge carried by the β particles. They are projected with definite velocities from the different radioactive substances, varying from 1.45×10^9 to 2.22×10^9 cm. per sec.

206. The γ rays. In addition to the α and β rays, which are formed of charged particles, radioactive substances also emit another type of radiation, the γ rays. According to theory, when a rapidly moving charged particle is accelerated, either positively or negatively, an electromagnetic pulse spreads out from it. It is probable that the γ rays are made up of a succession of these pulses, arising, mainly, from the sudden liberation and sudden stopping of the β particles. There is evidence that the α rays also produce γ rays.

207. The δ rays. When an α particle is ejected from an atom, the residue is negatively charged. It must move in a direction opposite to that of the α particle so that its momentum is equal to that of the particle. The δ rays are formed of the residues of the atoms after expulsion of α particles.

208. Effects produced by the rays. The α, β, and γ rays produce both photographic and ionising effects. To show the former effect, a photographic plate is exposed to a radioactive substance. It is found to be affected just as if it had been exposed to light. The ionising effects are shown by their rendering air a conductor of electricity. The neutral molecules of air are split into positive and negative ions through the action of the rays. When a potential difference is applied, these ions travel in opposite directions, thus setting up an electric current. The photographic effect is caused mainly by the β and γ rays and the ionising effect by the α rays.

The ionising effect is employed to measure the "activity" of a radioactive substance. Metallic uranium is taken as a standard, and by an activity of 100 times, is meant that the substance produces 100 times the effect of an equal weight of metallic uranium in rendering air a conductor of electricity under the same conditions.

209. Radioactive disintegration. The atoms of any radioactive element break down according to the law $N = N_0e^{-\lambda t}$. N_0 is the number of atoms initially present, N the number after a time t has elapsed, and λ is a constant which has a definite value for each radioactive substance. External conditions are found to have no effect on the rate of disintegration. For example, the same value of λ is found whether it be measured at the temperature of liquid air or at the high temperature of an electric furnace. Thus radioactive disintegration is a phenomenon of an altogether different kind from any known chemical change.

210. Radioactive elements. Of the chemical elements that have long been known, only uranium and thorium have marked radioactive properties. There is considerable evidence that rubidium, potassium and sodium are also radioactive, but to a much less degree. In fact it is not improbable that all the elements are radioactive, the rate of disintegration of all but a few of them being too slow for detection. The phenomenon of radioactivity must be regarded as evidence of the instability of the atoms of the elements. The most unstable atoms are those belonging to the most radioactive elements. There is an enormous difference in the rate of disintegration of the different radioactive products. For example, uranium decays to half its initial amount in 5×10^9 years, while actinium A requires but 0.002 sec. for half of it to disappear.

There are three known series of radioactive elements, the uranium series, the thorium series, and the actinium series; it is not improbable that the last two series, as well as the first, have uranium as their parent. In each of these series, any member arises from the previous one by a radioactive disintegration, accompanied by the expulsion of an α or a β particle, resulting in the formation of an atom of a different kind. In the uranium series is series, the constant λ of the disintegration of uranium itself has a value such that 5×10^9 years elapse before a given amount of uranium decays to half its initial value. Thus millions of years are necessary for the uranium series to come to equilibrium. In most uranium minerals the equilibrium condition is satisfied, so that there is a definite relation between the amounts of uranium and radium contained in them. It is found that the amount of radium associated with 1 g. uranium is 3.4×10^{-7} g.

212. Heating effects. The continual emission of particles projected with high velocities from radioactive substances results in heating effects. The kinetic energy of the particle is transformed into heat. The α particles produce about 90 per cent. of the heating effect; while their velocities are lower than those of the β particles, their mass is so much greater that the kinetic energy of an α particle is many times greater than that of a β particle. One gram of radium in equilibrium with all of its products sets free approximately 118 cal. of heat per hr.

213. Radioactive minerals. The principal source of radium and the other strongly radioactive elements of the uranium and actinium series is the mineral pitchblende, which is an oxide of uranium. From this radium may be separated by chemical processes, its behavior being the same as that of barium from which it is separated by fractional crystallization. Carnotite is another uranium mineral, but of rarer occurrence. The principal source of the elements of the thorium series is monazite sand.

214. Uses of radium. Aside from its great scientific interest, the only important use of radium is as a therapeutic agent. Many cures of cancerous growths have been reported to result from its application.

215. Mesothorium, one of the members of the thorium series, is coming to be employed widely as a therapeutic agent. It has the advantage over radium of being easier to obtain. It is found in the residues left in the manufacture of thorium salts used in making Welsbach gas mantles. But it is far less permanent than radium. While 2,000 years must elapse for a given amount of radium to decay to half its amount, a given amount of mesothorium is reduced one-half in less than 6 years.

216. Determination of physical constants. The study of radioactive phenomena has resulted in the most reliable determination that we have of certain important physical constants. Some of these are given in the following table:

The elementary electric charge................	1.59×10^{-20}
Number of molecules in 1 c.c. of a gas at 0 deg. Cent. and 760 mm. pressure of mercury..	2.7×10^{19}
Mass of the hydrogen atom....................	1.65×10^{-24} g.
Number of atoms of hydrogen in 1 g..........	6.0×10^{23}

217. Bibliography.

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THE ELECTRON THEORY

218. The electron. The electron theory is built upon the observed wide distribution of electrons or corpuscles and their capability of accounting for many otherwise unexplained phenomena. Electrons are identical with the beta particles; the latter term is used to denote them when they appear accompanying radioactive disintegration. Electrons appear also under the name of cathode particles, when they are projected from the negative electrode, or cathode, by an electric discharge through a gas at low pressure. Ultra-violet light falling upon the surface of a metal sets electrons free; they are also liberated from incandescent solids. Whatever their origin, all electrons appear to be identical in nature. Their velocity of projection depends upon the circumstances under which they appear, but the ratio of their charge to their mass is the same for all except for the highest velocities of projection; this ratio diminishes with increase of velocity according to the same law in every case. The conclusion is forced upon us that the electron is the one common constituent of all matter. We cannot go so far as to say that matter is built up wholly of electrons, for some means has to be found for holding the electrons together against their mutual repulsion. For this purpose, positive electricity is assumed, but our knowledge of this is meagre compared to our knowledge of negative electricity. The electron may be regarded either as a particle of matter charged with negative electricity, or as a particle of electricity endowed with mass in virtue of its motion.

219. Interpretation of electric phenomena in terms of the electron theory. In a conductor, in addition to the electrons contained in the atoms, which, in part, form the atoms, it is assumed that there are free electrons which pursue zigzag paths among the atoms. When the conductor is all at one potential there is no more tendency for these free electrons to travel in one direction than in any other. But when a difference of potential is applied to the conductor there is a force acting on the electrons driving them in a direction opposite the force, since they are negatively charged. Thus there is a drift of electrons in one direction, and this drift constitutes the electric current. An electric current, therefore, is to be regarded as a flow of electrons. In a perfect insulator, there are no free electrons but only those contained in the atoms. Thus there can be no continuous flow of electrons, *i.e.*, an electric current, in an insulator, under a constant electric force. When an electric field is applied to an insulator, the electrons inside the atoms move from their normal equilibrium positions until the forces of the external electric field balance the forces on the electrons arising from the atoms. There is thus a momentary flow of electrons inside the atoms and this constitutes the displacement or dielectric current. The displacement of the electrons from their normal position inside the atoms under the influence of an external electric force constitutes the polarization of the insulator.

220. Thermoelectric effects. The free electrons inside a conductor may be considered as moving about exactly as the molecules of a gas. They thus exert a pressure corresponding to the pressure of a gas on its enclosure. This electronic pressure varies for different metals so that if two different metals are in contact there will be a greater pressure of electrons on one side of the junction than on the other. Suppose now that we have a closed circuit consisting of two different metals, with, therefore, two junctions. Let the two junctions be at different temperatures. As in the case of gas pressure, the higher the temperature the greater the pressure. So there will be a greater pressure driving the electrons from, say, metal *A* to metal *B* at junction 1, than from *A* to *B* at junction 2. There will thus be a steady flow of electrons around the circuit, constituting the thermoelectric current.

221. Magnetic effects on the electric current. An electron in motion constitutes an element of an electric current. So that if a magnetic field is applied, there will be a force acting on the electrons in a direction perpendicular to both the direction of motion of the electron and the magnetic field, and proportional to the sine of the angle between them. Suppose now that in a metal plate there is an electric current from left to right, and therefore a flow of electrons from right to left. Let the plate be placed in a uniform magnetic field perpendicular to it, the electrons will then be acted upon by forces in a direction perpendicular to their motion, and they will therefore traverse shorter distances measured in the direction of their drift between collisions with the atoms of the metal, and thus the resistance of the metal will apparently be increased. This effect, which is observed in all metals, is especially marked in bismuth, and is made use of in measuring magnetic fields; the increase of resistance of bismuth is a measure of the strength of magnetic field.

222. Hall effect. If, in the case just considered (Par. 221), the ends of a wire be joined to two points at the ends of a line on the plate, which line is perpendicular to the direction of the current, a current will flow through this branch circuit when the magnetic field is applied. This is the "Hall effect," and may be explained by the bending of the paths of the electrons by the magnetic field which drives them through the branch circuit. According to this view, the Hall effect should have the same sign for all metals, *i.e.*, with the primary current kept in the same direction and the magnetic field in the same direction, the secondary current through the branch circuit should flow which is itself affected by the magnetic field.

223. Magnetism. In order to account for the magnetic properties of bodies it has been found necessary to consider the electrons contained in the atoms. We may consider the atoms as containing electrons circulating in closed orbits. It is a fundamental theorem in electromagnetism that a small closed current is equivalent, as far as its external effects are concerned, to a magnetic particle perpendicular to the plane of the current. An electron circulating in a closed orbit is equivalent to a current flowing in a closed circuit. So that if each atom contains a single circulating electron, it will be itself a magnet, *i.e.*, it will have a resultant magnetic moment. But it is necessary to suppose that the atoms contain many electrons, and so it may happen that the magnetic moments of the different circulating electrons will neutralize each other, in which case the atom will have no resultant magnetic moment. When this is the case, the theory shows that the effect of an external magnetic field is to modify slightly the electronic orbits in such a way as to make the atoms exhibit a diamagnetic property. On the other hand, the magnetic moments of the different electrons may not neutralize themselves so that the atoms have a résultant magnetic moment. In this case the atoms show a paramagnetic property. The effect of the external magnetic field is to orient the atoms in the same sense, and the substance as a whole becomes magnetised.

224. Electrons in optical theory. The electron theory has had its greatest triumphs in the field of optics. Let us consider first the part electrons play in the emission of light. According to our present view, light waves are of an electromagnetic nature. There is no difference between a train of light waves and a train of electromagnetic waves produced electrically except in wave length. The limitation as to the dimensions of the apparatus used in producing electric waves leaves a wide interval between the longest light or heat waves and the shortest electric waves. An electron circulating in an atom in a circular path is a generator for electromagnetic waves. The known order of magnitude of atomic size, and the known value of the charge and the mass of the electron enable us to calculate the wave lengths of the light so generated. The result is something of the order of magnitude of the known wave lengths of visible light. This in itself is an important result as it is the only mechanism known which leads to estimates of this magnitude.

When an incandescent gas is placed in a magnetic field it was discovered by Zeeman that some of the spectral lines become split up into a number of components. One frequent case is that of the splitting up of a single line into two or three components, depending upon whether the magnetic field is along the line of sight or perpendicular to it. This is accounted for by the change in the electron orbits produced by the magnetic force. An electron in motion behaves just as an element of a linear current; so in a magnetic field there is a force upon the electron at right angles to the motion and to the magnetic field. This force has the opposite direction for an electron moving in the opposite direction. The electrons circulating in one direction inside the atoms will thus have the radii of their orbits increased, and those circulating in the opposite direction, diminished. The frequency of the light emitted depends upon the radius of the orbit. Thus a spectral line, which corresponds to a definite frequency when no magnetic field is applied, splits up into two or three lines in a magnetic field. In addition, it is found that the two outer components are circularly polarised in opposite directions, which is what this theory demands. The distance between the spectral lines may be measured, and from this the ratio of charge to mass may be deduced. The results of this wholly independent method of determining the ratio of charge to mass, are so close to the values obtained for the cathode particles and the beta particles from radioactive substances, that there is little doubt but that the centres of light emissions are electrons—the same as the cathode and beta particles.

225. Bibliography. Lorentz: "The Theory of Electrons;" Leipsic. B. G. Teubner, 1904.

Richardson: "The Electron Theory of Matter;" New York, G. P. Putnam's Sons, 1914.

226. Discovery. In December, 1895, William Conrad Roentgen, then Professor of Physics at the University of Wurtsburg, announced that while experimenting with the vacuum tubes of Lenard, he had discovered a new form of radiation which he called X-ray, because its exact nature was unknown.

227. Properties. These rays differ from the cathode rays previously discovered by Lenard in having greater penetration and in not being deflected by magnets.

Roentgen found that these rays would pass through materials opaque to ordinary light and set up fluorescence in crystals of barium platinum cyanide. He found that they could not be sensibly refracted or reflected by any materials available; that they were not deflected by a magnetic field; that they penetrated different materials in a ratio approximately inversely proportional to the atomic weights, and that they acted like light on the silver salts used in photography.

228. Transparency of Various Substances to X-rays

(Batelli and Garbasso)

Material	Specific gravity, water = 1	Transparency, water = 1	Material	Specific gravity, water = 1	Transparency, water = 1
Solids:			Zinc	7.20	0.0116
Pinewood	0.56	2.21	Iron	7.87	0.101
Walnut	0.66	1.50	Nickel	8.67	0.095
Paraffin	0.874	1.12	Brass	8.70	0.093
Rubber	0.93	1.10	Cadmium	0.69	0.090
Wax	0.97	1.10	Copper	8.96	0.084
Stearine	0.97	0.94	Bismuth	9.82	0.075
Cardboard	....	0.80	Silver	10.5	0.070
Ebonite	1.14	0.80	Lead	11.38	0.055
Woolcloth	....	0.76	Palladium	11.3	0.053
Celluloid	....	0.76	Mercury	13.59	0.044
Whalebone	....	0.74	Gold	19.36	0.030
Silk	....	0.74	Platinum	22.07	0.020
Cotton	....	0.70			
Charcoal	....	0.63	Liquids:		
Starch	....	0.63	Ether	0.713	1.37
Sugar	1.61	0.60	Petroleum	0.836	1.37
Bone	1.9	0.56	Alcohol	0.793	1.22
Magnesium	1.74	0.50	Amylalcohol	....	1.20
Coke	....	0.48	Olive oil	0.915	1.12
Glue	....	0.48	Benzol	0.868	1.00
Sulphur	1.98	0.47	Water	1.0	1.00
Lead ointment	....	0.40	Hydrochloric acid	1.240	0.86
Aluminum	2.67	0.38	Glycerine	1.260	0.76
Talcum	2.6	0.35	Bisulphate of carbon	1.293	0.74
Glass	2.6	0.34	Nitric acid	1.420	0.70
Chalk	2.7	0.33	Chloroform	1.525	0.60
Antimony	6.7	0.126	Sulphuric acid	1.841	0.50
Tin	7.28	0.118			

229. Secondary rays. Roentgen showed that rays similar in all respects to X-rays but of comparatively small quantity were set up in most materials when X-rays passed through them.

230. Characteristic rays. J. J. Thompson has shown that when X-rays strike metallic plates such as copper, silver, lead, etc., new rays are set up at the metal surfaces, having penetrating properties peculiar to the metal the tube. The operation of this tube is radically different from that of the tubes which are dependent upon gaseous ions.

Earlier attempts to produce tubes operating on this principle were made by Wehnelt and Lillienfeld.

237. The electrical generating apparatus must be capable of maintaining a potential difference of 60 to 80 kilovolts across the terminals of the tube. For ordinary fluorscopy 2 or 3 milliamperes will suffice, but for rapid Roentgenographic work as much as 100 milliamperes may be used. The induction coil with interrupter is still in common use. For powerful discharges needed in short radiographic exposures, electrolytic interrupters of the Wehnelt or Caldwell type are preferred. For Roentgenoscopy and for therapeutic uses, mechanical interrupters of the vibrating type, rotary breaks or the mercury-jet interrupters are better. (See Sec. 6.) The so-called "interrupterless" machine consists of a high-tension transformer operated in connection with a synchronous rotary rectifier which transmits the peaks of the high-tension secondary discharge to the terminals of the machine always in the same direction. For operation with direct current the rotary rectifier is usually mounted on an extension of the shaft of a rotary converter which supplies the alternating current to primary of transformer. With alternating-current supply the high-tension rectifier is rotated by a small synchronous motor.

Influence machines or so-called electrostatic machines of the Holts and Wimshurst type may be used, but these are not so reliable or so powerful as induction coil or transformer with rectifiers.

238. Measurement. It is customary to measure the current passing through the tube, with an ordinary milliampere meter of d'Arsonval type mounted on an insulating support and having one terminal connected to the metal case. The potential difference across tube terminals is estimated by length of equivalent spark gap. Electrostatic voltmeters may be used for this purpose. There are several more or less commonly used empirical units for both quantity and penetrating quality of X-rays.

239. Penetrometers. There are several of these which depend upon the relative degree of transmission of the ray by two dissimilar metals such as aluminum and silver, the silver being especially pervious to the softer rays. The Benoist penetrometer consists of a series of steps of aluminum of varying thickness arranged around a thin disc of pure silver. Reading is made by observing what thickness of aluminum absorbs the same amount of X-rays as the thin disc of silver. In the Wehnelt penetrometer the principle is the same but the aluminum is in the form of a wedge. The electroscope and electrometer have long been used as indicators of penetration. The "Qualmeter" of Bauer is an electroscope provided with the empirical scale of Benoist or Wehnelt. It is connected to the negative terminal of the tube.

The measurement of quantity of X-ray is usually made by comparing, with a standard scale, the change in color produced in a chemical test piece which has been exposed to the rays.* Stern in 1903 proposed to use strips of bromide paper for measuring the dose of X-ray; the strips were developed, after exposure, for a standard time in a standard developer and then compared with a color scale. The Kienboeck quantimeter which appeared a few years later is essentially the same device. Sabarand and Noiré use discs coated with barium platinum cyanide which turns darker when exposed to X-rays.

240. Principal uses. The applications of X-rays in medicine and surgery for diagnosis and treatment overshadow all others in importance. Other uses for X-rays are: (a) detection of pearls in pearl-bearing mollusks; (b) customs examination of baggage for detection of smuggled articles; (c) sterilization of tobacco and foodstuffs to prevent hatching of eggs of worms or other parasites; (d) detection of flaws in metals; (e) the sterilization of testes and ovaries of criminals; (f) distinguishing between real and spurious diamonds, the real diamonds being more nearly transparent than the imitation.

241. Roentgenography. The so-called X-ray photography for medical or surgical diagnosis should not be undertaken by electricians or photographers. The safe interpretation of Roentgen ray shadows is difficult, and

* S. Stern, *Journal of Cutaneous Diseases*, Dec. 26, 1907.

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245. Source of atmospheric electricity. Among the many theories propounded that of Dr. George C. Simpson* appears perhaps most rational. In brief he concludes from laboratory experiments with drops of water in air that when such drops are broken up in smaller drops the water becomes positively and the air negatively charged. This fact used in conjunction with Lenards proof that drops larger than 0.2 in diameter are unstable when falling through air and that drops smaller than 0.2 in diameter attain a velocity less than 18 miles per hr., form the basis for the following brief explanation quoted in Dr. Simpson's words.

"It is exceedingly probable that in all thunderstorms ascending currents greater than 18 miles an hour occur. Such currents are the source of large amounts of water which cannot fall through ascending air. Hence at the top of the current, where the vertical velocity is reduced on account of the lateral motion of the air, there will be an accumulation of water. This water will be in the form of drops which are continually going through the process of growing from small drops into drops large enough to be broken. Every time a drop breaks a separation of electricity takes place, the water receives a positive charge, and the air a corresponding amount of negative ions. The air carries away the negative ions, but leaves the positively charged water behind.

"A given mass of water may be broken up many times before it falls, and in consequence may obtain a high positive charge. When this water finally reaches the ground it is recognised as positively charged rain. The ions which travel along with the air are rapidly absorbed by the cloud particles, and in time the cloud itself may become highly charged with negative electricity. Now, within a highly electrified cloud there must be a rapid combination of the water drops, and from it considerable rain will fall; this rain will be negatively charged, and under suitable conditions both the charges on the rain and the rate of the rainfall will be large.

"A rough quantitative analysis shows that the order of magnitude of the electrical separation which accompanies the breaking of a drop is sufficient to account for the electrical effects observed in the most violent thunderstorms. All the results of the observations of the electricity of rain described above are capable of explanation by theory, which also agrees well with the actual meteorological phenomena observed during thunderstorms."

246. Importance of lightning protection. Statistics show that in this country, between 700 and 800 persons are annually killed by lightning, and about twice as many seriously injured.† The efficiency of lightning rods for farm houses in the middle west can be judged from statistics gathered by Mr. E. W. Kellog§ who concludes that for an equal number of houses rodded and not rodded, the fires due to lightning are approximately 15 times greater with the buildings not rodded than with those which are rodded.

247. Nature of the discharge. Sir Oliver Lodge first suggested that there are at least two distinct kinds of discharges, one of which is relatively quiet and which results from the gradual breaking down of the air between the object struck and the charged cloud and another which is a violent secondary discharge caused by a primary discharge in the vicinity.‡ The first kind follows the well-known laws familiar to the electrical engineers—laws that deal with more or less permanent conditions. The nature of the discharge is governed by the resistance, inductance and capacity of the path. The path itself is almost certain to be the rod on account of the conducting streamers above it. The second kind is more complex, and the laws that it follows are less thoroughly understood. There is no conducting path above the rods because there may have been no potential difference between them

* Proceedings of the Royal Society, Series A, Vol. LXXXII, p. 169.
† Farmers' Bulletin, No. 367, U. S. Dept. of Agriculture.
§ University of Missouri, Bulletin No. 7, Eng. Exp. Station.
‡ Lightning Conduction, published by Whittaker & Co.

ycles is perhaps 50 times as great as that converted to heat in the rod. Whether, however, the energy is radiated or directly converted to heat is not so material. In either case the maximum current in the rod may be normous and depends upon the frequency of the discharge. With a lightning discharge this may be from 100,000 to perhaps 5,000,000 per sec., in which case the maximum value of the current is from 15,000 to 750,000 amp., t being proportional to the frequency. Steinmetz* has shown that the impedance or total obstruction of the high frequency conductor is about 0.1 ohm per ft. at 100,000 cycles, 0.5 ohm per ft. at 500,000 cycles, 1 ohm per t. at 1,000,000 cycles, and 2.5 ohms per ft. at 5,000,000 cycles. Thus the maximum drop of potential per ft. of lightning rod would be 1,500 volts at 100,000 cycles, 9,000 volts at 250,000 cycles, 37,000 volts at 500,000 cycles, 150,000 volts at 1,000,000 cycles and 1,880,000 volts at 5,000,000 cycles.

250. Relation of frequency to other factors. While in every discharge almost an infinite number of frequencies undoubtedly are represented, it s probable that one is preponderating. Were it permissible to consider that the frequency in the discharge after it reaches the rod is governed only by the electrical constants of the rod, the wave length would be somewhat more than four times the height of the rod. This would mean with an ordinary dwelling, with a rod of say about 50 ft., about 5,000,000 cycles. If on the other hand the effect of the rod is hardly noticeable and the frequency is governed by the distance between cloud and earth, the frequency will be much lower, say 250,000 cycles, with a distance of 2,000 ft. between the cloud and earth.

In the first case the drop in potential per ft. is about 2,000,000 volts, in the second case only 9,000 volts. The first case gives an idea of the conditions of a secondary stroke. It is of very high frequency and may be the result of the discharge of the air immediately surrounding the rod rather than the entire air between cloud and earth. The discharge area is in this case difficult to estimate; it may be quite limited or it may be quite great.

Assuming again an area of 100 ft. square and calculating the voltage and capacity, it is found that the capacity is increased in the same proportion as the voltage is decreased; therefore the charge and maximum vale of the current remains unchanged. The maximum value of the current would be, say 750,000 amp., and the drop per ft. of rod about 2,000,000 volts.

It is evident that only a very small part of such discharge would travel through the conductor, and that the main discharge would jump several feet in the air rather than travel 1 ft. in the conductor. (The drop in potential of 2,000,000 volts per ft. corresponds to 2 ft. striking distance between parallel planes and perhaps 10 ft. distance between projecting masses of metal.)

The second case is approached when a lightning discharge takes place from cloud to rod after a conducting path has been prepared by means of streamers. It is the first, the quiet type of lightning mentioned in the beginning of the paper.

251. Advantage of multiplicity of rod. A single lightning rod may be expected to take care of low frequency discharge from cloud to earth, but is entirely inadequate to cope with a violent secondary discharge, even if it struck the rod instead of the building proper.

One lightning rod, while offering some protection, may be considered, under abnormal conditions, entirely inadequate to cope with the situation. If the buildings were grounded by ten rods the condition would be much improved, and the lightning discharge would probably be confined to the system of rods.

252. Installations. Experience seems to have settled beyond reasonable doubt, that, if properly installed, lightning rods afford considerable protection. A large number of instances might be quoted, but suffice it here to mention only one. Before equipping the buildings of The University of Illinois with rods, three fires were caused by lightning; since that time, though the number of buildings has been greatly increased, there has been no damage from lightning. It should be remembered, however, that a rod faultily installed may make matters worse than would be found where no rods were used. Assume, for instance, that a large building is equipped with a high but broken rod having poor joints or a high resistance to ground, say several hundred ohms, which undoubtedly sometimes is the case. Such a rod could serve the function of equalising the potential between cloud and earth almost

* "Transient Phenomena." McGraw-Hill Book Company, Inc.

as effectively as a good rod, and were there only a sufficient number of them **it is conceivable that** the neutralization of potential would be so complete **as to make a flash discharge** practically impossible. A building having one **rod only, however, is considered** at present. The rod is assumed as projecting **considerably above** the building. If the electric tension is great, unquestionably **streamers** are emitted, the air above the rod is made fairly **conductive and thus the** discharge is invited. The question is then: How **can such a rod take care** of the discharge? It has been shown how the discharge **current frequently** is very large and while the ohmic resistance of **the rod is practically** immaterial as long as it is at all reasonable, it must **not approach or exceed** the normal value of the impedance. In a rod, say **30 ft. long, the ohmic resistance** of even the smallest practicable iron conductor **is a fraction of an ohm** only and the impedance is perhaps 30 to 75 ohms, **depending upon the height** and frequency of the discharge. It is easily **seen that a poor joint** may have many times this resistance; therefore, when **the discharge encouraged** by the streamers from the defective rod strikes the **building it finds the rod** entirely inadequate to cope with the situation. The **voltage drop in the rod** is so great that it is far easier for the current to split **up in a number of paths** and enter through the building than to confine itself **to the rod. An apparent** paradox thus exists. The rod should have good **joints, should have good** ground connection, and should be mechanically **secure against breaking**; although the shape of the rod, its metal or its general **dimensions are rather** immaterial.

253. Location. The rods should always be placed outside of the building and it is indeed a question whether the vertical part of the system, that is, the rod proper, should not be some little distance from the wall and possibly even insulated therefrom. They should be placed a considerable distance from gas pipes, stove pipes, water pipes and balconies or places where persons might be during a storm.

254. Material and construction. Lodge's experiments and theory show conclusively that there is no advantage in copper over iron. Copper may have mechanical advantages under certain conditions, for instance in cities where the atmosphere is charged with soot and a variety of fumes. Galvanized iron has the advantage of cheapness, with a possible electrical superiority. While flat conductors have a very slight advantage, it appears too small to be considered seriously. A round wire or a pipe can be handled conveniently, and seems preferable. In the installation of the rods, sharp bends should be avoided as much as possible. There is little or no advantage in using large and expensive copper conductors or cables; a size mechanically satisfactory is likely to serve all electrical purposes. Expensive sharp points offer little advantage over ordinary rather blunt points. The rods may advantageously terminate in a number of points projecting only a short distance above the part to be protected.

255. The ground connection should be of low resistance, and therefore the rods should preferably terminate in moist soil. "Salting" the ground may be an advantage, but experience with such grounds is not sufficient to warrant its adoption unless an occasional inspection is made. In many cases excellent connection can be made by driving a galvanized gas pipe a few feet into the ground. In installing the rod, allowance for expansion and contraction should be made. Gas pipes should not be connected to lightning rods, nor should the rods be placed in too close proximity to them.

256. Precautions. A building having its windows and doors open, affords opportunity for the entrance of air, perhaps ionized air made conductive by a previous discharge. It is, therefore, safer to keep the house closed during a violent storm. It is also well to keep away not only from the rod but from chimneys, kitchen ranges, metal pipes, etc.

The damage by lightning in cities is relatively small, and so far the modern sky scraper, with its vast amount of steel, appears to be lightning proof.

ELECTROSTATIC MACHINES

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257. Classification. There are two fundamental types of electrostatic generators, namely, those in which the e.m.f. is generated by contact of wo unlike substances and those in which it is generated by electric induction; he former are called frictional machines and the latter are called influence nachines.

258. Frictional machines. In a circuit composed of unlike materials here exists a difference of electric potential at the junction of these materials. However, from the law of the conservation of energy, no electricity will flow n the circuit unless energy from an external source is applied thereto. In rictional machines the energy which produces the flow of electricity is supplied by the heat due to mechanical friction.

259. Electrical Series*

(Riess)

Positive	Negative
Fur, human hair..................	Glass, porcelain, wood, metals, rosin, sulphur.
Glass............................	Zinc—tin amalgam on leather (sure).
Fur, wool, linen, silk, paper, metals	Rosin, sealing wax, sulphur, shellac, amber (sure).
Diamond, topas, thummer-stone, quartz, calcareous spar, mica, polished glass.	Wool, linen, silk, leather.
Glass, silk......................	Metals.

260. Theory of frictional machines. When two unlike bodies are rubbed together, the energy applied is partly stored by the establishment of a dielectric field and partly dissipated as radiated heat. The dielectric field established while the two bodies are in contact causes electricity to flow to the surface of the bodies, a positive charge being collected at one extremity and a negative charge at the other. The energy thus stored, in watt-seconds, is numerically equal to the product of the strength of the dielectric field, in volts, and the quantity of electricity transferred, in coulombs. The energy thus imparted to the dielectric field may be manipulated so as to raise the e.m.f. to a point limited only by the dimensions and insulation of the machine. For instance, in the case of two bodies in contact as at *a*, Fig. 32, the quantity

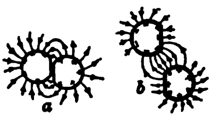

Fig. 32.

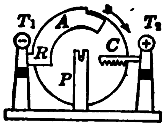

Fig. 33.

of electricity transferred by the dielectric field is $Q = CE$ and the energy thus absorbed is $W = EQ$ where Q is the quantity in coulombs, C is the capacity in farads, E is the potential difference in volts and W is the energy in joules. If the two bodies are separated as at *b*, Fig. 32, the capacity is reduced to C', and since the quantity Q is fixed, the strength of the dielectric field must increase to E' in accordance with the relation $E' = Q/C'$. However, $E'Q = W'$ is greater than W; therefore, it requires mechanical force to separate the bodies.

261. Construction of a laboratory type of friction machine is shown in Fig. 33. A glass plate, *P*, is rotated in the direction shown by the arrow and the rubbing surface, *R*, which is made of leather coated with an amalgam (a good amalgam recommended by Kienmayer is 1SN + 1Zn + 2Hg), rubs against the glass plate generating a dielectric field which conveys the negative electricity toward the terminal T_1 and the positive electricity to the opposite

* The substances at the left are each supposed to be rubbed with any one of the substances given at the right and in the same row.

side of plate *P*. At the comb *C* the dielectric flux is so dense that the air is rendered conducting and electricity passes between *P* and T_2. Thus the tendency is for positive electricity to be transferred to T_2 and the negative electricity to T_1. The energy for this transfer of electricity is generated by the friction between *R* and *P*, and the potential of the machine depends upon its own dimensions and its insulation.

262. Experiments by Reiss* disclose the relation between e.m.f. and friction. The results are given briefly as follows: a flat metallic cylinder, 1.575 in. (40 mm.) in diameter, covered with leather, was set upon an ebonite plate and drawn by an insulated handle over the surface, the charge being measured with a sine electrometer. The disc was drawn 1.18 in. (3 cm.) in one place; it was then set in another place and drawn 1.18 in. (3 cm.) again and so on, eight times, with the following results:

Number.......	1	2	4	8
Charge........	1	1.45	1.7	1.93

Next the disc was drawn 9.45 in. (24 cm.) without stopping and the same result (1.93) was obtained. It was also found that there was maximum value beyond which the charge was not increased by drawing the disc farther.

263. Influence machines. The second type of machine, based on the principle of electric induction, and commonly known as the influence machine, operates as follows: a conductor thrust into a field of dielectric flux will have an e.m.f. generated in it which will cause a certain quantity of electricity to flow, and store a corresponding amount of energy. Fig. 34 shows two bodies, 1 and 2, connected to a battery *B* as a source of e.m.f. The e.m.f. establishes a dielectric field between the bodies, drawing energy from the battery and storing it in the electric circuit. The energy stored is $W = C(E/2)$, wherein *C* is the capacity, and *E* the e.m.f. of the battery. Now if two bodies, 3 and 4, connected conductively, are inserted into the dielectric field, the capacity *C*, which is inversely proportional to the length of the dielectric will be increased, and the value of the dielectric flux correspondingly increased, thus drawing more energy from the battery and storing it in the system. Electromotive force will be generated in the bodies 3 and 4 which will tend to start a flow of electricity, and will transfer a quantity of electricity to the outside surface of the plates, sufficient to absorb the increase of energy stored in the system. If while in this position the two bodies are separated by severing the connecting link, the electricity will be unable to return to its state of equilibrium and the energy stored will remain bound. In order to utilise this energy, the bodies must be removed from the electric field of 1 and 2, and, now that each has a field of its own, mechanical energy equal in value to that stored in the bodies will be required to remove them. When the bodies are removed, the capacity of 1 and 2 will return to its original value, and the extra energy called forth for the placing of 3 and 4 in the field will be returned to the battery.

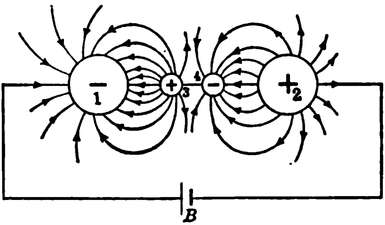

Fig. 34.

264. Excitation of influence machines. The influence machine does not employ a battery to maintain the e.m.f., but is given an initial charge of e.m.f., after which it is self-exciting. It will be noted that in this method a certain amount of electricity is stored in the bodies 3 and 4, and that the

* "Wiedemann Annalen," Bd. I, p. 1052.

value of e.m.f., and therewith the value of the energy can be changed at will by varying the capacity between them; an increase in capacity corresponds to a decrease in energy or motor action and *vice versa*.

265. The Toepler influence machine is shown schematically in Fig. 35; S is a fixed glass plate with two segment-shaped pieces of paper, p_1 and p_2 (called field pieces) fastened on the back (shown dotted); P is a glass plate mounted on an axle and can be rotated by a belt not shown in the sketch; on the plate, P, are mounted a number (8 in the sketch) of tin-foil discs, called carriers, each disc being armed with a small brass button which makes the contact with the various brushes; b_1 and b_2 are called appropriating brushes and are connected with the field plates p_1 and p_2. respectively; n is the neutralising rod and carries a brush at each extremity; c_1 and c_2 are metallic combs connected to the terminals, T_1 and T_2, of the machine. The Toepler machine is very reliable and is self-exciting regardless of weather conditions. By connecting a number of pairs of plates in multiple the load capacity of the machine can be increased.

266. The polarity of the Toepler type of machine is not always the same, depending on how the charges are distributed when it starts. Tests for polarity should be made, where it is of importance. The flame of a Bunsen burner will be attracted by the negative pole.

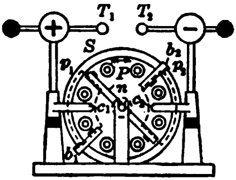

Fig. 35.

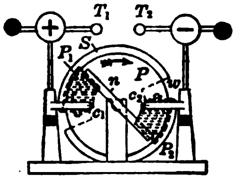

Fig. 36.

267. The Holtz machine is shown schematically in Fig. 36. S is a stationary glass plate on the back side of which are mounted two paper field plates, P_1 and P_2; small blunt tongues project through slots, w, in the glass plate S and nearly touch the rotating plate P. The rotating plate, P, is a plain glass plate covered with a coat of varnish; c_1 and c_2 are metallic combs connected to the terminals, T_1 and T_2. The rod, n, is a neutralising rod and carries a comb at each end.

268. The operation of the Holtz machine is as follows: The terminals T_1 and T_2, are put in contact and the machine started. One of the field plates is given a charge (let P_1 be charged positively). This charge will draw negative electricity to the comb, c_1, which will leak across to the glass plate, P. Passing around to the other side of the machine this negative charge on plate P attracts a positive charge from the plate, P_2, to the other side of the plate, leaving P_2 negative. Now the negative charge on P_2 draws positive electricity from c_2 which neutralizes the negative charge and leaves both sides of the plate negatively charged. Upon coming to the other side the positive charges on both sides of the plate draw negative electricity from the field plate, P_1, neutralising the charge on the lower side of P and completing the cycle. The neutralizer, n, serves to keep the machine from reversing its polarity and losing its excitation.

The Holtz machine is sensitive to atmospheric conditions and should be enclosed in a tight compartment for satisfactory results. The compartment can be heated or some moisture-absorbing agent can be used to keep the air dry. The polarity of the machine can be determined by observing the character of the sparks at each pole; at the negative pole the sparks between the comb and the plate are broad and occur in bunches giving a bluish light, while at the positive pole they appear as single points of light.

269. Effect of operation under air pressure. Influence machines can be greatly increased in e.m.f. by enclosing them in an air-tight case and operating them under air pressure. As discussed in Sec. 4, the dielectric three independent swell boxes. As there is no limit to the number of notes or combinations that can be put into operation simultaneously, the automatic player can produce effects that are impossible to the organist. The Tel-Electric system may also be applied to existing organs, and, in every case, the organs may be operated by hand in the usual way without removing the player.

274. Mechanism. The principle upon which the translating mechanism operates is shown in Fig. 37. The brass record, which is perforated with longitudinal slots, is wound from the roll *A* to the roll *M* over the so-called tracker roll *C*. Above the tracker roll there are arranged a number of reading fingers *D*, mounted on a shaft *R* about which they are free to rotate, there being a finger for each magnet on the piano, as well as for the expression magnets. These reading fingers each carry a contact wire *G* embedded in a piece of ivory *E*. Normally the reading fingers rest upon the surface of the brass record and the circuit of the magnet is open at the point *P*. As soon as a perforation passes underneath, the reading finger drops down and closes the circuit through its magnet, and remains closed for a length of time that depends upon the length of the slot. The amount of current in the circuit, that is, the dynamic power of the magnet, depends upon the value of resistance included in the circuit and this is regulated by magnets which cause the comb wire *J* to move up and down over the resistor unit *H*. The magnets all operate on the rotating armature principle. Fig. 38 shows one of the magnets as attached to a key on the pianoforte. The armatures of these magnets are laminated to minimise the retarding effect of eddy currents.

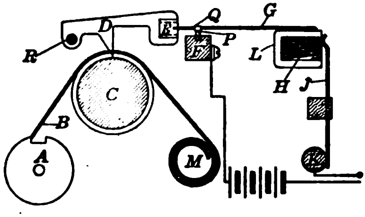

FIG. 37.—Skeleton diagram of the operating mechanism of a Tel-Electric piano player.

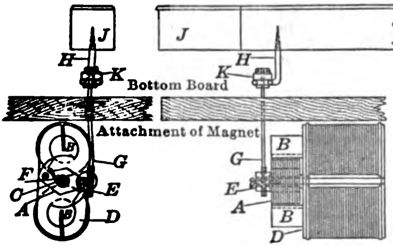

FIG. 38.—Showing attachment of magnets to key in a pianoforte.

275. Combination organ and piano players. Certain combinations are also made whereby the Tel-Electric transmitter operates a piano by means of a piano music roll. By turning over a coupler, the piano is cut out, and the same transmitter operates the organ by means of an organ music roll. With this type of combination, when the organ is coupled to the transmitter, the piano is played entirely automatically by means of the organ music sheet, so it is possible to play very closely organ and piano arrangements, the piano part being played nearly in full on the piano and the orchestral or organ accompaniment played in full on the organ. In this combination, the piano is used manually, similar to any stop in the organ, by means of one of the keyboards.

THE TELEGRAPHONE

BY OTIS ALLEN KENYON

Consulting Electrical Engineer, Assoc. Amer. Inst. Elec. Eng.

276. Theory. The telegraphone, which was invented by Valdemar Poulsen, is based upon the peculiar magnetic properties of hard steel which shown in Fig. 39. Assume an endless steel wire to be passed over two revolving drums at a suitable speed. If an electromagnet (Fig. 40) is brought into close proximity to the traveling wire, the wire will be magnetized to a degree corresponding to the strength of the magnet. If the exciting circuit through the magnet is alternately opened and closed the steel wire will become magnetized only during the periods when the circuit is closed and because of the coercive strength of steel the magnetism will remain fixed in the positions where it is received and not equalize itself; that is, the steel wire

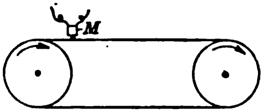

Fig. 39.—Principle of telegraphone.

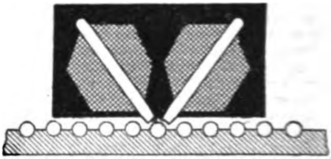

Fig. 40.—Electromagnet for wire recorder.

retains a permanent record of the magnetic fluctuations and if it were passed between the poles of a suitable electromagnet it would be capable of transforming the magnetic variations into electric variations by electromagnetic induction, the energy for which would be supplied entirely by the motor which drives the wire between the poles of the magnet.

277. In the Poulsen telegraphone these principles are utilized by connecting a system similar to that shown in Fig. 39 to telephone instruments. The electric currents produced by speaking into the transmitter (Fig. 41) are used to excite the recording magnet which leaves a permanent magnetic record in steel that is made to travel through the magnetic field. This record can reproduce the sounds that generated it by passing between the poles of a similar magnet that is connected to a telephone receiver as shown

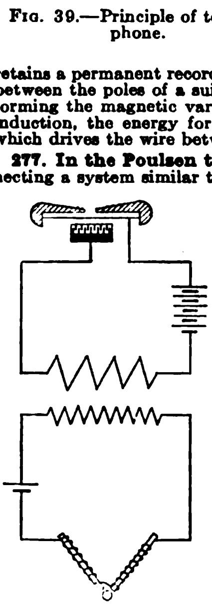

Fig. 41.—Transmitter.

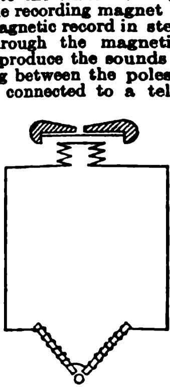

Fig. 42.—Receiver.

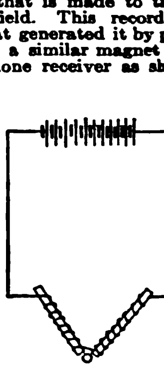

Fig. 43.—Eraser.

in Fig. 42. In order to make it possible to use the same steel over and over again a third magnet (Fig. 43) is provided which is excited with a relatively strong and constant current in the opposite direction to the transmitting magnet. This magnet obliterates all previous records and leaves the steel in condition to receive a new record.

magnet, by means of which the writing is to be performed is used to obliterate a prior magnetic record and also simultaneously magnetise the writing basis, then, during the inscription, the electromagnet is given a polarization opposed to that which it possessed when obliterating. In this way a lively movement of the molecular magnets is obtained at the very moment of forming the writing. The susceptibility seems to increase very much in that magnetic *status nascendi*, and every shade of the writing becomes extremely perceptible. Ordinarily the polarisation of the writing magnet is only a very small fraction of that of the obliterating one. The nearer its polarisation approaches the neutralization of that of the writing basis, however, the feebler may be the polarization of the obliterating magnet. The coercive force determines the degree of polarisation which exactly neutralizes the magnetization of the writing basis. It is found that the writing is somewhat weak when the polarisation of the electromagnet during the process of inscription is just equal to that used in the preceding obliteration. In order to polarise the electromagnet, either a constant-current or a permanent magnet may be used.

279. Recorders. There are three distinct forms of recorders which are as follows: (a) the wire recorder; (b) the tape recorder; (c) the disc recorder.

The type of magnet used with the **wire recorder** is shown in Fig. 40, the wire being wound upon grooved drums first in one direction and then in the other. The disc and tape recorders use magnets with straight cores.

In the **tape recorder** the tape is wound up like a ribbon without any intervening substance. There is no perceptible effect from this method of procedure as experience has shown that the magnetism does not traverse the tape but is present only in the uppermost portions near the surface.

The **disc recorder** is constructed somewhat similar to the disc form of phonograph and the electromagnet is provided with a very sharp point.

280. Adaptations. There are many practical uses to which the telegraphone may be adapted and a number of commercial forms have been placed upon the market. These are described in Par. 281 to 286.

281. Amplification of weak voice currents. In telephone work it sometimes happens that the current impulses received over the line are so weak that they do not furnish sufficient energy to produce records of proper magnetic intensity. However, in such cases the only effect is a diminution in the volume of sound. In an attempt to avoid this effect William A. Rosenbaum patented in 1903 a modified form of magnet for use with Poulsen's apparatus. In this improved construction a permanent magnet is used and a variation in intensity is obtained by varying the distance between the poles of the magnet and the steel record. Fig. 44 shows the principle of the construction. The permanent magnet is mounted upon an iron diaphragm which is vibrated by electric impulses received over the telephone line.

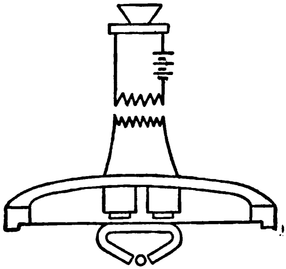

Fig. 44.—Rosenbaum's recorder.

282. A type of telegraphone intended for use in connection with the ordinary telephone is so arranged that it will perform three distinct services: (a) it may be set to record all messages received during the absence of the operator; (b) it may be set to record complete telephone conversations for the purpose of accurate record; (c) it may be set to repeat messages left by the operator. When the telegraphone is set for operation during the absence of the operator it is arranged to start automatically when a call is received and to run for a definite period of time, usually 2 min. It usually begins by sending a buzzing signal which apprises the speaker at the other end of the fact that the telegraphone is in operation, either to receive or transmit a message.

by the pull due to the series winding of a solenoid, acting on a compression rheostat in series with the generator field. Meanwhile, the ampere-hour meter is running in the direction of "charge," and, when the contact-making needle has reached its point of contact, the resistance, *R*, is short-circuited.

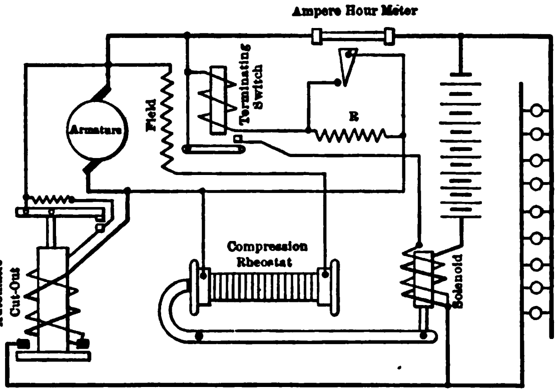

Fig. 45.—Simplified diagram of typical train-lighting system.

By this means, the solenoid of the terminating switch becomes sufficiently energized to close the contact points, thereby energizing the potential winding of the solenoid governing the field rheostat. This pull is added to the action of the series winding, and the effect is a sudden reduction in generator voltage by such percentage as the regulator has been adjusted for. The

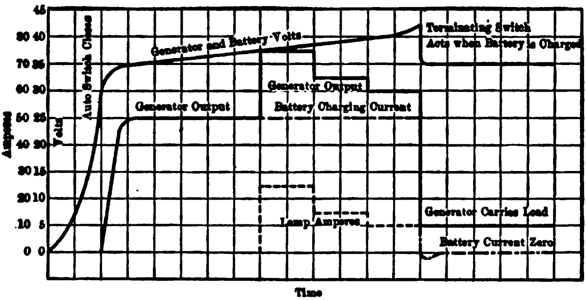

Fig. 46.—Curves illustrating performance of U-S-L-Axle equipment with type S-2 panel, starting from stand-still, with various lamp loads, and finally with battery fully charged.

battery is, by this process, floated on the supply circuit, the generator feeding the lamp load directly. See curves of Fig. 46. In this connection it is usual to employ what is known as a **lamp regulator**, in order that constant voltage may be applied to the lamps under all conditions of normal operation. Such a device consists of a potential solenoid controlling a series rheostat.

303. Telegraphs

	Year		
	1902	1907	1912
Number of companies or systems	25	26	27
Miles of pole line	237,990	239,646	247,528
Miles of single wire	1,318,350	1,577,961	1,814,196
Nautical miles of ocean cable	16,677	46,301	67,676
Number of messages	91,655,287	103,794,076	109,377,698
Number of telegraph offices	27,377	28,110	30,864
Total income	$40,930,038	$51,583,868	$64,762,843

304. Electrical machinery, apparatus and supplies, according to the 1910 Census, had a total value as follows:

Year	Total value
1899	$218,238,277
1904	309,775,089
1909	405,600,727

See Thirteenth Census of the U. S., 1910; Bulletin on Manufactures.

ENGINEERING SPECIFICATIONS AND CONTRACTS

305. Contracts. Since a contract which is good in law embraces for the most part questions which are wholly legal in character, it is beyond the function of an engineering handbook to go into the matter. The advice of competent legal counsel is always advisable in all matters connected with contracts, even though the engineer may have acquired an extensive knowledge of the law of contracts. Such knowledge should never be relied upon as a final guide, but is frequently useful in assisting the engineer to avoid serious mistakes and difficulties. The bibliography appended hereto is recommended as a course of reading for engineers who wish to equip themselves with a general knowledge of the subject.

306. Specifications. An engineering specification is almost always made part of a contract, either by direct embodiment in the contract or by reference. It is therefore essential that such a specification should be clear, direct, definite, conclusive, and legally sound. The art of drawing specifications is acquired necessarily by practice, founded upon a thorough technical knowledge of the subject matter in hand. General rules for guidance have been formulated by numerous authorities and references to a number of these will be found in the appended bibliography. These general rules will usually be found helpful as to the proper or desirable scope of the subject matter in a specification, but it is frequently more helpful to have before one a specification covering similar or identical subject matter which was drawn by a competent engineer. If no other source is available, the specifications used by the U. S. Government are sometimes obtainable through the Supt. of Documents, at Washington, D. C.

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SECTION 23

MECHANICAL SECTION

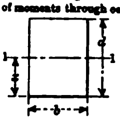
COMPILED FROM STANDARD AUTHORITIES

CONTENTS

(Numbers refer to Paragraphs)

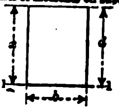
2. Mathematical Properties of Sections.—*Continued*

Rectangle
Axis of moments through center



$$A = bd$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{bd^3}{12}$$
$$S_{1-1} = \frac{bd^2}{6}$$
$$r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$$

Rectangle
Axis of moments on base

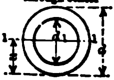


$$A = bd$$
$$x = d$$
$$I_{1-1} = \frac{bd^3}{3}$$
$$S_{1-1} = \frac{bd^2}{3}$$
$$r_{1-1} = \frac{d}{\sqrt{3}} = 0.577350d$$

Circle
Axis of moments through center

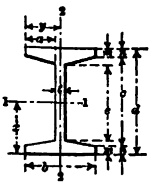
$$A = \frac{\pi d^2}{4} = 0.785398d^2$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi d^4}{64} = 0.049087d^4$$
$$S_{1-1} = \frac{\pi d^3}{32} = 0.098175d^3$$
$$r_{1-1} = \frac{d}{4}$$

Hollow Circle
Axis of moments through center



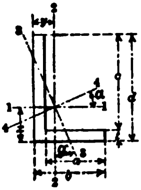
$$A = \frac{\pi(d^2 - d_1^2)}{4} = 0.785398(d^2 - d_1^2)$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi(d^4 - d_1^4)}{64} = 0.049087(d^4 - d_1^4)$$
$$S_{1-1} = \frac{\pi(d^4 - d_1^4)}{32d} = 0.098175\frac{(d^4 - d_1^4)}{d}$$
$$r_{1-1} = \frac{\sqrt{d^2 + d_1^2}}{4}$$

BEAM



$$A = dt + 2a(m + n)$$
$$x = \frac{d}{2}$$
$$y = \frac{b}{2}$$
$$I_{1-1} = \frac{bd^3 - \frac{a}{4(m-n)}(c^4 - e^4)}{12}$$
$$I_{2-2} = \frac{2nb^3 + et^3 + \frac{m-n}{4a}(b^4 - t^4)}{12}$$

UNEQUAL ANGLE



$$A = t(b+c)$$

$$x = \frac{t(b+2c)+c^2}{2(b+c)}$$

$$y = \frac{t(2a+d)+a^2}{2(a+d)}$$

$$\text{Tan } 2\alpha = \frac{t[(2y-t)d(d-2x)+a(2x-t)(b+t-2y)]}{2(I_{1-1}-I_{2-2})}$$

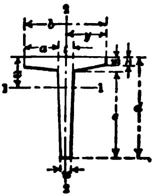
$$I_{1-1} = \frac{t(d-x)^3+bx^3-a(x-t)^3}{3}$$

$$I_{2-2} = \frac{t(b-y)^3+dy^3-c(y-t)^3}{3}$$

$$I_{3-3} = \frac{I_{2-2}\cos^2\alpha - I_{1-1}\sin^2\alpha}{\cos 2\alpha}$$

$$I_{4-4} = \frac{I_{1-1}\cos^2\alpha - I_{2-2}\sin^2\alpha}{\cos 2\alpha}$$

TEE



$$A = \frac{e(t+u)}{2}+mt+a(m+n)$$

$$x = \frac{6an^2+2a(m-n)(m+2n)+3td^2-e(t-u)(3d-e)}{6A}$$

$$y = \frac{b}{2}$$

$$I_{1-1} = \frac{e^3(3u+t)+4bm^3-2a(m-n)^3}{12}-A(x-m)^2$$

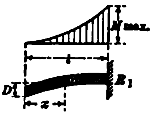
$$I_{2-2} = \frac{nb^3+(m-n)t^3+eu^3}{12} + \frac{a(m-n)[2a^2+(2a+3t)^2]}{36} + \frac{e(t-u)[(t-u)^2+2(t-2u)^2]}{144}$$

BEAMS

3. Moments. The moment of a force with respect to any given point is equal to the product of the force and its perpendicular distance from the point. If the force is expressed in lb. and the distance in in., the moment will be expressed in in-lb.

4. Reaction at supports. In the case of a horizontal beam supported at two or more places, each support reacts against the beam, and the sum of all these reactions is equal to the combined weight of the beam and its loading.

5. Shear. The loads and the reactions of the supports are vertical forces tending to shear or cut the beam across, and the stresses they produce within the beam are, therefore, called shearing stresses. The shearing force at any section is the force with which the part of the beam on one side of the section tends to slide past the part on the opposite side. The shear at each support is equal to the reaction of the support; the shear at any point between the supports is equal to the reaction of the support less the total load between the support and the point; or if the upward reaction is considered



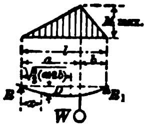
M, distance x $= \frac{Wx^2}{2l}$

M max. at R_1 $= \frac{Wl}{2}$

W max. $= \frac{2fS}{l}$

D max. $= \frac{Wl^3}{8EI}$

III. BEAM SUPPORTED AT ENDS—Concentrated load near one end



R(max. shear if $b>a$) $= \frac{Wb}{l}$

R_1(max. shear if $a>b$) $= \frac{Wa}{l}$

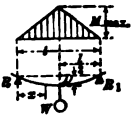
M, distance x $= \frac{Wbx}{l}$

M max. at point of load $= \frac{Wab}{l}$

W max. $= \frac{fSl}{ab}$

D max. $= \frac{Wab(a+2b)\sqrt{3a(a+2b)}}{27EIl}$

IV. BEAM SUPPORTED AT ENDS—Concentrated load at centre



R (max. shear) $= R_1$ $= \frac{W}{2}$

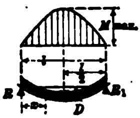
M, distance x $= \frac{Wx}{2}$

M max., at point of load $= \frac{Wl}{4}$

W max. $= \frac{4fs}{l}$

D max. $= \frac{Wl^3}{48EI}$

V. BEAM SUPPORTED AT ENDS—Uniformly distributed load



R(max. shear) $= R_1$ $= \frac{W}{2}$

M, distance x $= \frac{Wx}{2}(1-\frac{x}{l})$

M max. at centre $= \frac{Wl}{8}$

W max. $= \frac{8fs}{l}$

D max. $= \frac{5Wl^3}{384EI}$

allowable for shear, and A is the area of the section in sq. in.

10. Safe unit stresses for steel beams. Steel beams are usually I-beams; however they may be of almost any section demanded by structural conditions. See Par. 9. The allowable unit stresses for general structural work will not usually depart from the following values* expressed in lb. per sq. in.; care, however, should be exercised in the assumption of unit stresses for structures which will be called upon to meet unusual requirements.

Tension, net section, rolled steel	16,000
Direct compression, rolled steel and steel castings	16,000
Bending, on extreme fibres of rolled shapes, built sections, girders, and steel castings	16,000
Bending on extreme fibres of pins	24,000
Shear on shop rivets and pins	12,000
Shear on bolts and field rivets	10,000
Shear—average—on webs of plate girders and rolled beams, gross section	10,000
Bearing pressure on shop rivets and pins	24,000
Bearing on bolts and field rivets	20,000

11. Safe unit stresses for wooden beams. The maximum safe loads, as limited by the allowable shearing stresses along horizontal axes of the beams, or allowable longitudinal shear, should be calculated from the formula

$$\text{Maximum safe load} = \tfrac{2}{3}Af \quad \text{(lb.)} \tag{4}$$

where A is the area of the section and f is the allowable working stress in longitudinal shear. These limits should not be exceeded to avoid failure of the beam in the horizontal direction of the grain of the wood. The bending stress should be calculated as shown in Par. 9.

For a full discussion of the theory of longitudinal shear, see Chap. VI of Lanza's "Applied Mechanics." A table of allowable working stresses for structural timber is given in Sec. 4. The proper factor of safety is usually determined by the character or conditions of service.

12. Concrete beams and floor slabs. The arrangement of concrete beams follows the same principles as in structural-steel construction. On short spans, floor cross beams may be omitted, or used only at columns in order to secure lateral stiffness. Beams are usually designed as tee beams, and a part of the floor slab thus comprises part of the beam. The width of the slab considered to act as part of the beam should not exceed five times the slab thickness.

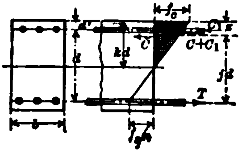
The reinforcement of floor slabs may be of small rods, wires or metal fabric, the latter especially on cross spans. Cross reinforcement of small rods or wires about 2 ft. apart laid parallel to the beam supporting the slab, should be used to prevent cracks, shrinkage, etc. If the length of the slab exceeds one and one-half times its width, the entire load should be carried by transverse reinforcement. The distribution of the load on a rectangular slab supported on four sides and reinforced in both directions may be approximately determined by the formula

$$R = \frac{l^4}{l^4 + b^4} \tag{5}$$

where R is the ratio of the load, l the length and b the width of the slab. An effective bond should be provided at the junction of the beam and the slab, and if the principal reinforcement of the slab is parallel to the beam, transverse reinforcement should be used extending over the beam and well into the slab.

In the calculation of shear or web reinforcement, concrete may be assumed to carry one-quarter to one-third of the total shear, the remainder being taken

* "Pocket Companion," Carnegie Steel Co., 1913; pp. 126 and 127.



$$z = \frac{\frac{1}{3}k^3d + 2p'nd'(k - \frac{d'}{d})}{k^2 + 2p'n(k - \frac{d'}{d})}$$

$$f_s = \frac{M}{pjbd^2} = \frac{nf_c(1-k)}{k}$$

$$f_s' = \frac{nf_c(k - \frac{d'}{d})}{k}$$

$$f_c = \frac{6M}{bd^2\left[3k - k^2 + \frac{6p'n}{k}(k - \frac{d'}{d})(1 - \frac{d'}{d})\right]}$$

A' = Area of compressive steel, in sq. in.
p' = Steel ratio for compressive steel.
f'_s = Unit compressive stress in steel, in lb. per sq. in.
C = Total compressive stress in concrete, in lb. per sq. in.
C' = Total compressive stress in steel, in lb. per sq. in.
d' = Depth to centre of compressive steel, in in.
z = Depth to resultant of $C+C'$, in in.

16. Shear and bond in reinforced concrete beams.*

Rectangular Beams $\quad f_v = \frac{V}{bjd} \quad (6) \qquad f_u = \frac{V}{jd\Sigma o} \quad (7)$

T Beams $\quad f_v = \frac{V}{b'jd} \quad (8) \qquad f_u = \frac{V}{jd\Sigma o} \quad (9)$

V = Total shear, in lb.; f_v = Unit shearing stress in concrete, in lb. per sq. in.; f_u = Unit bonding stress in concrete, in lb. per sq. in.: Σ_o = Sum of the perimeters of the tension bars.

17. Unit allowable stresses in reinforced-concrete beams. The following working stresses are in current use for reinforcing bars of medium structural steel and good Portland cement and gravel concrete of a 1 : 2 : 4 or 1 : 2½ : 5 mixture:

f_c = unit compressive stress of concrete	650 lb. per sq. in.
f_v = unit shearing stress of concrete,	
straight reinforcement	30 to 40 lb. per sq. in.
special shear reinforcement	60 to 100 lb. per sq. in.
f_u = unit bond stress of concrete,	
smooth rods	60 to 80 lb. per sq. in.
deformed bars	100 to 175 lb. per sq. in.
f_s = unit tensile stress of steel	16,000 lb. per sq. in.
f_k = unit compressive stress of steel	10,000 lb. per sq. in.
$n = E_s \div E_c = 15$.	

for notation, see Par. 13 to 16.

COLUMNS

18. Discussion of column formulas. Due to the tendency to buckling, compression members are assumed to carry bending stresses. Failure of a column may, then, be due to direct compression, to bending or to a combination of both. No rigorous formula has ever been deduced for columns under all conditions of loading. However, several empirical formulas (Par. 21) have proven satisfactory when checked by tests made on full-sized members. All these formulas take into consideration the properties of the section (Par. 1), the allowable unit stress and the ratio of slenderness (Par. 20).

19. Radius of gyration is defined in Par. 1. For purposes of computation it is more convenient to employ the radius of gyration than either the moment of inertia or the section modulus.

* See footnote, Par. 13 and 14.

are produced. In Fig. 1 a column is pictured as carrying a beam supported on a bracket with a load W_1, and also a direct loading W. Selection of the proper column size may be accomplished by repeated trials, using the following formula:

$$f \geqq \frac{w + w_1}{A} + \frac{Mn}{I} \quad \text{(lb. per sq. in.)} \qquad (10)$$

where W and W_1 are expressed in lb.; A is the area of the column section in sq. in.; M is the bending moment in in-lb., $(= w_1 x)$ due to eccentric loading; n is the distance of the extreme fibre from the neutral axis, measured in the direction of bending; and f is the allowable axial unit compression stress, in lb. per sq. in.

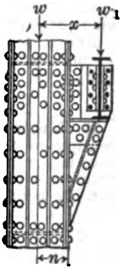


Fig. 1.—Column with eccentric superposed load.

23. Wooden columns.* The safe load tables of wooden columns which follow, based upon the working unit stresses adopted by the American Railway Engineering Association, give the allowable direct compressive loads for square and round columns.

The safe loads of rectangular columns may be found from the safe loads of square columns by direct proportion of areas, using the safe load unit stress of the square column whose side is equal to the least side of the rectangular section.

The following table gives the safe load in lb. per sq. in. of sectional area for ratios of

$$\frac{l}{d} = \frac{\text{effective length of column, in in.}}{\text{least side or diameter, in in.}} \qquad (11)$$

ranging between limits of 15 and 30.

Unit Working Stresses in Lb. per Sq. In.

$\frac{l}{d}$	Longleaf pine, white oak	Douglas fir, Western hemlock	Shortleaf pine, spruce, bald cypress	White pine, tamarack	Red cedar, redwood	Norway pine
	$1{,}300 \times (1 - l/d60)$	$1{,}200 \times (1 - l/d60)$	$1{,}100 \times (1 - l/d60)$	$1{,}000 \times (1 - l/d60)$	$900 \times (1 - l/d60)$	$800 \times (1 - l/d60)$
15	975	900	825	750	675	600
16	953	880	807	733	660	587
17	931	860	788	717	645	573
18	910	840	770	700	630	560
19	888	820	752	683	615	547
20	867	800	733	667	600	533
21	845	780	715	650	585	520
22	823	760	697	633	570	507
23	802	740	678	617	555	493
24	780	720	660	600	540	480
25	758	700	642	583	525	467
26	737	680	623	567	510	553
27	715	660	605	550	495	440
28	693	640	587	533	480	427
29	672	620	568	517	465	413
30	650	600	550	500	450	400

24. Concrete columns may be reinforced by means of longitudinal bars, by bands or hoops, or by both. The general effect of the banding or hooping is to permit the use of somewhat higher working stresses; the value

* "Pocket Companion," Cambria Steel Co., 1913; p. 327.

27. Horse-power of Shafts for Simply Transmitting Power.

$$\text{H.p.} = \frac{D^3R}{50}$$

Diam. of shaft, in.	Rev. per min.								
	1	50	100	150	200	250	300	400	500
1 3/16	0.0335	1.67	3.35	5.02	6.70	8.37	10.05	13.40	16.74
1 7/16	0.0594	2.97	5.94	8.91	11.88	14.85	17.82	23.76	29.70
1 11/16	0.0961	4.81	9.61	14.42	19.22	24.03	28.83	38.44	48.05
1 15/16	0.1455	7.27	14.55	21.82	29.09	36.37	43.64	58.18	72.73
2 3/16	0.2094	10.47	20.94	31.40	41.87	52.34	62.80	83.74	104.7
2 7/16	0.2896	14.48	28.96	43.45	67.93	72.41	86.89	115.9	144.8
2 11/16	0.3882	19.41	38.82	58.23	77.64	97.05	116.5	155.3	194.1
2 15/16	0.5069	25.35	50.69	76.04	101.4	126.7	152.1	202.8	253.5
3 3/16	0.6477	32.39	64.77	97.15	129.5	161.9	194.3	259.1	323.9
3 7/16	0.8124	40.62	81.24	121.9	162.5	203.1	243.7	324.9	406.2
3 11/16	1.003	50.14	100.3	150.4	200.6	250.7	300.8	401.1	501.4
3 15/16	1.221	61.04	122.1	183.1	244.2	305.2	366.2	488.3	610.4
4 7/16	1.748	87.38	174.8	262.1	349.5	436.9	524.3	699.0	
4 15/16	2.407	120.4	240.7	361.1	481.5	601.8	722.5	962.9	
5 1/2	3.328	166.4	332.8	499.1	665.5	831.9	998.2		
6	4.320	216.0	432.0	648.0	864.0	1080.0	1296.0		
6 1/2	5.493	247.6	549.3	823.9	1099.0	1373.0			
7	6.860	343.0	686.0	1029.0	1372.0	1715.0			
7 1/2	8.438	421.9	843.8	1266.0	1688.0				
8	10.24	512.0	1024.0	1536.0	2048.0				

GEARING AND CHAIN DRIVE

28. Toothed gearing is used for positive drive between shafts, that is, where the requirements will permit no slippage. There are two styles of teeth, the cycloidal and the involute. The former is used where the distance between centres of driving and driven member can be rigidly maintained. **Cycloidal gears** do not wear so rapidly as involute gears, and are used to transmit energy at rather high speeds. **Involute gears**, on the other hand, do not require so accurate a spacing of centres, although, after wearing for some time, this advantage becomes lessened, and such gearing is no longer insensible to badly adjusted bearings. Involute teeth are thicker at the root than cycloidal gears, and this added strength has considerable weight in the selection of gears for high-torque service. They operate at somewhat lower allowable speeds than cycloidal gears.

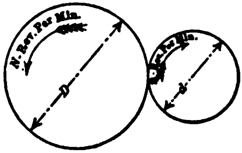


Fig. 2.—$D : d :: n : N$.

29. Gear pitch.* When, as in Fig. 2, two elemental circles may be said to roll one on the other with no slippage, their speeds in rev. per min. are inversely proportional to their diameters. In the case of gearing, the elemental circle just mentioned is known as the **pitch circle**, and the ratio of rotational speeds of a pair of meshed gears follows the relation above expressed. There are two common methods of describing the pitch of gear teeth. **Diametral pitch** is an expression derived by dividing the number of teeth on the gear by the diameter of the pitch circle in in. Thus, an eight-pitch gear has eight teeth per in. of pitch-circle diameter. **Circular**

* Schwamb & Merrill. "Elements of Mechanism," John Wiley & Sons.

ever with ordinary gears it would be exceptional to secure speeds, satisfactory from a standpoint of noise, which would range as high as 1,200 ft. per min. With herring-bone gears running in oil, pitch-line speeds as great as 5,000 ft. per min. have been reached. In the case of rawhide and cloth pinions, operation with a satisfactory minimum of noise can be attained at speeds ranging from 2,000 to 3,000 ft. per min.

32. Maximum Speed of Gearing

(A. Towler, *Engineering*, April 19, 1889, p. 388)

Ordinary cast-iron wheels............ (ft. per min.)	1,800
Helical cast-iron wheels..................................	2,400
Mortise cast-iron wheels..................................	2,400
Ordinary cast-steel wheels................................	2,600
Helical cast-steel wheels.................................	3,000
Special cast-iron machine-cut wheels......................	3,000
Double herringbone gears in oil*..........................	5,000

33. Horse-power and working loads of cut cast-iron gears.† For significance of symbols, see Par. **30**.

Diametral pitch	Circular pitch	No. of teeth	Speed of pitch line (ft. per min.)											
			100		200		300		600		900		1200	
			w.l.	h.p.	w.l.	h.p.	w.l.	h.p.	w.l.	h.p.	w.l.	h.p.	w.l.	h.p.
10	0.3142	12	90	0.27	79	0.47	70	0.63	53	0.96	42	1.15	35	1.27
		20	120	0.36	105	0.63	94	0.85	70	1.27	56	1.53	47	1.71
		40	145	0.44	127	0.76	113	1.02	85	1.55	68	1.86	56	2.04
		60	152	0.46	133	0.80	119	1.07	89	1.62	71	1.94	60	2.18
		130	160	0.49	140	0.84	124	1.12	94	1.71	74	2.02	62	2.26
8	0.392	12	113	0.34	98	0.59	87	0.78	66	1.20	52	1.42	44	1.60
		20	150	0.45	130	0.78	116	1.04	87	1.58	70	1.91	58	2.11
		40	180	0.55	158	0.95	141	1.27	105	1.91	84	2.29	70	2.54
		60	190	0.58	165	0.99	148	1.33	110	2.00	88	2.40	74	2.69
		130	200	0.61	174	1.04	155	1.40	115	2.09	92	2.51	77	2.80
4	0.785	12	225	0.68	195	1.17	175	1.58	130	2.36	105	2.86	87	3.16
		20	300	0.91	260	1.56	230	2.08	175	3.18	140	3.82	116	4.22
		40	360	1.09	315	1.89	280	2.52	210	3.82	170	4.64	140	5.09
		60	380	1.15	330	1.98	295	2.68	220	4.00	177	4.83	147	5.35
		130	400	1.21	350	2.10	310	2.79	230	4.18	185	5.05	155	5.64
3	1.047	12	300	0.91	260	1.56	232	2.08	175	3.18	140	3.82	116	4.22
		20	400	1.21	350	2.10	310	2.79	232	4.22	185	5.05	155	5.64
		40	480	1.45	420	2.52	373	3.36	280	5.10	225	6.14	187	6.80
		60	503	1.52	440	2.64	391	3.52	295	5.37	235	6.42	196	7.13
		130	530	1.61	462	2.77	411	3.70	310	5.64	248	6.77	206	7.50
2	1.57	12	450	1.37	390	2.34	350	3.15	260	4.73	209	5.71	174	6.33
		20	600	1.82	520	3.12	467	4.20	350	6.37	280	7.64	232	8.44
		40	720	2.18	630	3.78	560	5.04	420	7.64	348	9.50	280	10.20
		60	760	2.30	663	3.98	592	5.33	442	8.05	355	9.70	295	10.72
		130	795	2.40	695	4.17	619	5.57	462	8.40	370	10.10	309	11.23
1½	2.09	12	595	1.80	520	3.12	462	4.16	348	6.34	278	7.59	230	8.37
		20	800	2.42	700	4.20	620	5.58	466	8.47	372	10.15	310	11.28
		40	963	2.92	840	5.04	750	6.75	560	10.20	450	12.28	372	13.52
		60	1010	3.06	880	5.28	780	7.03	585	10.65	470	12.82	390	14.20
		130	1060	3.21	925	5.55	820	7.38	617	11.22	493	13.44	410	14.90

* This figure was supplied in 1913 by Mr. W. C. Bates, Engineer of the Faucus Machine Co.

† Data Book 125, Link-Belt Co., New York, 1914, p. 106.

36. Horse-power Transmitted by Belts*

Pulley Running at 100 Rev. per Min.

Diameter of pulley (in.)	Width of belt: 2 in.	3 in.	4 in.	5 in.		6 in.		8 in.		10 in.		12 in.	14 in.	16 in.	18 in.	20 in.
	S	S	S	S	D	S	D	S	D	S	D	D	D	D	D	D
	4 ply	4 ply	4 ply	4 ply	6 ply	4 ply	6 ply	4 ply	6 ply	4 ply	6 ply	6 ply	8 ply	8 ply	8 ply	8 ply
6	0.29	0.43	0.57	0.71	1.3											
8	0.38	0.57	0.76	0.95	1.7	1.1	2.1									
10	0.48	0.71	0.95	1.2	2.2	1.4	2.6	2.1	4.2							
12	0.57	0.86	1.1	1.4	2.6	1.7	3.1	2.5	5.0	3.1	6.3					
14	0.67	1.0	1.3	1.7	3.1	2.0	3.7	2.9	5.9	3.7	7.3	11.0				
16	0.76	1.1	1.5	1.9	3.5	2.3	4.2	3.4	6.7	4.2	8.4	12.6	14.7			
18	0.86	1.3	1.7	2.1	3.9	2.6	4.7	3.8	7.5	4.7	9.4	14.1	16.5	18.8		
20	0.95	1.4	1.9	2.4	4.4	2.9	5.2	4.2	8.4	5.2	10.5	15.7	18.3	21.0	23.6	
22	1.0	1.6	2.1	2.6	4.8	3.1	5.8	4.6	9.2	5.8	11.5	17.3	20.2	23.0	25.9	28.8
24	1.1	1.7	2.3	2.9	5.2	3.4	6.3	5.0	10.0	6.3	12.6	18.8	22.0	25.1	28.3	31.4
26	1.2	1.9	2.5	3.1	5.7	3.7	6.8	5.4	10.9	6.8	13.6	20.4	23.8	27.2	30.6	34.1
28	1.3	2.0	2.7	3.3	6.1	4.0	7.3	5.9	11.7	7.3	14.7	22.0	25.7	29.3	33.0	36.7
30	1.4	2.1	2.9	3.6	6.5	4.3	7.9	6.3	12.6	7.9	15.7	23.6	27.5	31.4	35.3	39.3
32	1.5	2.3	3.0	3.8	7.0	4.6	8.4	6.7	13.4	8.4	16.8	25.1	29.3	33.5	37.7	41.9
34	1.6	2.4	3.2	4.0	7.4	4.9	8.9	7.1	14.2	8.9	17.8	26.7	31.2	35.6	40.1	44.5
36	1.7	2.6	3.4	4.3	7.9	5.1	9.4	7.5	15.1	9.4	18.8	28.3	33.0	37.7	42.4	47.1
38	.....	.....	3.6	4.5	8.3	5.4	10.0	8.0	15.9	10.0	19.9	29.9	34.8	39.8	44.8	49.8
40	.....	.....	3.8	4.8	8.7	5.7	10.5	8.4	16.8	10.5	20.9	31.4	36.6	41.9	47.1	52.4
42	.....	.....	4.0	5.0	9.2	6.0	11.0	8.8	17.6	11.0	22.0	33.0	38.5	44.0	49.5	55.0
44	.....	.....	4.2	5.2	9.6	6.3	11.5	9.2	18.4	11.5	23.0	34.6	40.3	46.1	51.8	57.6
46	.....	.....	4.4	5.5	10.0	6.6	12.0	9.6	19.3	12.0	24.1	36.1	42.1	48.2	54.2	60.2
48	.....	.....	4.6	5.7	10.5	6.9	12.6	10.1	20.1	12.6	25.1	37.7	44.0	50.3	56.6	62.9
50	.....	.....	.....	6.0	10.9	7.1	13.1	10.5	20.9	13.1	26.2	39.3	45.8	52.4	58.9	65.5
60	.....	.....	.....	7.1	13.1	8.6	15.7	12.6	25.1	15.7	31.0	47.1	55.0	62.8	70.7	78.6
72	.....	.....	.....	.....	.....	10.3	18.9	15.1	30.2	18.9	37.7	56.6	66.0	75.4	84.8	94.3
84	.....	.....	.....	.....	.....	.....	.....	17.6	35.2	22.0	44.0	66.0	77.0	88.0	99.0	110.0

* Link-Belt Co., Data Book, No. 125, 1914.

S and *D* refer to thickness of leather belting; 4 ply, 6 ply, and 8 ply refer to thickness of cotton or rubber belting. 5
min. is the limiting speed for iron pulleys. A good belt speed is 3,500 ft. per min. If possible, use pulleys listed below

(American) system, one rope is used; this is wrapped around the sheaves the desired number of times, and then carried over from the last groove of one sheave to the first groove of the other by a guide pulley which, at the same time, maintains a constant tension in the rope. It is clearly seen that while the latter system is the more flexible and easily installed of the two, the results of a single breakage would be much more serious.

The angle of the groove should be about as shown in Figs. 5 and 6, which illustrate the grooves used for manila, hemp, or cotton ropes on the driving sheaves of both the English system and the American. For economical wear the pulleys should be not less than forty times the diameter of the rope.

The horse-power which can be transmitted by ropes at various speeds is the subject of much controversy, some engineers imposing loads greater by 35 or 40 per cent. than the recommendations of others. The data offered

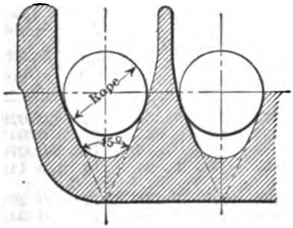


Fig. 5.—Standard groove of English system.

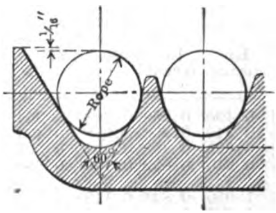


Fig. 6.—Standard groove of American system.

in Par. 42 represent conservative practice. Lansa* and the Link-Belt Co.† in their tables advocate values considerably higher, while J. J. Flather‡ is even more conservative than the accompanying authority.

42. Horse-power of Transmission Rope at Various Speeds**

Diam. of rope	Speed of the rope in ft. per min.											Smallest diam. of pulley in in.
	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	6,000	7,000	8,000	
½	1.45	1.9	2.3	2.7	3.0	3.2	3.4	3.4	3.1	2.2	0	20
⅝	2.3	3.2	3.6	4.2	4.6	5.0	5.3	5.3	4.9	3.4	0	25
¾	3.3	4.3	5.2	5.8	6.7	7.2	7.7	7.7	7.1	4.9	0	30
⅞	4.5	5.9	7.0	8.2	9.1	9.8	10.8	10.7	9.3	6.9	0	36
1	5.8	7.7	9.2	10.7	11.9	12.8	13.6	13.7	12.5	8.8	0	42
1¼	9.2	12.1	14.3	16.8	18.6	20.0	21.2	21.4	19.5	13.8	0	54
1½	13.1	17.4	20.7	23.1	26.8	28.8	30.6	30.8	28.2	19.8	0	60
1¾	18.0	23.7	28.2	32.8	36.4	39.2	41.5	41.8	37.4	27.6	0	72
2	23.1	30.8	36.8	42.8	47.6	51.2	54.4	54.8	50.0	35.2	0	84

* Lansa, G. "Notes on Friction," J. S. Cushing & Co., Boston.
† Data Book, No. 125, Link-Belt Co., New York, 1914.
‡ Flather, J. J. "Rope Driving," John Wiley & Sons, New York, 1895.
** Hunt, C. W. "Manila Rope," Cat. 054, C. W. Hunt Co., New York.

EXTRA STRONG PIPE

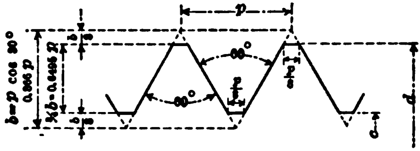
Size (in.)	Diameter (in.) External	Diameter (in.) Internal	Thickness (in.)	Weight per ft. (lb.) Plain ends
1/8	0.405	0.215	0.095	0.314
1/4	0.540	0.302	0.119	0.535
3/8	0.675	0.423	0.126	0.738
1/2	0.840	0.546	0.147	1.087
3/4	1.050	0.742	0.154	1.473
1	1.315	0.957	0.179	2.171
1¼	1.660	1.278	0.191	2.996
1½	1.900	1.500	0.200	3.631
2	2.375	1.939	0.218	5.022
2½	2.875	2.323	0.276	7.661
3	3.500	2.900	0.300	10.252
3½	4.000	3.364	0.318	12.505
4	4.500	3.826	0.337	14.983
4½	5.000	4.290	0.355	17.611
5	5.563	4.813	0.375	20.778
6	6.625	5.761	0.432	28.573
7	7.625	6.625	0.500	38.048
8	8.625	7.625	0.500	43.388
9	9.625	8.625	0.500	48.728
10	10.750	9.750	0.500	54.735
11	11.750	10.750	0.500	60.075
12	12.750	11.750	0.500	65.415
13	14.000	13.000	0.500	72.091
14	15.000	14.000	0.500	77.431
15	16.000	15.000	0.500	82.771

DOUBLE EXTRA STRONG PIPE

Size (in.)	Diameters (in.) External	Diameters (in.) Internal	Thickness (in.)	Weight per ft. (lb.) Plain ends
1/2	0.840	0.252	0.294	1.714
3/4	1.050	0.434	0.308	2.440
1	1.315	0.599	0.358	3.659
1¼	1.660	0.896	0.382	5.214
1½	1.900	1.100	0.400	6.408
2	2.375	1.503	0.436	9.029
2½	2.875	1.771	0.552	13.695
3	3.500	2.300	0.600	18.583
3½	4.000	2.728	0.636	22.850
4	4.500	3.152	0.674	27.541
4½	5.000	3.580	0.710	32.530
5	5.563	4.063	0.750	38.552
6	6.625	4.897	0.864	53.160
7	7.625	5.875	0.875	63.079
8	8.625	6.875	0.875	72.424

Taper of pipe threads is ¾ in. diameter per ft. length. Report Com. Pipe and Threads, A. S. M. E., Nov., 1886.

45. Screw Threads
(United States Standard)



Diameter		Area		No. of threads per in.	Diameter		Area		No. of threads per in.
Total *d* (in.)	Net *c* (in.)	Total dia., *d* (sq. in.)	Net dia., *c* (sq. in.)		Total *d* (in.)	Net *c* (in.)	Total dia., *d* (sq. in.)	Net dia., *c* (sq. in.)	
¼	0.185	0.049	0.027	20	2½	2.175	4.909	3.716	4
⅜	0.294	0.110	0.068	16	2⅝	2.300	5.412	4.156	4
½	0.400	0.196	0.126	13	2¾	2.425	5.940	4.619	4
⅝	0.507	0.307	0.202	11	2⅞	2.550	6.492	5.108	4
¾	0.620	0.442	0.302	10					
⅞	0.731	0.601	0.419	9	3	2.629	7.069	5.428	3½
					3¼	2.879	8.296	6.509	3½
1	0.838	0.785	0.551	8	3½	3.100	9.621	7.549	3¼
1⅛	0.939	0.994	0.693	7	3¾	3.317	11.045	8.641	3
1¼	1.064	1.227	0.890	7					
1⅜	1.158	1.485	1.054	6	4	3.567	12.566	9.993	3
1½	1.283	1.767	1.294	6	4¼	3.798	14.186	11.330	2⅞
1⅝	1.389	2.074	1.515	5½	4½	4.028	15.904	12.741	2¾
1¾	1.490	2.405	1.744	5	4¾	4.255	17.721	14.221	2⅝
1⅞	1.615	2.761	2.049	5					
					5	4.480	19.635	15.766	2½
2	1.711	3.142	2.300	4½	5¼	4.730	21.648	17.574	2½
2⅛	1.836	3.547	2.649	4½	5½	4.953	23.758	19.268	2⅜
2¼	1.961	3.976	3.021	4½	5¾	5.203	25.967	21.262	2⅜
2⅜	2.086	4.430	3.419	4½	6	5.423	28.274	23.095	2¼

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SECTION 24

STANDARDIZATION RULES OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

APPROVED BY THE BOARD OF DIRECTORS, JUNE 28, 1916.

CONTENTS

(*Numbers refer to Paragraphs*)

14. Non-sinusoidal quantities. Quantities that cannot be represented by vectors of constant length in a plane. The following definitions of phase, active component, reactive component, etc., are not in general applicable thereto. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

15. Crest-factor or peak-factor. The ratio of the crest or maximum value to the r.m.s. value. The crest factor of a sine-wave is $\sqrt{2}$.

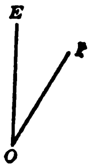
16. Form factor. The ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine wave is 1.11.

17. The distortion factor of a wave. The ratio of the r.m.s. value of the first derivative of the wave with respect to time, to the r.m.s. value of the first derivative of the equivalent sine-wave.

18. Equivalent sine-wave. A sine-wave which has the same frequency and the same r.m.s. value as the actual wave.

***19. Phase difference: lead and lag.** When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values, *e.g.*, the phase angle between their nearest corresponding values; *e.g.*, the phase angle between their nearest ascending zeros or between their nearest positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.

***20. Counter-clockwise convention.** It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector,† as in the accompanying diagram, where *OI* represents the vector of a current in a simple alternating-current circuit, lagging behind the vector *OE* of impressed e.m.f.



***21. The active or in-phase component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

* **22. Reactive or quadrature component of the current in a circuit.** That component which is in quadrature with the voltage across the circuit; similarly, the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

***23. Reactive factor.** The sine of the angular phase difference between voltage and current; *i.e.*, the ratio of the reactive current or voltage to the total current or voltage.

***24. Reactive volt-amperes.** The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

***25. Non-inductive load and inductive load.** A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

26. Power in an Alternating-current circuit. The average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as indicated by a wattmeter.

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* NOTE.—Definitions 19, 20, 21, 22, 23, 24, 25 refer strictly only to cases where the voltage and current are both sinusoidal (see Par. 11 and 12).

† See Publication 12 of the International Electrotechnical Commission (Report of Turin Meeting, Sept., 1911, p. 78).

60. Diversity factor. The ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

61. Connected load. The combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration.

62. The saturation factor of a machine. The ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

63. The percentage saturation of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage of saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

64. Magnetic degree. The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One **mechanical degree** is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

65. The variation in prime movers which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 deg.

66. The variation in alternators or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees (1 cycle = 360 deg.) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

67. Relations of variations in prime mover and alternator. If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

68. The pulsation in prime movers, or in the alternator connected thereto. The ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

80. Capacity. The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term *power capacity* or *current capacity* be used, when referring to the power or current which a device can safely carry, and that the term "*Capacitance*" be used when referring to the electrostatic capacity of a device.

81. Resistor. A device, heretofore commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits. See Par. 740.

Phase displacement........	θ, φ	degree or radian	°
Frequency................	f	cycle per second	~
Angular velocity..........	ω	radians per second	....
Velocity of rotation.......	n	revolutions per second	rev. per sec.
Number of conductors or turns..................	N	convolutions or turns of wire	
Temperature..............	T, t, θ	degree centigrade	°C
Energy in general.........	U or W	joule, watt-hour	....
Mechanical work..........	W or A	joule, watt-hour	....
Efficiency................	η	per cent.	....
Length...................	l	centimeter	cm.
Mass.....................	m	gram	g.
Time.....................	t	second	sec.
Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665*.........	g_0	centimeter per second per second	cm. per sec. per sec.

91. E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see Par. **10**) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with continuous-current circuits. In print, vector quantities should be represented by bold-face capitals.

CLASSIFICATION OF MACHINERY

100. The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are direct-current or alternating-current, rotating or stationary. Under rotating apparatus there are two principal classifications: *First*, according to the function of the machines; motors, generators, boosters, motor-generators, dynamotors, double-current generators, converters and phase advancers; *Second*, according to the type of construction or principle of operation; commutating, synchronous, induction, unipolar, rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, motor-generators and rectifying machines.

In the following, self-evident definitions have, for the most part, been omitted.

ROTATING MACHINES

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES

101. Generator. A machine which transforms mechanical power into electrical power.

102. Motor. A machine which transforms electrical power into mechanical power.

* This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45 deg. latitude and sea level. Later researches, however, have shown that the most reliable value for 45 deg. and sea-level is slightly different; but this does not affect the standard value given above.

motion of the machine; *i.e.*, having a frequency strictly proportional to the speed of the machine. They may be subdivided as follow:

134. An alternator is a synchronous alternating-current generator, either single-phase or polyphase.

135. A polyphase alternator is a polyphase synchronous alternating-current generator, as distinguished from **a single-phase alternator.**

136. An inductor alternator is an alternator in which both field and armature windings are stationary, and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

137. A synchronous motor is a machine structurally identical with an alternator, but operated as a motor.

138. Induction machines include apparatus wherein primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

139. An induction motor is an alternating-current motor, either single-phase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

140. An induction generator is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

141. Unipolar or acyclic machines are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS

150. Motors may, for convenience, be classified with reference to their speed characteristics as follows:

151. Constant-speed motors, whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

152. Multispeed motors (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load; such as motors with two armature windings, or induction motors in which the number of poles is changed by external means.

153. Adjustable-speed motors, in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of speed variation.

154. Varying-speed motors, or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors. As a subclass of varying-speed motors, may be cited, **adjustable varying-speed motors,** or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION

160. The following types are recognised:

Open	Self-ventilated
Protected	Drip-proof
Semi-enclosed	Moisture-resisting
Enclosed	Submersible
Separately ventilated	Explosion-proof
Water-cooled	Explosion-proof slip-ring enclosure

161. An "open" machine is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

162. A "protected" machine is one in which the armature, field coils,

206. The **"current ratio"** of a current-transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified conditions of load.

207. The **"marked ratio"** of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power-factor of the load.

208. Volt-ampere ratio of transformers. The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power-factor.

209. Auto-transformers have a part of their turns common to both primary and secondary circuits.

210. Voltage regulators have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit-voltages is variable at will. They are of the following three classes:

211. Contact voltage regulators, in which the number of turns in one or both of the coils is adjustable.

212. Induction voltage regulators, in which the relative positions of the primary and secondary coils are adjustable.

213. Magneto voltage regulators, in which the direction of the magnetic flux with respect to the coils is adjustable.

214. Reactors, heretofore commonly called **reactance-coils,** also called **choke coils;** a form of stationary induction apparatus used to supply reactance or to produce phase displacement. See also Par. **82** and **726.**

METERS AND INSTRUMENTS

225. Although the terms **instruments** and **meters** are frequently used synonymously in referring to electrical measuring devices, the meter departments of manufacturing and operating companies commonly use the word "meters" in the collective sense to designate only those devices which register the total energy or quantity of electricity consumed in or supplied to a circuit, and reserve the term "instruments," in the collective sense, for all other electrical measuring or indicating devices.

226. In general, the names of meters and instruments are self-defining, particularly when considered in connection with existing definitions. The following terms are preferred to other terms sometimes used for the same devices: **Reactive-factor meter, power-factor meter, watt-hour meter,** etc.

227. Crest voltmeter. A voltmeter depending for its indications upon the crest, that is the maximum value of the voltage of the system to which it is connected. The instruments are so calibrated that they indicate the r. m. s. value of the sinusoidal voltage having the same crest value.

228. Synchronoscope (also called a synchroscope or synchronism indicator). A device which in addition to indicating synchronism between two machines, shows whether the speed of the incoming machine is fast or slow.

229. Reactive volt-ammeter (also called a reactive-volt-ampere indicator). An instrument which indicates the reactive volt-amperes of the circuit to which it is connected.

230. Line drop voltmeter compensator. A device used in connection with a voltmeter which causes it to indicate the voltage at some distant point of the circuit.

231. Recording ammeters, voltmeters, wattmeters, etc., are instruments which record graphically upon time-charts the values of the quantities they measure.

232. A demand meter is a device which indicates or records the demand or maximum demand (see Par. **57** and **58**). In practice two types are recognized:

233. An integrated-demand meter is one which indicates or records the maximum demand obtained through integration.

234. A lagged-demand meter is one in which the indication of maximum demand is subject to a characteristic time lag.

when operating with a cooling medium of the ambient temperature of reference (40 deg. for air or 25 deg. for water, see Par. 305 and 309) and with barometric conditions within the range given in Par. 308. See Par. 305A, 307, 320 and 321.

266. The temperature rises specified in these rules apply to all ambient temperatures up to and including, but not exceeding, 40 deg. cent., for air and 25 deg. cent. for water. (For definition of ambient temperature see Par. 303.)

267. Any machinery destined for use with higher ambient temperatures of cooling mediums, and also any machinery for operation at altitudes for which no provision is made in Par. 306, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these rules will, however, afford guidance in such cases.

UNITS IN WHICH RATING SHALL BE EXPRESSED

274. The rating of **direct-current generators**, shall be expressed in **kilowatts** (kw.) available at the terminals.

275. The rating of **alternators** and **transformers**, shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified power factor.

276. It is strongly recommended that the **rating of motors** shall be expressed in kilowatts* (kw.) available at the shaft. (An exception to this rule is made in the case of Railway motors, which, for some purposes, are also rated by their *input*, see Par. 302.)

277. Auxiliary machinery, such as regulators, resistors, reactors, balancer sets, stationary and synchronous condensers, etc.; shall have their ratings appropriately expressed. It is essential to specify also the voltage (and frequency, if a-c.), of the circuits on which the machinery may appropriately be used.

KINDS OF RATING

There are various kinds of rating such as:

281. Continuous rating. A machine, rated for continuous service, shall be able to operate continuously at its rated output, without exceeding any of the limitations referred to in Par. 260.

282. Short-time rating. A machine rated for short-time service; (*i.e.*, service including runs alternating with stoppages of sufficient duration to ensure substantial cooling), shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations referred to in Par. 260. Such a rating is a **short-time rating.**

283. Nominal ratings. For railway motors and sometimes for railway substation machinery, certain nominal ratings are employed. See Par. 765 and 800. Nominal ratings for automobile propulsion motors and generators are not recommended; see Par. 837.

284. Duty-cycle operation. Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load, may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty cycle.

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* Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

kw.———————approx. equiv. h.p.———————

For the purposes of these rules the horse power shall be taken as 746.0 watts.

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, load in excess of the rating should not be taken from a machine.

306. The permissible rises in temperature given in column 2 of Table III in Par. 276 have been calculated on the basis of the standard ambient temperature of reference, by subtracting 40 deg. from the highest temperatures permissible, which are given in column 1 of the same table.

307. A machine may be tested at any convenient ambient temperature, preferably not below 15 deg. cent., but *whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in column 2 of the table in Par.* **276.**

308. Altitude. Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1,000 meters (3,300 ft.). For machinery operating at an altitude of 1,000 meters or less, a test at any altitude less than 1,000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See Par. 267. It is recommended that when a machine is intended for service at altitudes above 1,000 meters (3,300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent. for each 100 meters (330 ft.) by which the altitude exceeds 1,000 meters. Water-cooled oil transformers are exempt from this reduction.

309. Ambient temperature of reference for water-cooled machinery. For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25 deg. cent., measured at the intake of the machine.

310. In testing of water-cooled transformers, it is not necessary to take into account the surrounding-air temperature, except where the cooling effect of the air is 15 per cent. or more of the total cooling effect, referred to the standard ambient temperature of reference of 25 deg. cent. for water and 40 deg. cent. for air. When the effect of the cooling air is 15 per cent. or more of the total, the temperature of the cooling water should be maintained within 5 deg. cent. of the surrounding air. Where this is impractical, the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

311. In the case of rotating machines, cooled by forced draft, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts (see Par. **304**), and a weight of one to the surrounding room air. **In the case of air-cooled transformers,** see "exception" Par. **321.**

312. Machines cooled by other means. Machines cooled by means other than air or water shall receive special consideration.

313. Outdoor machinery exposed to sun's rays. Outdoor machinery not protected from the sun's rays at times of heavy load, must receive special consideration.

314. Measurement of the ambient temperature during tests of machinery. The ambient temperature is to be measured by means of several thermometers placed at different points around and half-way up the machine, at a distnce of 1 to 2 meters (3 to 6 ft.), and protected from drafts, and abnormal heat radiation, preferably as in Par. **316.**

315. The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

316. In order to avoid **errors due to the time lag** between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitable heavy metal cup. This can be made to respond to various rates of change, by pro-

TEMPERATURE MEASUREMENTS

340. The life of the insulation of a machine depends in great measure upon the actual temperatures attained by the different parts, rather than on the rises of temperature in those parts.

341. The temperature in the different parts of a machine which it would be desirable to ascertain, are the maximum temperatures reached in those parts.

342. (Deleted in the last revision of the Standardisation Rules.)

343. As it is usually impossible to determine the maximum temperature attained in insulated windings, it is convenient to apply a correction to the observable temperature, so as to approximate the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

344. In determining the temperature of different parts of a machine three methods are provided. The appropriate method for any particular case is set forth below.

345. Method No. 1. Thermometer method. This method consists in the determination of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermo-couples, any of these instruments being applied to the hottest accessible part of the *completed* machine, as distinguished from the thermo-couples or resistance coils embedded in the machine as described under method No. 3.

346. When method No. 1 is used, the hottest-spot temperature for windings shall be estimated by adding a hottest-spot correction of 15 deg. cent. to the highest temperature observed, in order to allow for the practical impossibility of locating any of the thermometers at the hottest spot.

347. Exception. When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, a hottest-spot correction of 5 deg. cent., instead of 15 deg. cent., shall be made. For commutators, collector rings, bare metallic surfaces not forming part of a winding, or for oil in which apparatus is immersed, no correction is to be applied.

348. Method No. 2. Resistance method. This method consists in the measurement of the temperature of windings by their increase in resistance, corrected* to the instant of shut-down when necessary. In the application of this method, thermometer measurements shall also be made whenever practicable without disassembling the machine† in order to increase the probability of revealing the highest observable temperature. Whichever measurement yields the higher temperature, that temperature shall be taken as the "highest observable" temperature and a hottest-spot correction of 10 deg. cent. added thereto.

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* Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve, with temperature readings as ordinates and times as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied. In transformers of 200 kv-a. and less the measured temperature shall be increased one degree for every minute between the instant of shut-down and the time of the final temperature measurement, provided this time does not exceed three minutes.

In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

† As one of the few instances in which the thermometer check cannot be applied in Method No. 2, the rotor of a turbo-alternator may be cited.

in column 2, and are found by subtracting 40-deg. cent. from the figures in column 1. Whatever be the ambient temperature at the time of the test, the rise of temperature must never exceed the limits in column 2 of the table. The highest temperatures, and temperature rises, attained in any machine at the output for which it is rated, must not exceed the values indicated in the table and clauses following.

376. Permissible temperatures and temperature rises for insulating materials. Table III (following) gives the highest temperatures and temperature rises to which various classes of insulating materials may be subjected, based on a standard ambient temperature of reference of 40 deg. cent.

377. NOTE. The Institute recognizes the ability of manufacturers to ploy class B insulation successfully at maximum temperatures of 150 deg. cent. and even higher. However, a sufficient data covering experience over a period of years at such temperatures are at present unavailable, the institute adopts 125 deg. cent. as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

Table III.—Permissible Temperatures and Temperature Rises for Insulating Materials

		1	2
Class	Description of material	Maximum temperature to which the material may be subjected	Maximum temperature rise
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire*	105 deg. cent.	65 deg. cent.
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any class A. material or binder is used for structural purposes only, and may be destroyed without impairing† the insulating or mechanical qualities of the insulation	125 deg. cent.	85 deg. cent.
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc	No limits specified	

378. When a lower-temperature class material is comprised in a completed product to such an extent, or in such ways, that its subjection to the temperature limits allowed for the higher-temperature class material, with which it is associated, would affect the integrity of the insulation either mechanically or electrically, the permissible temperature shall be fixed at such a value as shall afford ample assurance that no part of the lower-temperature class material shall be subjected to temperatures higher than those approved by the Institute and set forth above.

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* For cotton, silk, paper and similar materials, when neither treated, impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10 deg. cent. below the limits fixed for class A, in Table III.

† The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

386A. Enclosed motors and generators. In an enclosed machine (see Par. 164) the limiting observable temperature and the limiting observable temperature rise shall be taken as 5 deg. cent. higher than in Table IV. This is not to be interpreted as an increase in the permissible hottest spot temperature, but is in recognition of the lesser difference between the hottest spot temperature and the observable temperature within an enclosed machine. This rule does not apply to those types of machines defined in Par. 163, 165 and 167.

387. Railway motor temperature limits, see Par. 304 and 305.

387A. Automobile propulsion motors and generators, see Par. 338.

388. Squirrel-cage and amortisseur windings. In many cases the insulation of such windings is largely for the purpose of making the conductors fit tightly in their slots, and the slightest effective insulation is ample. In other cases, there is practically no insulating material on the windings. Consequently, the temperature rise may be of any value such as will not occasion mechanical injury to the machine.

389. Collector rings. The temperature of collector rings shall not be permitted to exceed the "hottest spot" values set forth in Par. 376 and 379 for the insulations employed either in the collector rings themselves, or in adjacent insulations whose life would be affected by the heat from the collector rings.

390. Commutators. The observable temperature shall in no case be permitted to exceed the values given in Par. 376 and 379 for the insulation employed, either in the commutator or in any insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts, and are not intended as a criterion of successful commutation. See Par. 402.

391. Cores. The temperature of those parts of the iron core in contact with insulating materials must not be such as to occasion in those insulating materials temperatures or temperature rises in excess of those set forth in Par. 376 and 379.

392. Other parts, (such as brush-holders, brushes, bearings, pole-tips, cores, etc.) All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material, may be operated at such temperatures as shall not be injurious in any respect.

METHODS OF LOADING TRANSFORMERS FOR TEMPERATURE TESTS

393. Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time. See Par. 322–324. The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load.

An approved method of making these tests is the **"loading-back"** method. The principal variations of this method are:

394. With duplicate single-phase transformers. Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions, while the other may be operating under slightly abnormal conditions.

395. With one 3-phase transformer. One 3-phase transformer may be tested in a manner similar to (a), provided the primary and secondary windings are each connected in delta for the test. Normal 3-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

396. With three single-phase transformers. Duplicate single-phase transformers may be tested in banks of three, in a manner similar to (b) by connecting both primary and secondary windings in delta, and applying normal 3-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that machine or part during the specified interval. These losses may be appreciably different from the losses at 75 deg. cent., which latter shall be the standard temperature of reference for all efficiency guarantees. See Par. **432.**

422. In the case of machinery two efficiencies are recognized, conventional efficiency (see Par. **423**) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood whether the efficiency be the conventional or directly measured efficiency.

423. Conventional efficiency of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practicably indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

424. (Deleted in last revision of Standardization Rules.)

425. Directly measured efficiency. Input and output determinations of efficiency may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

426. Values of the indeterminate losses may also be obtained by brake or other direct test, and used in estimating actual efficiencies of similar machines, by the separate-loss method.

427. Normal conditions. The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave shape, speed, temperature, or such of them as may apply in each particular case.

428. Measurement of efficiency. Electric power shall be measured at the terminals of the apparatus. In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

429. Point at which mechanical power shall be measured. Mechanical power delivered by machines, shall be measured at the pulley, gearing, or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in Par. **800.**

430. The efficiency specified for alternators and transformers shall be of the ratio of the kilowatt output to the kilowatt input at the rated kv-a. and power factor.

431. Efficiency of alternating-current machinery in regard to wave shape. In determining the efficiency of alternating-current machinery, the sine-wave is to be considered as standard, unless a different wave form is inherent in the operation of the system. See Par. **405.**

432. Temperature of reference for machine efficiency. The efficiency, at all loads, of all apparatus, shall be corrected to a reference temperature of 75 deg. cent., but tests may be made at any convenient ambient temperature, preferably not less than 15 deg. cent. See Par. **348** and **445.**

433. The losses in constant-potential machinery, either of the stationary type, or of the constant-speed rotary type, are of two classes, namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no-load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

method of determination has been found, shall be included as zero per cent. in estimating conventional efficiency.

441. Synchronous motors and generators.

Core losses. See Par. **452**.

I^2R loss in all windings, based upon rated k-va. and power factor.

Stray load-losses. In approximating these losses, the method described in Par. **458** shall be employed.

Friction of bearings and windage.

Brush friction and brush-contact loss is negligible, except in the case of revolving armature machines.

Rheostat losses, when present. corresponding to rated kv-a. and power factor.

442. Induction machines.

Core losses. See Par. **452**.

I^2R losses in all windings.

Stray load-losses. In approximating these losses, the method described in Par. **459** shall be employed.

Brush friction when collector rings are present.

Brush-contact loss. Unless otherwise specified, use the Institute standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See Par. **454**.

Friction of bearings and windage.

443. Communicating a-c. machines.

Core losses. See Par. **452**.

I^2R losses in all windings.

Brush friction.

Brush-contact loss. Unless otherwise specified, use the Institute standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See Par. **454** and **819**.

Friction of bearings and windage.

Short-circuit loss of commutation. Iron loss due to flux distortion. Eddy-current losses due to fluxes varying with load and saturation.	The Institute is not at this time prepared to make recommendations for approximating these losses.

444. Synchronous converters.

Core losses. See Par. **452**.

I^2R losses in all windings, based on rated kw. and unity power factor. The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

Brush friction.

Rheostat losses when present, corresponding to rated kw. and unity power factor.

Brush-contact loss. Unless otherwise specified, use the Institute standard of 1 volt for contact drop per brush, for either carbon or graphite brushes. See Par. **454**.

Short-circuit loss of commutation. Iron loss due to flux distortion when present. Eddy-current losses due to fluxes varying with load and saturation.	These losses, while usually of low magnitude, are erratic, and the institute is not at this time prepared to make recommendations for approximating them.

Friction of bearings and windage.

For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

445. Transformers.

No-load losses. These include the core loss, and the I^2R loss due to the exciting current, also the dielectric loss in the insulation. See Par. **470**.

Load losses. These include I^2R losses, and stray load-losses due to eddy currents caused by fluxes varying with load. See Par. **471**.

DETERMINATION OR APPROXIMATION OF LOSSES IN ROTATING MACHINERY

450. Bearing friction and windage may be determined as follows. Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes

Stray load-losses are to be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the institute is not yet prepared to specify a method for measuring them.

459. Stray load-losses in induction machines. These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined I^2R and stray load-losses due to eddy currents in the stator copper. Deduct the I^2R loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

460. Polyphase induction-motor rotor I^2R loss. This should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{output} \times \text{slip}}{1 - \text{slip}}$$

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to 3-phase rotors. For rotors wound for 2 phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

DETERMINATION OR APPROXIMATION OF LOSSES IN TRANSFORMERS

470. No-load losses. These shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated load conditions.

471. Load losses. These include I^2R and stray load-losses. They shall be measured by applying a primary voltage, preferably at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short circuited.

TESTS OF DIELECTRIC STRENGTH OF MACHINERY

480. Basis for determining test voltages. The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machinery, and its normal operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended, have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

481. Condition of machinery to be tested. Commercial tests shall, in general, be made with the completely assembled machinery and not with individual parts. The machinery shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied before the machine is put into commercial service, and shall not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing. High-voltage tests to determine whether specifications are fulfilled, are admissible on new machines only. Unless otherwise agreed upon, high-voltage tests of a machine shall be understood as being made at the factory.

482. Points of application of voltage. The test voltage shall be sucstandstill with normal voltage impressed on the primary.

When induction motors with phase-wound rotors are reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage, plus 1,000 volts.

509. Exception—switches and circuit control apparatus above 600 volts, shall be tested with two and one-fourth times rated voltage, plus 2,000 volts. See Par. **720** to **741**.

510. Exception—assembled apparatus. Where a number of pieces of apparatus are assembled together and tested as an electrical unit, they shall be tested with 15 per cent. lower voltage than the lowest required on any of the individual pieces of apparatus.

510A. Exception—meters and instruments. The Institute is not at present in a position to make a recommendation in regard to the dielectric tests of meters and instruments.

511. Testing transformers by induced voltage. Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage," is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

512. Transformers with graded insulation shall be so marked. They shall be tested by including the required test-voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. (See Par **500**.)

MEASUREMENT OF VOLTAGE IN DIELECTRIC TESTS OF MACHINERY

530. Use of voltmeters and spark-gaps in insulation tests. When making insulation tests on electrical machinery, every precaution must be taken against the occurrence of any spark-gap discharges in the circuits from which the machinery is being tested. A non-inductive resistance of about 1 ohm per volt shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode. If neither terminal is grounded, one-half shall be inserted directly in series with each electrode. In any case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. The resistance will damp high-frequency oscillations at the time of breakdown and limit the current which will flow. A water-tube is the most reliable form of resistor. Carbon resistors should not be used because their resistance may become very low at high voltages.

531. For machinery of low capacitance. When the machinery under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark-gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark-gap just breaks down. This adjustment should be made with the apparatus under test disconnected. The apparatus should then be connected, and with the spark gap about 20 per cent. longer, the testing apparatus is again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage is to be maintained for the required interval.

532. For machinery of high capacitance. When the charging current of the machinery under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage should be made with the apparatus under test connected to the circuit and in parallel with the spark-gap.

When making arc-over tests of large insulators, leads, etc., partial arc-

Diameter of sphere in mm.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125.0	45	35
250.0	65	45
500.0	100	65

539A. In using sphere gaps constructed as above, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap; *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

540. The sparking distances between different spheres for various r.m.s. sinusoidal voltages shall be assumed to be as follows:

Table IX.—Sphere-gap Spark-over Voltages

(At 25 deg. cent. and 760 mm. barometric pressure)

Kilovolts	Sparking distance in millimeters							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	......	......	......	......	......	......
20	8.6	8.6	......	......	......	......	......	......
30	14.1	14.1	14.1	14.1	......	......	......	......
40	19.2	19.2	19.1	19.1	......	......	......	......
50	25.5	25.0	24.4	24.4	......	......	......	......
60	34.5	32.0	30.0	30.	29	29	......	......
70	46.0	39.5	36.0	36.	35	35	......	......
80	62.0	49.0	42.0	42.	41	41	41	41
90	......	60.5	49.0	49.	46	45	46	45
100	......	......	56.0	55.	52	51	52	51
120	......	......	79.7	71.	64	63	63	62
140	......	......	108.	88.	78	77	74	73
160	......	......	150	110.	92	90	85	83
180	......	......	......	138.	109	106	97	95
200	......	......	......	......	128	123	108	106
220	......	......	......	......	150	141	120	117
240	......	......	......	......	177	160	133	130
260	......	......	......	......	210	180	148	144
280	......	......	......	......	250	203	163	158
300	......	......	......	......	......	231	177	171
320	......	......	......	......	......	265	194	187
340	......	......	......	......	......	......	214	204
360	......	......	......	......	......	......	234	221
380	......	......	......	......	......	......	255	239
400	......	......	......	......	......	......	276	257

The order of magnitude of the values obtained by this rule is shown in the following table:

Table XI.—Insulation Resistance of Machinery

Rated voltage of machine	Megohms		
	100 kv-a.	1,000 kv-a.	10,000 kv-a.
100	0.091	0.05	.....
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	.....	50.0	9.1

551. It should be noted that the insulation resistance of machinery is of doubtful significance by comparison with the dielectric strength. The insulation resistance is subject to wide variation with temperature humidity and cleanliness of the parts. When the insulation resistance falls below that corresponding to the above rule, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying out the machine. The insulation-resistance test may therefore afford a useful indication as to whether the machine is in suitable condition for the application of the dielectric test.

REGULATION

DEFINITIONS

560. Regulation. The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be expressed by the "percentage regulation," which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75 deg. cent. shall be considered as standard. If change of temperature should occur during the tests, the results shall be corrected to the reference temperature of 75 deg. cent.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a-c. generators.

It is usual to state the regulation of d-c. generators by giving the numerical values of the voltage at no-load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

561. The **regulation of d-c. generator** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound d-c. generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

562. In **constant-potential a-c. generators**, the regulation is the rise in voltage (when the specified load at specified power factor is reduced to zero) expressed in per cent. of normal rated-load voltage.

563. In **constant-current machines**, the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

564. In **constant-speed d-c. motors**, and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

necessary to determine the regulation from such other tests as can be readily made.

585. Method b. This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero power-factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by running the generator with overexcitation on a load of idle-running underexcited synchronous motors. The power-factor under these conditions is very low and the load saturation curve approximates very closely the zero power-factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve, for any power-factor, can be obtained by means of vector diagrams.

To apply Method b, it is necessary to obtain from test, the open-circuit saturation curve *OA*, Fig. 1, and the saturation curve *BC* at zero power-factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ac*, the terminal voltage at zero power-factor is *bc*, and the apparent internal drop is *ab*. The terminal voltage *dc* at any other power-factor can then be found by drawing an e.m.f. diagram* as in Fig. 2, where ϕ is an angle such that $\cos\phi$ is the power-factor of the load, *be* the resistance drop (*IR*) in the stator winding, *ba* the total internal drop, and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 1. The terminal voltage at power-factor $\cos\phi$, is then *cb* of Fig. 2, which, laid off in Fig. 1, gives point *d*. By finding a number of such points, the curve *Bdd'* for power-factor $\cos\phi$ is obtained and the regulation at this power-factor (expressed in per cent.) is $\frac{100 \times a'd'}{d'c'}$, since *a'd'* is the rise in voltage when the load at power-factor $\cos\phi$ is thrown off at normal voltage *c'd'*.

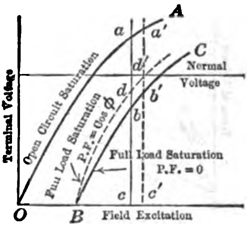


Fig. 1.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation, except in very low-speed machines where the armature resistance is relatively high, or in some cases where regulation at unity power-factor is being estimated. For low power-factors, its effect is negligible in practically all cases. If resistance is neglected, the simpler e.m.f. diagram, Fig. 3, may be used to obtain points on the load saturation curve for the power-factor under consideration.

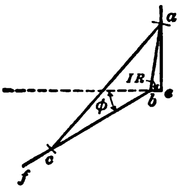


Fig. 2.

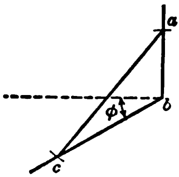


Fig. 3.

586. Method c. Where it is not possible to obtain by test a zero power-factor saturation curve as in Method b, this curve can be estimated closely from open-circuit and short-circuit curves, by reference to tests at zero power-factor on other machines of similar magnetic circuit. Having obtained the estimated zero power-factor curve, the load saturation for any other power-factor is obtained as in Method b.

* Method b, for deducing the load saturation curve, at any assigned power-factor, from no-load and zero power-factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

connections, and all terminals and taps of the transformer shall be marked to correspond with letters and numbers in the sketch. This sketch should preferably be on a metal plate on the transformer case.

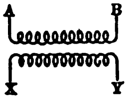
SINGLE-PHASE TRANSFORMERS

601. Marking of leads. The leads of single-phase transformers shall be distinguished from each other by marking the high-voltage leads with the letters *A* and *B*, and the low-voltage leads with the letters *X* and *Y*.

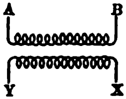
The terminals (by terminals is meant the ends of the windings) shall be so marked that the potential difference in all windings at any instant shall have the same sign, that is, the potential difference between *A* and *B* shall have the same sign at any instant as the potential difference between *X* and *Y*.*

602. In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

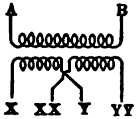
(1) High- and low-voltage windings in phase:



603. (2) High- and low-voltage windings 180 deg. apart in phase:

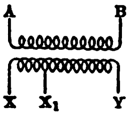


604. Single-phase transformers with more than two windings. Transformers with three or more windings (each provided with separate outgoing leads) shall have the leads of two of their windings lettered in accordance with the preceding paragraph. The remaining leads shall be designated *AA*, *BB*, etc. in the case of high-voltage leads and *XX*, *YY*, etc. in the case of low-voltage leads. For example, transformers having four secondary leads from two distinct, similar windings shall be lettered as follows:



This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals *X*, *Y* and the other part having terminals *XX*, *YY*. For multiple connection, *X* and *XX* are to be connected and *Y* and *YY* are to be connected. For series operation, *Y* is to be connected to *XX*.

605. Tap connections. All tap connections which are not brought outside the transformer case shall be marked serially with numerals only. Where tap leads are brought out of the transformer case they shall be given the letter designation together with a subscript indicating the relative position of the tap, as in the following diagram.



* To test the correctness of single-phase markings, connect *A* to *X* and apply voltage to the high voltage winding *A-B*. Voltage *B-Y* must be numerically less than voltage *A-B*.

610. Angular displacement. The angular displacement between high- and low-voltage windings, is the angle in the diagram in Par. **608** between the lines passing from the neutral point through A and X respectively for three-phase transformers and through A and U for six-phase transformers. Thus, in group 1, the angular displacement is zero degrees; in group 2, the angular displacement is 180°, and in group 3, the angular displacement is 30°.

611. Parallel operation. Three-phase and six-phase transformers marked as above may be operated in parallel, by connecting similarly marked terminals together, provided their ratios, voltages, resistances, reactances and angular displacements are such as to permit parallel operation.

INFORMATION ON THE RATING PLATE OF A MACHINE

620. It is recommended that the rating plate of machines which comply with the Institute rules shall carry a distinctive special sign, such as "A. I. E. E. 1916 Rating" or "A 16" Rating.

621. The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature of reference. See Par. **287, 305, 308,** and **309**.

622. The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

623–630. (Deleted in the last revision of the Standardization Rules.)

STANDARDS FOR WIRES AND CABLES

TERMINOLOGY*

635. Wire. A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

636. Conductor. A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as bus bars) are, of course, conductors, but are not considered under the terminology here given.

637. Stranded conductor. A conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together,

638. Cable. (1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one and, in practice, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or with steel wires or bands.

639. Strand. One of the wires, or groups of wires, of any stranded conductor.

640. Stranded wire. A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is

* From Circular No. 37 of the Bureau of Standards.

Table XII.—Standard Stranding of Concentric-lay Cables

Size (see note 1)	Number of wires (see note 2) A Bare, insulated or weather-proof cables for aerial use	B Insulated cables for other than aerial use
2.0 cir. in.	91	127
1.5 cir. in.	61	91
1.0 cir. in.	61	61
0.6 cir. in.	37	61
0.5 cir. in.	37	37
0.4 cir. in.	19	37
0000 A.W.G.	19 or 7 (See note 3)	19
00 A.W.G.	7	19
2 A.W.G.	7	7
7 and smaller	..	7

NOTE 1. For intermediate sizes, use stranding for next larger size.
NOTE 2. Conductors of 0000 A.W.G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.
NOTE 3. Class A cable, sizes 0000 and 000 A.W.G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

Table XIII.—Proposed Standard Stranding of Flexible Cables

Nearest A.W.G. size (see note 1)	Circular mils (see note 3)	Diameter of cable, mils	Number of wires	Size of each wire A.W.G.	Diameter, mils	Make-up (see note 2)
....	2,039,000	1,836.	703	15.5	53.9	37×19
....	1,816,000	1,778.	703	16.0	50.8	37×19
....	1,617,000	1,680.	703	16.5	48.0	37×19
....	1,440,000	1,586.	703	17.0	45.3	37×19
....	1,282,000	1,495.	703	17.5	42.7	37×19
....	1,103,000	1,372.	427	16.0	50.8	61×7
....	874,500	1,223.	427	17.0	45.3	61×7
....	693,400	1,088.	427	18.0	40.3	61×7
....	550,000	969.	427	19.0	35.9	61×7
....	436,400	864.	427	20.0	32.0	61×7
....	345,900	770.	427	21.0	28.5	61×7
....	274,300	686.	427	22.0	25.4	61×7
....	264,700	672.	259	20.0	32.0	37×7
0000	209,800	599.	259	21.0	28.5	37×7
000	171,300	539.	133	19.0	35.9	19×7
00	135,900	480.	133	20.0	32.0	19×7
0	107,700	428.	133	21.0	28.5	19×7
1	82,780	332.	91	20.5	30.2	Concentric
2	65,660	296.	91	21.5	26.9	Concentric
3	58,460	279.	91	22.0	25.4	Concentric
4	39,190	229.	61	22.0	25.4	Concentric
5	31,080	203.	61	23.0	22.6	Concentric
6	24,650	181.	61	24.0	20.1	Concentric
8	17,400	152.	61	25.5	16.9	Concentric
10	10,560	118.	37	25.5	16.9	Concentric
12	6,442	94.	37	27.5	13.4	Concentric
14	4,177	74.	37	29.5	10.6	Concentric
Smaller	......	.....	To equal required size	30.0	....	Bunched

NOTE 1. The A.W.G. sizes except for 61 strands are approximated within 2 per cent. In the case of 61-strand cables the approximation is 6 per cent.
NOTE 2. "61 × 7" signifies a rope-lay cable composed of 61 strands of wires each.
NOTE 3. Circular mils are based on theoretical diameters of A.W.G. sizes which vary above or below values given in table by less than 0.1 mil.

657. The lay of any layer of wires of a cable or strand shall not exceed 5 times the pitch diameter of that layer. The lay of any layer of strands f rope-lay cables shall not exceed 12 times the pitch diameter of the layer.

CONDUCTIVITY OF COPPER

675. The following I. E. C. rules are adopted:*

The following shall be taken as normal values for standard annealed opper:

(1) At a temperature of 20 deg. cent., the resistance of a wire of standard nnealed copper 1 m. in length and of a uniform section of 1 sq. mm. is ohm = 0.017241 . . . ohm.

(2) At a temperature of 20 deg. cent., the density of standard annealed opper is 8.89 g. per cu. cm.

(3) At a temperature of 20 deg. cent., the "constant mass" temperature efficient of resistance of standard annealed copper, measured between two otential points rigidly fixed to the wire, is $0.00393 = \frac{1}{254.45}$ . . . per deg. nt.

(4) As a consequence, it follows from (1) and (2) that, at a temperature of) deg. cent., the resistance of a wire of standard annealed copper of uniform ction, 1 m. in length and weighing 1 g., is $(\frac{1}{58}) \times 8.89 = 0.15328$ . . . ohm.†‡

676. Copper-wire tables. The copper-wire tables published by the ureau of Standards in Circular No. 31 are adopted. These tables are based pon the I. E. C. rules stated in Par. **675.**

HEATING AND TEMPERATURE OF CABLES

677. Maximum safe limiting temperatures. The maximum safe niting temperature in deg. cent. at the surface of the conductor in a cable all be:

For impregnated paper insulation	$(85 - E)$
For varnished cambric	$(75 - E)$
For rubber insulation	$(60 - 0.25E)$

here E represents the r.m.s. operating e.m.f. in kilovolts between conictors.

Thus, at a working pressure of 3.3 kv., the maximum safe limiting temrature at the surface of the conductor, or conductors, in a cable would be:

For impregnated paper	81.7 deg. cent.
For varnished cambric	71.7 deg. cent.
For rubber insulation	59.2 deg. cent.

ELECTRICAL TESTS

678. Lengths tested. Electrical tests of insulation on wires and cables all be made on the entire lengths to be shipped.

679. Immersion in water. Electrical tests of insulated conductors not closed in a lead sheath, shall be made while immersed in water after an mersion of twelve (12) consecutive hours, if insulated with rubber comund, or if insulated with varnished cambric. It is not necessary to imerse in water insulated conductors enclosed in a lead sheath.

In multiple-conductor cables, without waterproof overall jacket of insulan, no immersion test should be made on finished cables, but only on the lividual conductors before assembling.

680. Dielectric-strength tests. Object of tests. Dielectric tests are ended to detect weak spots in the insulation and to determine whether e dielectric strength of the insulation is sufficient for enabling it to withnd the voltage to which it is likely to be subjected in service, with a suitle factor of assurance.

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* See I. E. C. Publication No. 28 "International Standard of Resistance for opper" March, 1914.

† Paragraphs (1) and (4) of Par. **675** define what are sometimes called olume resistivity," and "mass resistivity" respectively. This may be exessed in other units as follows: volume resistivity = 1.7241 microhm-cm. microhms in a cm. cube) at 20 deg. cent. = 0.67879 microhm-in. at 20 g. cent., and mass resistivity = 875.20 ohms (mile, pound) at 20 deg. cent.

‡ For detailed specifications of commercial copper, see the "Standard ecifications" of the American Society for Testing Materials.

690. Linear insulation resistance, or the insulation resistance of unit length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet.

691. Megohms constant. The megohms constant of an insulated conductor shall be the factor "K" in the equation

$$R = K \log_{10} \frac{D}{d}$$

where R = The insulation resistance, in megohms, for a specified unit length.
D = Outside diameter of insulation.
d = Diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

692. Test. The apparent insulation resistance should be measured after the dielectric-strength test, measuring the leakage current after a 1-min. electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

693. Multiple-conductor cables. The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from such conductor to all the other conductors in multiple with the sheath or water.

CAPACITANCE OR ELECTROSTATIC CAPACITY

694. Capacitance is ordinarily expressed in microfarads. Linear capacitance, or capacitance per unit length, shall be expressed in microfarads per unit length (kilometer, or mile, or 1,000 ft.) and shall be corrected to a temperature of 15.5 deg. cent.

695. Microfarads constant. The microfarads constant of an insulated conductor shall be the factor "K" in the equation

$$C = \frac{K}{\log_{10} \frac{D}{d}}$$

where C = the capacitance in microfarads per unit length.
D = the outside diameter of insulation.
d = the diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

696. Measurement of capacitance. The capacitance of low-voltage cable, shall be measured by comparison with a standard condenser. For long lengths of high-voltage cables, where it is necessary to know the true capacitance, the measurement should be made at a frequency approximating the frequency of operation.

697. Paired cables. The capacitance shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

698. Electric light and power cables. The capacitance of low-voltage cables is generally of but little importance. The capacitance of high-voltage cables should be measured between the conductors, and also between each conductor and the other conductors connected to the lead sheath or ground.

699. Multiple-conductor cables (not paired). The capacitance of each conductor of a multiple-conductor cable shall be the capacitance measured from such conductor to all of the other conductors in multiple with the sheath or the ground.

STANDARDS FOR SWITCHES AND OTHER CIRCUIT-CONTROL APPARATUS*

SWITCHES

720. The following rules apply to switches of above 600 volts. (For 600 volts and below, see *National Electric Code.*†)

* These rules do not apply to magnetically-operated or air-operated switches used for motor control.

† By the term "Code" is meant "National Electrical Code" as recommended by the National Fire Protection Association.

highest temperature for the fuse proper should not exceed the safe limit for the material employed (*e.g.*, the temperature of the fibre tube of an enclosed fuse should not exceed the safe limit for this material, but an open-link metal fuse may be run at any temperature which will not injure the fuse material; except that no application of the above rule shall contravene the *National Electric Code*).

732. Test. For fuses intended for use on circuits of small capacity, or in protected positions on systems of large capacity, see *National Electric Code.* For large power fuses intended for service similar to that required of circuit breakers, see Par. **724** to **728**, or the *National Electric Code*, as far as the latter applies.

NOTE.—Complete standardization of these fuses above 600 volts, according to the method of the *National Electric Code*, is not advisable at this time, but is expected to be accomplished by an eventual extension of the *National Electric Code*. Until such extension is made, the following definitions and ratings may be followed.

LIGHTNING ARRESTERS

733. Definition. A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

734. Rating. Arresters shall be rated by the voltage of the circuit on which they are to be used.

Lightning arresters may be divided into two classes: (*a*) Those intended to discharge for a very short time. (*b*) Those intended to discharge for a period of several minutes.

735. Performance and tests. Dielectric test same as Par. **723.**

The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

(*c*) In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle a-c. excitation. (*d*) The equivalent sphere gap under disruptive discharge shall also be measured, using a considerable quantity of electricity. (*e*) The endurance of the arrester to continuous surges shall be tested.

PROTECTIVE REACTORS

736. Definition. A reactor (see Par. **82** and **214**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

737. Rating. (*a*) In kilovolt-amperes absorbed by normal current. (*b*) By the normal current, frequency and line (delta) voltage for which the reactor is designed. (*c*) By the current which the device is required to stand under short-circuit conditions.

738. Performance and tests. **The heat test** shall be made with normal current and frequency applied until the temperature is constant. The temperature should not exceed the safe limits for the materials employed. See Par. **376** to **379.**

739. Dielectric test. Two and one-fourth times line voltage plus 2,000, for 1 min., from conductor to ground.

NOTE.—The reactor shall be so designed as to be capable of withstanding, without mechanical injury, rated current at normal frequency, suddenly applied.

RESISTOR OR RHEOSTAT

740. Definition. Any device heretofore commonly known as a resistance, used for operation or control. (Par. **81.**) See *National Electric Code.*

INSTRUMENT TRANSFORMERS

741. Definition. An instrument transformer is a transformer for use with measuring instruments, in which the conditions in the primary circuit as to current and voltage are represented with high numerical accuracy in the secondary circuit.

Under this heading and for more general use: (*a*) A current transformer is a transformer designed for series connection in its primary circuit with the ratio of transformation appearing as a ratio of currents. (*b*) A

772. Gage of third rail. The distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the *contact surface* of the third rail.

773. Elevation of third rail. The elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

774. Standard gage or third rails. The gage of third rails shall be not less than 26 in. (66 cm.) and not more than 27 in. (68.6 cm.).

775. Standard elevation of third rails. The elevation of third rails shall be not less than 2¾ in. (70 mm.), and not more than 3½ in. (89 mm.).

776. Third rail protection. A guard for the purpose of preventing accidental contact with the third rail.

777. Trolley wire. A flexible contact conductor, customarily supported above the cars.

778. Messenger wire or cable. A wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

779. Classes of construction. Overhead trolley construction will be classed as *direct suspension* and *messenger or catenary suspension.*

780. Direct suspension. All forms of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

781. Messenger or catenary suspension. All forms of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *simple catenary, i.e.,* by primary messengers, or in *compound catenary, i.e.,* by secondary messengers.

782. Supporting systems shall be classed as follows:

783. Simple cross-span systems. Those systems having at each support a single flexible span across the track or tracks.

784. Messenger cross-span systems. Those systems having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

785. Bracket systems. Those systems having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

786. Bridge systems. Those systems having at each support a rigid member, supported at both sides of the track or tracks.

787. Standard height of trolley wire on street and interurban railways. It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 ft. (5.5 m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 ft. (6.4 m.) above the top of rail, under conditions of maximum sag.

RAILWAY MOTORS

RATING

800. Nominal rating. The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 deg. cent. at the commutator, and 75 deg. cent. at any other normally accessible part after 1 hr.'s continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100 deg. cent.*

* This definition differs from that in the 1911 edition of the Rules, principally by the substitution of a kilowatt rating for the horse-power rating

(*Cont. on next page.*)

806. Field-control motors. The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

CHARACTERISTIC CURVES

810. The characteristic curves of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

811. Characteristic curves of direct-current motors shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

812. In the case of field-control motors, characteristic curves shall be given for all operating field connections.

EFFICIENCY AND LOSSES

815. The efficiency of railway motors shall be deduced from a determination of the losses enumerated in Par. **816** to **820**. (See also Par. **1100** and **1101**.)

816. The copper loss shall be determined from resistance measurements corrected to 75 deg. cent.

817. The no-load core loss, brush friction, armature-bearing friction and windage shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

818. The **core loss** in direct-current motors shall be separated from the friction and windage losses above described by measuring the power required to drive the motor at any given speed without gears, by running it as a series motor on low voltage and deducting this loss from the sum of the no-load losses at corresponding speed. (See Par. **1101** for alternative method.)

The friction and windage losses under load shall be assumed to be the same as without load, at the same speed.

The core loss under load shall be assumed as follows:

Table XVII.—Core Loss in D-C. Railway Motors at Various Loads

Per cent. of input at nominal rating	Loss as per cent. of no-load core loss	Per cent. of input at nominal rating	Loss as per cent. of no-load core loss
200	165	75	125
150	145	50	123
100	130	25 and under	122

NOTE.—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above table.

819. The brush-contact resistance loss to be used in determining the efficiency, may be obtained by assuming that the sum of the drops at the contact surfaces of the positive and negative brushes is 3 volts.

820. The losses in gearing and axle bearings for single-reduction single-geared motors, varies with type, mechanical finish, age and lubrication. The following values, based on accumulated tests, shall be used in the comparison of single-reduction single-geared motors.

ILLUMINATION AND PHOTOMETRY

The following paragraphs, **850** to **895**, are the rules of the Nomenclature and Standards Committee of the Illuminating Engineering Society. They are here included by permission.

850. Luminous flux is radiant power evaluated according to its capacity to produce the sensation of light.

851. The stimulus coefficient $K\lambda$ for radiation of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

852. The mean value of the stimulus coefficient, K_m, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, but more commonly in watts).

853. The luminous intensity of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.
Defining equation:
Let I be the intensity, F the flux and ω the solid angle.

Then if the intensity is uniform,

$$I = \frac{F}{\omega},$$

854. Illumination, on a surface, is the luminous flux-density over that surface, or the flux per unit of intercepting area.
Defining equation:
Let E be the illumination and S the area of the intercepting surface.

Then when uniform,

$$E = \frac{F}{S},$$

855. Candle, the unit of luminous intensity maintained by the National Laboratories of France, Great Britain, and the United States.*

856. Candle-power, luminous intensity expressed in candles.

857. Lumen, the unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of 1 candle-power.†

858. Lux, a unit of illumination equal to one lumen per sq. m. The C.G.S. unit of illumination is one lumen per sq. cm. For this unit Blondel has proposed the name "Phot." One millilumen per sq. cm. (milliphot) is a practical derivative of the C.G.S. system. One foot-candle is one lumen per sq. ft., and is equal to 1.0764 milliphots.

859. (Deleted in the last revision of the Standardization Rules.)

860. Specific luminous radiation, the luminous flux-density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per sq. cm.
Defining equation:
Let E' be the specific luminous radiation.
Then, for surfaces obeying Lambert's cosine law of emission.

$$E' = \pi b_0$$

861.
862. } (Deleted in the last revision of the Standardization Rules.)

863. The lambert, the C.G.S. unit of brightness, the brightness of a perfectly diffusing surface radiating or reflecting one lumen per sq. cm. This is equivalent to the brightness of a perfectly diffusing surface having a coefficient of reflection equal to unity and illuminated by one phot.

864. For most purposes, the millilambert (0.001 lambert) is the preferable practical unit. A perfectly diffusing surface emitting one lumen per sq. ft. will have a brightness of 1.076 millilamberts.

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* This unit, which is used also by many other countries, is frequently referred to as the international candle.

† A uniform source of one candle emits 4π lumens.

recommended that in vertical distribution curves, angles of elevation shall e counted positively from the nadir as zero, to the zenith as 180 deg. In ne case of incandescent lamps, it is assumed that the vertical distribution urve is taken with the tip downward.

880. Mean horizontal candle-power of a lamp—the average candle-ower in the horizontal plane passing through the luminous center of the amp.

It is here assumed that the lamp (or other light source) is mounted in the sual manner, or, as in the case of an incandescent lamp, with its axis of ymmetry vertical.

881. Mean spherical candle-power of a lamp—the average candle-ower of a lamp in all directions in space. It is equal to the total luminous ux of the lamp, in lumens, divided by 4π.

882. Mean hemispherical candle-power of a lamp (upper or lower)—he average candle-power of a lamp in the hemisphere considered. It is qual to the total luminous flux emitted by the lamp, in that hemisphere, ivided by 2π.

883. Mean zonal candle-power of a lamp—the average candle-power f a lamp over the given zone. It is equal to the total luminous flux emitted y the lamp in that zone, divided by the solid angle of the zone.

884. Spherical reduction factor of a lamp—the ratio of the mean spher-cal to the mean horizontal candle-power of the lamp.*

885. Photometric tests in which the results are stated in candle-power hould be made at such a distance from the source of light that the latter nay be regarded as practically a point. Where tests are made in the neasurement of lamps with reflectors, the results should always be given as 'apparent candle-power" at the distance employed, which distance should lways be specifically stated.

886. The output of all illuminants should be expressed in lumens.

887. Illuminants should be rated upon a lumen basis instead of a andle-power basis.

888. The specific output of electric lamps should be stated in lumens er watt; and the specific output of illuminants depending upon combustion hould be stated in lumens per b.t.u. per hour. The use of the term "effi-iency" in this connection should be discouraged.

When auxiliary devices are necessarily employed in circuit with a lamp, he input should be taken to include both that in the lamp and that in the uxiliary devices. For example, the watts lost in the ballast resistance of an rc lamp are properly chargeable to the lamp.

889. The specific consumption of an electric lamp is its watt consump-ion per lumen. "Watts per candle" is a term used commercially in con-ection with electric incandescent lamps, and denotes watts per mean orizontal candle-power.

890. Life tests. Electric incandescent lamps of a given type may be ssumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life-test results, in order to be compared, nust be either conducted under, or reduced to, comparable conditions of peration.

891. In comparing different luminous sources, not only should their andle-power be compared, but also their relative form, brightness, distri-ution of illumination and character of light.

892. Lamp accessories. A reflector is an appliance, the chief use of which is to redirect the luminous flux of a lamp in a desired direction or irections.

893. A shade is an appliance, the chief use of which is to diminish or to nterrupt the flux of a lamp in certain directions, where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

894. A globe is an enclosing appliance of clear or diffusing materials, the chief use of which is either to protect the lamp, or to diffuse its light.

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* In case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

force of given frequency is the ratio of the conductance of the condenser or simple circuit at that frequency, to twice the capacity of the condenser at the same frequency.

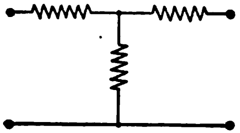
Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of given frequency is the ratio of the resistance of the coil or circuit at that frequency, to twice the inductance at the same frequency.

913. Equivalent circuit. An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network at the same frequency and under steady-state conditions.

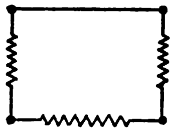
NOTE.—As ordinarily considered, the simple networks as defined are the electrical equivalents of complex networks only with respect to definite pairs of terminals, and only as to sending-end impedances and total attenuation. A further requirement is that the only connections between the pairs of terminals are those through the network itself.

914. "T" equivalent circuit. A "T" equivalent circuit is a triple-star or "Y" connection of three impedances externally equivalent to a complex network.

915. "U" equivalent circuit. A "U" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "Π" equivalent circuit.



Symbol for "T" equivalent circuit.



Symbol for "U" equivalent circuit.

IMPEDANCE

916. Mutual impedance. The mutual impedance, for alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative vector ratio of the electromotive force produced between either pair of terminals on open circuit, to the current flowing between the other pair of terminals.

917. Self impedance. The self impedance between a pair of terminals of a network, under any given condition, is the vector ratio of the electromotive force applied across the terminals to the current produced between them.

LINE CHARACTERISTICS

918. Characteristic impedance. The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

NOTE.—In telephone practice, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance, and (8) free impedance have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

919. Sending-end impedance. The sending-end impedance of a line is the vector ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

NOTE.—See note under "Characteristic Impedance." In case the line is of infinite length, of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

920. Propagation constant. The propagation constant per unit length of a uniform line, or per section of a line of periodic recurrent structure, is the natural logarithm of the vector ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite

957. Resonance. Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

958. Retardation coil. A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

Note.—In telephone and telegraph usage, the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

959. Skin effect. Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

960. Telephone receiver. A telephone receiver is an electrically operated device designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

961. Telephone transmitter. A telephone transmitter is a sound-wave or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond in form to the sound waves or vibrations actuating it.

962. The coefficient of coupling of a transformer. The coefficient of coupling of a transformer at a given frequency, is the vector ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

963. Repeating coil. A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

APPENDIX I

STANDARDS FOR RADIO COMMUNICATION

The following Par. **1000** to **1028** have been abstracted from the report of the Standardization Committee of the Institute of Radio Engineers, and are here included by permission as an Appendix, until further revised. For full particulars, see the I.R.E. Standardization Committee report.

1000. Acoustic resonance device. One which utilizes, in its operation, resonance to the audio frequency of the received signals.

1001. Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

1002. Atmospheric absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

1003. Audio frequencies. The frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

1004. Capacitive coupler. An apparatus which, by electric fields, joins portions of two radio frequency circuits, and which is used to transfer electrical energy between these circuits through the action of electric forces.

1005. Coefficient of coupling (inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

1006. Direct coupler. A coupler which magnetically joins two circuits having a common conductive portion.

1007. Counterpoise. A system of electrical conductors forming one portion of a radiating oscillator, the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

1008. A damped alternating current is an alternating current whose amplitude progressively diminishes.

1024. A standard resonance curve is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresponding wave length to the resonant wave length; the abscissas and ordinates having the same scale.

1025. (Deleted in the last revision of the Standardization Rules.)

1026. Sustained radiation consists of waves radiated from a conductor in which an alternating current flows.

1027. Tuning. The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

1028. A wave-meter is a radio frequency measuring instrument, calibrated to read wave lengths.

1029. (Deleted in the last revision of the Standardization Rules.)

1030. Decremeter. An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

1031. Attenuation, radio. The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

1032. Attenuation coefficient of (radio). The coefficient, which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

1033. Coupler. An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

APPENDIX II

ADDITIONAL STANDARDS FOR RAILWAY MOTORS

1100. In comparing projected motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

Table XX.—Approximate Losses in D-c. Railway Motors

Input in per cent. of that at nominal rating	Losses as per cent. of input	Input in per cent. of that at nominal rating	Losses as per cent. of input
100 or over	5.0	40	8.8
75	5.0	30	13.3
60	5.3	25	17.0
50	6.5		

1101. The core loss of railway motors is sometimes determined by separately exciting the field, and driving the armature of the motor to be tested, by a separate motor having known losses and noting the differences in losses between driving the motor light at various speeds and driving it with various field excitations.

1102. Selection of motor for specified service. The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(*a*) Weight of total number of cars in train (in tons of 2,000 lb.) exclusive of electrical equipment and load. (*b*) Average weight of load and durations of same, and maximum weight of load and durations of same. (*c*) Number of motor cars or locomotives in train, and number of trailer cars in train. (*d*) Diameter of driving wheels. (*e*) Weight on driving wheels, exclusive of electrical equipment. (*f*) Number of motors per motor car. (*g*) Voltage at train with power on the motors—average, maximum and minimum. (*h*) Rate of acceleration in miles per hr. per sec. (*i*) Rate of

1111. (*d*) The thermal capacity of a motor is approximately measured by he ratio of the electrical loss in kw. at its nominal (1-hr.) capacity, to he corresponding maximum observable temperature rise during a 1-hr. est starting at ambient temperature.

1112. (*e*) Consider any period of peak load and determine the electrical osses in kilowatt-hours during that period from the *electrical* efficiency curve. 'ind the excess of the above losses over the losses with r.m.s. service current nd equivalent voltage. The excess loss, divided by the coefficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and quivalent voltage, gives the total temperature rise. If the total temperaure rise in any such period exceeds the safe limit, the motor is not sufficiently owerful for the service.

1113. (*f*) If the temperature reached, due to the peak loads, does not exceed he safe limit, the motor may yet be unsuitable for the service, as the peak oads may cause excessive sparking and dangerous mechanical stresses. It s, therefore, necessary to compare the peak loads with the short-period verload capacity. If the peaks are also within the capacity of the motor, it nay be considered suitable for the given duty cycle.

APPENDIX III

BIBLIOGRAPHY OF LITERATURE RELATING TO ELECTRICAL ENGINEERING STANDARDIZATION

1114. Engineering Manual of the American Electric Railway Engineering Association.
Standardization Rules of the Electric Power Club.
Report of the Committee on Standardization of the Institute of Radio Engineers.
National Electric Code.
Meter Code—Code for Electricity Meters of the A. E. I. C. and N. E. L. A.
Standardization Reports of the Association of Railway Electrical Engineers.
Publications of American Society for Testing Materials.
The U. S. Bureau of Standards' various publications including Circulars 15, 22, 23, 29, 31, 34, and 37.
Reports of Committee on Nomenclature and Standards of Illuminating Engineering Society.
National Electric Light Association.
American Institute of Electrical Engineers, Specifications.

FOREIGN PUBLICATIONS

Publications of the Engineering Standards Committee of Great Britain.
Institution of Electrical Engineers, London, Wiring Rules and other publications.
Verband Deutscher Elektrotechniker.
British Electrical and Allied Manufacturers' Association, Reports.

INTERNATIONAL PUBLICATIONS

Publications of the International Electrotechnical Commission.

SECTION 25

GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS

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CONTENTS

(Numbers refer to Paragraphs)

GENERAL ENGINEERING ECONOMICS

CENTRAL STATION ECONOMICS

general subject. Those principles of economics which are especially useful to the engineer are covered or touched upon in the succeeding treatment.

4. Engineering economics may be defined as that field or body of knowledge which is concerned with the *economic* results of engineering, and the application of the principles and laws of economics to engineering undertakings. Since the purpose of all engineering is avowedly utilitarian, it seems unnecessary to offer proof that engineering should invariably justify itself upon economic grounds. Obviously no contemplated engineering project can be reasonably sure of success, however sound it may be upon purely technical grounds, until it has been most carefully considered on economic grounds and the conclusion reached that barring unforeseen casualties it will become a paying and profitable enterprise.

5. The fundamental elements of engineering economics may be grouped into four broad classes, with certain subdivisions, as indicated below. This classification is here presented for the first time and hence it should be regarded as tentative. The main thought, however, is to make as clear as possible the principal economic considerations in engineering work as they exist to-day.

The Elements of Engineering Economics	Cost Analysis	Principles of accountancy Capital and operating charges Total annual charges Costs per unit Fixed and variable costs Cost balance
	Social-Economic Investigations	Traffic analysis Statistics of consumption Probable future development
	Valuation of Property	Purchase or sale Rate making Taxation Issuance of securities Adjustment of book values
	Rate Making	Public utilities Common carriers

The skeleton definition of engineering economics given above should be interpreted in a somewhat liberal sense; the predominant idea to be emphasized is the unavoidable contact of the modern engineer with countless economic questions involving cost, price and value, and those social-economic questions connected with the operation and development of engineering projects directly affecting the public or the public welfare.

The subsequent presentation of the subject is not offered in the sense that it is complete or exhaustive; on the contrary, it is somewhat fragmentary, but has been prepared with the object of making it as useful as possible.

VALUE, PRICE AND COST

6. Value defined in the economic sense is power in exchange, or purchasing power. Ely states that value in the generally accepted sense is exchange value, or objective value as distinguished from subjective value. The measure of importance attached to a commodity or article by some one individual is subjective value, and obviously may differ in extreme degree from the value placed upon the same commodity or article by some other person. Hadley states that value is essentially an ethical term and therefore there may be as many theories of value as there are views of business ethics; he also points out that while the term value may be used in the sense of utility, it ordinarily means the proper and legitimate price, or an estimate of what the price ought to be. Walker drew a very careful distinction between value and utility, the latter being always present where there is value, whereas utility alone does not invariably imply value in the economic sense. Utility does not imply value in the economic sense until it is coupled with desire. Among other elements which go to comprise economic value, the factors of time, place, cost and demand are of major importance. Therefore in speaking of value it is essential to employ such qualifying adjectives or phrases as will serve to make clear the particular kind of value in mind. The term value should never be confused with the terms price or cost, since the several meanings are distinctly different.

n the market. When the price increases, the supply will increase; and conversely, when the price drops, the supply will fall. This relation is expressed by the supply curve in Fig. 1, which occupies different positions for different commodities.

In a stable market the supply will equal the demand, at the normal price. If the price is forced upward, the demand will fall and the supply will increase; the attendant reaction will naturally tend to restore the normal conditions. If the price is manipulated downward the demand will increase, but the supply will diminish; and the attendant natural reaction is again such as to tend toward the restoration of normal conditions.

Should there come about a permanent condition in the market, resulting in greater normal demand, the position of the demand curve will shift in such manner that the demand at the former normal price will be greater than before. The result will be a higher normal price at increased normal quantity or sales. In like manner, a permanent reduction in demand will result in a lower normal price, at diminished normal quantity. A permanent change in the supply, such as might result from a decrease in the sources of raw materials, or, on the other hand, a discovery of new sources of raw materials, will likewise cause the supply curve to shift to a new position.

Generally speaking, a condition of gradually rising normal demand is closely succeeded by a rise in prices, until the demand reaches an even level. A falling demand is similarly followed by diminishing prices, until the demand strikes bottom. Such phenomena will be observed quite generally in studying the prices of any article through a series of years.

CAPITAL, RENT AND INTEREST

12. Wealth in the economic sense may be defined as all property which possesses money value or economic utility. In the broadest possible sense it means an abundance of things which are objects of human desire, but especially an abundance of worldly estate or riches, such as land, goods, money and securities.

13. Property is defined by Webster as follows: The exclusive right to possess, enjoy, and dispose of, a thing; ownership; in a broad sense, any valuable right or interest considered primarily as a source or element of wealth; practically all valuable rights except, generally, those involved in public or family relations; various incorporeal rights, patents, copyrights, rights of action, etc.; anything, or those things collectively, in or to which a man has a right protected by law. Property is commonly regarded as comprising two kinds: real property, or land, buildings, fixed plant and improvements in connection therewith; personal property, or furniture, tools, implements, live stock, money, securities, etc. There is also a more modern distinction, as between tangible and intangible property: the former includes real and personal property which exists in tangible physical form; intangible property comprises rights, franchises, good will, going-concern value, patents, copyrights and contracts.

14. Capital may be defined in the economic sense as a stock of accumulated wealth; or the amount of property owned by an individual or a corporation at a specified time, in distinction from the income received during a given period. Capital may be in the form of money, or some readily salable article for which there is a constant and general demand, in which case it is said to be liquid capital; or it may be in the form of property which is not readily salable on sudden notice, such as land, buildings, or manufacturing plant, in which case it is termed invested capital. In other words, liquid capital can be readily and quickly converted into money if it is not already such, whereas invested capital usually cannot.

15. Money is a common medium of exchange, issued by duly constituted authorities, and, as such, is a commodity the same as any other article which passes frequently from hand to hand in trade or exchange. Therefore, being a commodity, the price of money is regulated by the law of supply and demand. Thus when money is scarce and the demand normal, or heavy, it will command a premium; conversely, if money is overplentiful and the demand low, it can be had at a discount. While true in theory, such fluctuations in the price of money from its face or par value, are disturbing to trade and therefore undesirable; one of the fundamental purposes of our present currency system is to provide elasticity in the supply of money, in order suitably to meet changes in the demand for it and avoid both premiums and

20. Interest rates vary to a considerable extent, depending upon the class of investment. U. S. Government bonds pay different rates, from 2 per cent. to 4 per cent.; savings-banks deposits, from 3 to 4 per cent.; checking deposits in banks, above a certain minimum amount, frequently draw 2 per cent. on daily balances; certificates of bank deposit, or time deposits, 3 per cent.; railroad and public utility bonds, from 3.5 to 6 per cent.; industrial bonds, 5 to 7 per cent.; short-term notes of railroads and public utilities, 5 to 6 per cent.; real-estate mortgages, 5 to 6 per cent.; railroad and public utility stocks; whatever may be earned, but seldom in excess of 8 per cent.

21. Compound interest is based upon the computation of simple interest for stated periods and the addition of the interest to the principal at the end of each period, thus enlarging the principal for each consecutive period, progressively. Let

P = the principal in dollars.

n = the number of years for which the compound interest is to be computed.

t = the ratio of 1 year to the period during which simple interest is computed; thus if compounded annually, $t = 1$ and if compounded semi-annually, $t = 0.5$.

r = the annual percentage rate of interest expressed as a decimal; thus if the rate is 6 per cent., $r = 0.06$.

S = the amount of P dollars at compound interest for n years, compounded at intervals of t years, at the annual rate r

The formula for calculating S is as follows:

$$S = P\,(1+tr)^{\frac{n}{t}} \quad \text{(dollars)} \quad (1)$$

This can also be expressed in another form

$$\log S = \log P + \frac{n}{t}\log(1+tr) \quad (2)$$

The latter form indicates the manner of calculating problems; in most cases the interest is compounded annually, which makes $t = 1$.

22. Present worth of a future lump payment. If the sum of S dollars is due at the end of n years, the amount which would have to be set aside at the present date, compounded at intervals of t years at the annual interest rate r (decimally expressed), is expressed by the following formula:

$$P = \frac{S}{(1+tr)^{\frac{n}{t}}} \quad \text{(dollars)} \quad (3)$$

This can also be expressed in a form suitable for numerical calculation:

$$\log P = \log S - \frac{n}{t}\log(1+tr) \quad (4)$$

The symbols used have the same significance as stated in Par. 21.

23. Annuities. An annuity is a fixed sum of money payable at equal intervals of time (see Wells, W. "College Algebra;" chapter on "Compound Interest and Annuities"). In most discussions of the subject it is assumed that the payments are made annually and the interest compounded annually. When an annuity is defined as beginning at a certain date, the first payment will fall due 1 year from that date.

24. The present worth of an annuity of A dollars per annum, commencing at once and continuing for n years, allowing interest compounded annually at the annual rate r (decimally expressed), may be calculated from the following formula:

$$P = \frac{A}{r}\left[\frac{(1+r)^n - 1}{(1+r)^n}\right] \quad \text{(dollars)} \quad (5)$$

The present worth of a perpetual annuity, commencing at once, is equal to A/r.

The present worth of an annuity to commence after m years and then continue for n years, is expressed by the formula,

$$P = \frac{A[(1+r)^n - 1]}{r(1+r)^{m+n}} \quad \text{(dollars)} \quad (6)$$

(2) expenditures for salaries, wages, rents, taxes, insurance, depreciation, repairs, supplies, etc., all constituting charges to operation, or **operating expenses.** The distinction between these two classes of costs is fundamental in its importance.

28. Cost comparisons are of two kinds: (1) comparisons of capital costs, or construction costs; (2) comparisons of operating costs. When comparing one plant with another, as to overall results, it is necessary to reduce all costs to one basis; this is most frequently done by comparing the total annual charges (Par. 29), but in some instances the operating expenses (excluding interest and profits) are capitalized at the prevailing interest rate and added to the capital or investment. The latter method is rarely used.

29. The total annual charges may be defined as the sum of all operating expenses (Par. 27) plus interest and profit on the investment or capital; or the total charge for operation. The total annual charges may be classified as shown below.

- Total annual charges for operation
  - Investment costs
    - Taxes
    - Insurance
    - Depreciation
    - Maintenance
    - Interest
    - Profits
  - Production costs
    - Traffic
    - Transportation
    - Operating
    - Commercial
    - General

These charges are defined in the succeeding paragraphs.

30. Taxes constitute a charge based on the assessed value of the property and require no explanation. This charge varies from about 1 per cent. to 2 per cent. per annum on the capital invested in physical or tangible property.

31. Insurance can be defined as a cooperative method of distributing the burden of losses or casualties. The annual assessments or rates are determined by actuaries who apply the theory of probability to the problem of determining the probable risk of loss or damage, based upon the statistics of a large number of past losses. There are many different kinds of insurance, such as life, health, fire, boiler, accident, marine, employers' liability, automobile, plate glass, burglar, hurricane, cyclone, etc. The insurance rate is usually based on a percentage of the investment in insured property, or face value of the total risk, per unit of time or per annum.

32. Depreciation is fully covered in another portion of this section; see Par. 41, *et seq.* It is quite as much an expense of operation as the cost of labor, supplies and other items which are currently paid by the day, week or month.

33. Maintenance defined in its broadest sense means upkeep of all kinds, including both repairs and renewals, but in the technical sense in which it is usually employed it means repairs exclusively. The repair charge is frequently reduced to terms of a percentage of the capital invested in plant, or the original cost of the plant.

34. Interest has been defined at length in Par. 17 to 20, and need not be further considered here.

35. Profits represent a return on the investment over and above the normal rate of interest. For instance, a return of 8 per cent. has been held reasonable in the case of certain public utilities, on the theory that in addition to interest at a rate, say, of 6 per cent., the investor is entitled to a profit of 2 per cent. as an inducement to himself and others to engage in the particular class of business in question. The term profit is often employed, however, in the sense of including true interest in addition to true profit.

36. Investment costs are those, as the name implies, which bear some direct ratio or proportion to the investment. They are defined in Par. 29 to 35, above. In the case of maintenance expense, there is probably some portion of it, but not all, which is more nearly a production expense than an investment expense; this seems to be obviously true, because of the fact th-

43. The two classes of depreciation usually recognized are physical depreciation and functional depreciation. These are defined in the next succeeding paragraphs.

44. Physical depreciation is the result of age, wear and tear, corrosion, and decay. This form of depreciation is constantly in progress; the rate of its progress depends upon the conditions of service or use, protection from ravaging elements, and the degree of care exercised in making prompt repairs when necessary. This rate of course varies greatly with different forms of machinery, apparatus, plant, etc.

45. Functional depreciation is the result of failure to function properly, in consequence of lack of adaptation to the service demanded. It has two principal causes, inadequacy and obsolescence.

46. Inadequacy is the result of unexpected or premature growth in the demand for service, requiring enlarged capacity which can be provided only by removing the old plant or equipment to make way for new before physical depreciation has run its full course. Depreciation resulting from this cause usually makes it imperative to replace equipment or plant sooner than otherwise, but the displaced equipment is sometimes useful for a further period if re-installed in a new location or in some other plant where its capacity is suited to the demands for service. One of the functions of sound engineering, of course, is to study the probable future demands and so arrange a plant or installation that new units can be provided as occasion may demand, without disturbing the units already in operation. In other words, part of the inherent economy in efficient engineering consists in securing if possible the maximum physical life from any piece of plant or apparatus, unless, of course, it appears conclusively that the total annual charges (Par. **29**) will be actually lessened by deviating to some other plan or policy. It is conceivable, for instance, that the maximum physical life will exceed the economical life, but this is predicated upon the assumption of a progressively diminishing efficiency with increasing age, attended by a marked increase in the total annual charges per unit of production or output before approaching the end of the maximum physical life.

47. Obsolescence is that form of functional depreciation which results from new inventions or radical improvements in the art, causing a set-back of present methods or machinery in the scale of efficiency, or creating new demands which it was not possible to serve under the past state of the art. Whether all forms of obsolescence, or allowances for their probable occurrence and effect, should be included in depreciation is perhaps an open question. Many advances in the art relate wholly to improvements in efficiency or reductions in the cost of production. When comparing a new and improved machine with one of obsolete type but not yet worn out in the physical sense, the question whether the new shall immediately supplant the old is usually regulated by the consideration whether the saving in total annual charges (Par. **29**) resulting from the substitution will extinguish the remaining service value of the old machine within a reasonable period, or much sooner than the expiration of the probable life period of the new machine. Thus there are certain types of cases in which obsolescence is not a proper charge against depreciation, but should be amortized (Par. **68**) through the application of those annual charges which represent the savings in operation secured by discarding obsolete machinery or plant. Cases of the latter type are probably typical, as a rule, of the greater number of advances in the art; whereas that type of obsolescence which makes it almost imperative to discard the old for the new, springs into existence with the relatively infrequent advances in the arts which are fundamental or revolutionary in character, as distinguished from those advances which can be classed as mere improvements of things which are already old in the arts.

48. The insurance element in depreciation. It is almost self-evident that any provision in depreciation for probable future inadequacy and obsolescence partakes of the nature of insurance to cover a risk. In this sense, therefore, provisions for future inadequacy and obsolescence are, in reality, insurance charges, and not depreciation in the technical sense—at least not in the physical sense. Such provisions should be based, therefore, upon the law of probability applied to the statistics of past occurrences with respect to the abandonment of plant or machinery strictly on account of inadequacy and obsolescence. This mode of procedure will develop the monetary

60. The annual depreciation charge (d) is the ratio of the number of dollars which must be set aside every year and placed in the depreciation reserve, to the original cost or investment; it is usually expressed as a percentage. The yearly (or monthly) accretions to the **depreciation reserve** are calculated in such manner as to produce, at the end of the life expectancy, a total fund equal to the wearing value. The annual sum (D), in dollars, charged to expense and credited to the depreciation reserve, can then be expressed by $D = dI$.

61. Segregation of plant into classes, for the purpose of computing the annual depreciation charge, is very essential for the reason that different kinds and types of plant have different life expectancies, and therefore depreciate at different rates. After the segregation process is completed and the annual depreciation is determined for each class or type, the sum of the annual charges for all the classes, in dollars, will give the total charge in dollars; the latter sum divided by the original cost or physical value of the whole plant will give the **composite depreciation charge** for the physical property as a whole.

62. Theories of depreciation.* There is no agreement at present concerning the question as to how, or in what manner, depreciation accrues from year to year during the life period. The discussion centres for the most part, in this country, around two well-known theories, one known as the straight-line method and the other as the sinking-fund method. There is also the method of diminishing values or reducing balances, and the annuity method. The first two methods are presented briefly in the following paragraphs.

63. The straight-line method is based on the assumption that depreciation accrues according to a straight-line law, in the simple ratio of age to life, as shown in Fig. 2. The formulas expressing the several relationships among the foregoing quantities or values (Par. 50 to 60) are as follows:

$$\left.\begin{array}{llll} d = \dfrac{W}{lI} & \text{(per cent.);} & A = adI & \text{(dollars)} \\ p = 1 - \dfrac{a}{l} = 1 - \dfrac{A}{W} & \text{(per cent.);} & P = I(1 - ad) & \text{(dollars)} \end{array}\right\} \quad (12)$$

The values of W and I are expressed in dollars and a and l in years. This method, as ordinarily applied, depends in no way upon the amount or rate of interest earned by the depreciation reserves, pending their use for renewals. The straight-line method of computing depreciation is in wide use and has received the approval of several Public Utility Commissions.

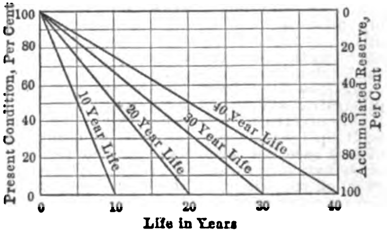

Fig. 2.—Depreciation diagram; straight-line theory.

64. The sinking-fund method is based on the assumption that depreciation accrues according to the law which expresses the accumulation of a sinking fund at compound interest (Par. 25), as shown in Fig. 3. The formulas for use in this case are as follows:

$$\left.\begin{array}{ll} d = \dfrac{W}{I}\left[\dfrac{r}{(1+r)^l - 1}\right] & \text{(per cent.)} \\ p = \dfrac{(1+r)^l - (1+r)^a}{(1+r)^l - 1} & \text{(per cent.)} \\ A = W(1-p) & \text{(dollars)} \\ P = I - A = pW - R + S & \text{(dollars)} \end{array}\right\} \quad (13)$$

* Erickson, H. "Depreciation;" address before Central Water Works Association, Detroit, Mich., Sept. 25, 1912. Also see Bibliography, Par. 88.

The values of W and I are expressed in dollars, a and l in years, anc the annual rate of interest on the fund, decimally expressed. This me requires that the depreciation reserves be left undisturbed for the e period of life expectancy, in order that the full amount or sum require extinguish the wearing value may be realized; otherwise the sums rece as interest will be impaired. The sinking-fund method has been empl by the Railroad Commission of Wisconsin: also see Floy, H., "Valuatio Public Utility Properties;" New York, 1912; Chap. VIII.

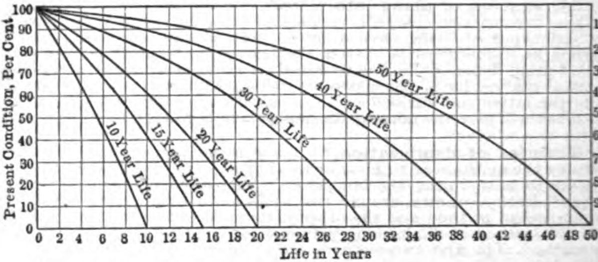

FIG. 3.—Depreciation curves; based on 5 per cent. sinking fund.

65. The method of reducing balances is rarely used in this coun It consists briefly in reducing the book value or worth of the plant each by a fixed percentage. If this figure, for instance, is 10 per cent., the v at the commencement of the second year will be 90 per cent.; the third y 81 per cent.; the fourth year, 72.9 per cent., etc. This method is interes theoretically, but is not regarded as very practical.

66. Reserves for accrued depreciation. Expert opinions differ a whether it is necessary to lay aside depreciation reserves for future use. the case of a new property, just starting operations, there is no doubt it is very essential to lay aside something for accruing depreciation, u low finances make it absolutely impossible; unquestionably the time arrive, at some future date, when replacements in this plant become ne sary and the current revenues will be inadequate to meet the outlay, so the wisdom of setting up a reserve is almost self-evident. The case just c represents one extreme, in the range of possible or probable cases; the illustration will be at the opposite extreme. Conceive a very large prop highly diversified as to different kinds and types of plant or equipment, built up by piecemeal growth extending over a very long series of y in this case the renewals from year to year probably will not vary to great extent in number and cost, but perhaps increase slightly from ye year, on the whole, as the property increases in total bulk or size. T are many properties which are intermediate between these two extre and a reserve for accrued depreciation is therefore a very wise, if not a ne sary provision; at the same time, this is not the universally accepted vi

From another standpoint, however, there is a very strong reason creating depreciation reserves. Quite aside from the question as to whe a reserve is necessary in order to distribute the cost of renewals unifor from year to year in the expenses of operation, it is unquestionably true plants of practically every kind depreciate with age; that is to say, depre tion is always going on, beyond any power to prevent it. This being s becomes evident that the present worth of almost every kind of plant c mences to decrease from the first day it enters service; therefore it is esse from the standpoint of the stockholder or investor, to protect the orig investment by creating a reserve to offset the accrued depreciation. the depreciation which accrues annually is offset by charging an equal to expenses and crediting it to the reserve, each year, and if the cost o newals as they occur is charged to the reserve, the whole matter of protec the investment will take care of itself, in theory. In other words, under plan, the sum of the present worth of the property plus the total reserv hand, at any date, will always equal the original investment; this wi true, whether the property grows rapidly, or slowly, and without regard to the size of the expenditures for renewals, provided only that the life expectancy of each increment or fragment of the property is realized with substantial accuracy.

67. Investment of depreciation reserves. The proper disposition of depreciation reserves, pending their use for the purpose originally intended, is a subject which has received much discussion without evolving any hard-and-fast rule that meets with general approval. If the funds are not invested in some form of security, or in a business enterprise, they can hardly draw a rate of interest in excess of the usual rates on time deposits, or say 3 per cent. per annum. If invested in conservative bonds, the rate may be as high as 5 per cent. If the property is one which earns more than 5 per cent., there will be some advantage in investing the depreciation reserve, or some portion of it, in extensions of the plant. The last plan also possesses the advantage of reducing the requirements for fresh capital in extending the business; indeed, in some cases it has become the policy to invest the whole depreciation reserve in this manner.

When the depreciation reserve is set up on the basis that the total reserve should always equal the accrued depreciation on the entire property, and the entire reserve is invested in the property, there is one consequence which it is important not to overlook; namely, the present worth of the property will always be equal, in theory, to the total investment in it by the stockholders or owners, assuming that the property is free of debt of any kind. The propriety of investing the whole depreciation reserve in this manner is probably open to some question: in new plants just commencing operations, this procedure may possibly lead to financial embarrassment some years later, when extensive renewals become necessary during some particular year, and the necessary cash is not available except through the sale of new securities; in properties, however, of a highly diversified character as to types and kinds of plant, built up by piecemeal growth through a long series of years, the funds required for renewals during any particular year are not likely to exceed the total sum set aside that year for accrued depreciation, and therefore this plan is not very likely to lead to difficulties in such cases. Between these extremes, nevertheless, there are many intermediate situations, and the ruling local conditions in each instance must largely determine the best course to pursue.

In the case of public utilities, or quasi-public corporations, the depreciation reserve is virtually a trust fund created by public contribution through the assessments or charges for service, and the income from the fund is properly returnable to the fund and belongs thereto; but whether this income is treated as a credit against current charges (expense) for accrued depreciation, or whether it is treated as part of the total corporate income, makes no difference in fixing the amount of the reasonable return on the investment.

Those who are particularly interested in this question should read the literature which is to be found in the transactions of engineering societies, the technical press, the literature of accountancy and the authorities cited in the Bibliography, Par. **86**.

68. Amortization is a term used in finance and accounting in the sense of extinguishment; for example, to amortize a debt by means of a sinking fund (Par. **25**), or to amortize the principal of an issue of bonds, or an indebtedness represented by an issue of notes. The term should not be confused with depreciation. It can be correctly said, however, that the annual sums set aside for depreciation, and placed in a reserve fund, are for the purpose of amortizing the wearing value. Amortization means merely the extinguishment of a parcel of value or money equivalent, by means of periodical charges spread over a period of time.

69. Depreciation accounting is too extended a subject to explain briefly. In general, the periodical sums necessary to cover depreciation are charged to operating expenses and concurrently credited to the reserve for accrued depreciation. When plant is displaced, its original cost is credited to the fixed capital account and charged to the reserve; the reserve is also charged with the cost of removal and credited with the salvage, the latter being concurrently charged to supplies. The new plant, which displaces the old, is charged to the fixed capital account, under the appropriate sub-accounts. Some authorities hold that accrued depreciation should be

75. Application of the law of probability. Experience shows that demand and consumption fluctuate to some extent, under similar conditions as to time, locality, weather, etc., even when the periods compared are separated by no more than a day or a week intervening. Given a sufficient number of observations on demand or consumption, taken under precisely similar conditions but on successive occasions, it becomes quite evident that the mathematical law of probability may be useful in computing the most probable demand or consumption, and also in computing the probability that the demand or consumption will deviate by a specified amount from the most probable value. The theory of probability constitutes the entire foundation for the discussion of precision of measurements (Sec. 3), and has been applied in a number of other connections in engineering, among them being the analysis of telephone traffic. It also forms the whole basis, of course, of every form of insurance.

VALUATION AND RATE MAKING

76. General. Valuation and rate making have become so important that at least five important and authoritative works dealing with this field have been published since 1911. Only the barest outlines of the subject can be given here, with references in the succeeding paragraphs and the Bibliography to some of the principal authorities. Central-station valuation and rate making are treated at some length in Par. **128 to 158**, which should also be consulted for a more detailed exposition of the fundamentals of the subject.

77. Standards of value by which to measure the fair value of a public utility have been the subject of extended discussion and litigation, without establishing up to this time any well-defined conclusions except of the broadest character. Although the matter is still in its formative phases, the general principle that investors in public utility enterprises are entitled to fair and reasonable treatment at the hands of the public is well recognized. An excellent discussion of the present status of the matter will be found in Dr. R. H. Whitten's "Valuation of Public Service Corporations;" Supplement, 1914, Chap. II.

The courts have held that original cost, estimated present reproduction cost, and outstanding securities issued against the property, are all competent evidence on the question of value; but the conclusion in every case must be tempered by a consideration of all the facts and circumstances. This is very well expressed by the decision in the Minnesota Rate Cases (230 U. S. 352, 33 Sup. Ct. 729, June 9, 1913), "It is not a matter of formulas, but there must be a reasonable judgment having its basis in a proper consideration of all relevant facts."

78. Valuations under the cost-of-reproduction theory resolve themselves into two main questions: (1) What is the value of the tangible property; (2) what is the value of the intangible property?

79. Tangible property consists of physical plant, such as right-of-way, land, buildings, machinery, distribution system, meters, etc., organization and engineering expense, interest and taxes during construction; supplies and materials on hand, and working capital.

80. Intangible property consists of franchises, licenses, rights, contracts, good will and going value. The modern rule is to allow nothing for **franchise value** unless something was or is actually paid for it, or unless some value for it has been capitalized in the past with public approval. Under monopoly, **good will** has been held to have no value for rate-making purposes. **Going value**, or going-concern value, has been extensively discussed by engineers and commissions, but no recognized or authoritative rule is yet in existence; an excellent summary of the theories of going value, and the tendencies of courts and commissions with respect thereto, is contained in Dr. Whitten's two volumes on "Regulation of Public Service Corporations." See also Par. **156**.

81. Valuation of tangible property under the cost-of-reproduction theory involves two separate steps or procedures: (1) The preparations of an **inventory** of the property; (2) the determination of **unit costs** and their application to the quantities in the inventory, for the purpose of computing the total reproduction cost-value, new or undepreciated. The unit costs should be those, if possible, determined from the actual current construction costs shown by the corporate books, unless known to be objectionable for

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Dunham, H. P.—"The Business of Insurance." 1912.
Leake, P. D.—"Depreciation and Wasting Assets." 1912.
Matheson, E.—"Depreciation of Factories." 1910.
Also see the Transactions of the national engineering societies; files of the technical and engineering periodicals; files of accounting periodicals; other sections of this book, including Sec. 10, 11, 12 and 13.

CENTRAL STATION ECONOMICS

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CENTRAL-STATION FACTORS RELATING TO UTILIZATION OF INVESTMENT AND APPARATUS

89. Definition. In all engineering study of the economics of central stations for the supply of electric light and power for various purposes in a community, it is convenient and customary to use certain factors or unit values derived from other similar plants. The factors given here apply to electric generating and distribution systems only and do not include other utilities such as electric railways, water works, gas works, ice plants and steam heating systems sometimes operated in connection with electric light and power plants and included in their reports.

90. Cost of plant per kw. of yearly maximum load. Since the cost of a plant depends so much upon the maximum load it must carry, this is an important factor as showing the amount of money actually invested to create a plant sufficient to carry a given maximum load. This cost usually varies between $200 and $500 per kw. The average is probably somewhere between $250 and $300 per kw. Of this 50 to 75 per cent. is usually in the distribution systems leaving 25 to 50 per cent. for the power plant. The cost of the distribution system part will be highest with underground distribution or where the consumers are scattered, and will be the least with overhead construction or in those localities where the density of consumption per mile of distribution mains is greatest. The cost of steam power plants will be from $55 per kw. up to $150. The lower figure is for the largest steam-turbine stations in locations where land is cheap and there are no expensive preparations of the site. The higher figure is for reciprocating-engine plants on expensive land, with all refinements, so situated that the labor cost of construction is high. If a plant has a very large reserve amount of apparatus in excess of that required to carry the maximum load of the year, this first cost per kw. of peak load will, of course, be higher than if there is little or no reserve.

91. Cost of plant per kw. of maximum capacity. This item is similar to the foregoing item except that it is based on the maximum capacity of the plant rather than the maximum load on the plant. It will consequently vary within about the same limits as the previous item. In general it is not as useful a unit of comparison as the previous item because it is more likely to be affected by increase of the power plant from time to time in excess of the actual maximum demand.

92. Gross annual earnings per kw. of yearly maximum load. These usually are between the limits of $60 and $140. They are most frequently between $80 and $100. This factor indicates whether the gross is now common in the smaller plants having a moderate amount of power business. In some manufacturing cities load factors over 50 per cent. have sometimes been attained, but such cases are rare. A combination of lighting, power, and railway loads in a large city gives a load factor between 40 and 45 per cent. The load factor indicates the percentage of time which the plant apparatus is lying idle, and it is the constant aim of central station companies to increase the load factor and reduce the idle time, because interest must be paid on the investment whether the apparatus is in use or not.

CENTRAL STATION FACTORS RELATING TO TERRITORY SERVED BY SYSTEM

101. Gross yearly earnings per capita of population. This factor varies through a large range. Ten dollars per capita may be considered near the maximum at the present writing. This factor is usually higher in the Western part of the United States than in the Eastern. Some engineers in making preliminary estimates on the possibilities of future gross earnings, adopt a step-by-step schedule which increases from East to West. Gross earnings of $6 to $7 per capita may now be considered reasonably attainable under ordinary conditions in most towns on the western side of the Mississippi Valley.

102. Cost of plant per capita. This is a factor used by some engineers to indicate whether an excessive amount of plant has been put in for the population to be served. Aside from this it is evidently dependent upon the gross earnings per capita and the degree to which the territory has been developed for electric service. An investment of $40 per capita in an electric plant might be justified if the gross earnings were $10 per capita. In practice we find this varying from $3 to $35 per capita.

103. Watts maximum load per capita. This factor is also an indication of the extent to which the territory has been developed. If excessive in proportion to gross earnings per capita, it would indicate bad management. It usually ranges from 30 to 100.

104. Population per consumer. This will range from 5 to an indefinite figure. Of course 5 represents near saturation. Such a condition can only be attained in a prosperous country or suburban town.

105. Gross earnings per consumer. This factor when taken in connection with a knowledge of the territory served may help to indicate whether the large manufacturing power business or the small residential business has been neglected. This factor may vary between $18 and $159, but its most usual range is between $40 and $70.

106. Demand factor. This is the actual maximum demand divided by the connected load, expressed in per cent. It may be applied to a system, a group of consumers or any individual consumer. It is useful in determining the apparatus which must be provided and the rates which can be made for serving any given class of business. These factors can be determined only by actual measurement for different classes of customers with maximum-demand meters.

For example, suppose we find by inserting maximum-demand meters in the services supplying a number of drug-stores that the total maximum demand made by these stores during a year is 75 per cent. of what it would have been had the total connected load been turned on by each consumer at some time during the year. We would then say that the demand factor of these drug-store consumers is 75 per cent. In figuring on the amount of apparatus needed to serve other drug-stores we would multiply the connected load by the demand factor which would give the probable maximum demand.

Mr. E. W. Lloyd in a paper entitled "Compilation of Load Factors," before the National Electric Light Association in 1909, gave the results of the experience of the Commonwealth Edison Co. of Chicago with a large number of consumers equipped with maximum-demand meters. The demand factors of some of the most important classes of small and medium lighting consumers given by Mr. Lloyd are shown by the table in Par. **107,** where the classification is according to business, without regard to the size of the installation. Some of the more important demand factors of power consumers taken from the same paper are also given in Par. **109,** where the classification is by size of installation. The load and demand factors of a number of larger consumers using both power and light as given by Mr. Lloyd appear in Par. **108.**

108. Demand and load factors of large Chicago consumers; combined power and light
(E. W. Lloyd)

Kind of business	Load factor 8,760-hr. year, per cent.	Demand factor (ratio of actual max. to connected load, per cent.)
Butter and creamery	20	60
Breweries	45	60
Brass and iron beds	20	60
Biscuit manufacturers	35	55
Boots and shoes	25	65
Brass manufacturing	28	50
Boiler shops	18	45
Can manufacturers	30	70
Candy manufacturers	18	45
Clothing manufacturers	15	55
Clubs (large)	40	85
Department stores (large)	30	55
Electrical manufacturing	25	55
Express companies	40	60
Electroplating	25	75
Engraving and printing	19	60
Fertiliser manufacturing	75	40
Furniture manufacturing	28	65
Foundries	15	75
Forge shops	30	49
Grain elevators	10	75
Glove manufacturing	25	55
Grocers (wholesale)	20	55
Hotels (small)	35	50
Hotels (large)	50	40
Ice-cream manufacturing	45	75
Jewelry manufacturing	18	50
Laundries	25	70
Machine shops	26	55
Newspapers	20	75
Packing houses	30	75
Paint, lead and ink manufacturers	23	45
Paper-box manufacturers	25	50
Plumbing and pipe fitting	26	55
Post offices	50	30
Power buildings	27	40
Refrigeration	50	90
Railroad depots	50	50
Pneumatic tube	50	90
Soap manufacturers	25	60
Seed cleaners	25	55
Screw manufacturers	30	75
Spice mills	20	55
Saw manufacturers	30	55
Structural steel	22	40
Sheet-metal manufacturers	18	70
Stone cutters	17	55
Twine mills	30	60
Theatres	16	60
Large restaurants	50	60
Small restaurants	30	70
Woolen mills	27	80
Wood-working	28	65
Textile mills	20	65

112. Demand factors compiled by Wisconsin commission from companies using Wright demand meters

	Per cent.		Per cent.
Stores	40 to 100	Laundries	60 to 75
Offices	57 to 87	Livery stables	52 to 58
Saloons	62 to 92	Lodge and dance halls	68
Restaurants	52 to 62	Depots	75 to 95
Factories	53 to 56	Theatres	49 to 89
Churches	56 to 85	Shops	55
Hotels	28	Machine shops	37 to 54
Clubs	28	Blacksmith shops	66
Schools	37 to 52	County and federal building	33 to 31

113. Diversity factor, as here used is the maximum simultaneous demand of a number of individual services for a specified period, such as 1 hr., divided by the sum of the individual maximum demands of these services for the same period, this result being expressed in per cent. For example, suppose two consumers each have a maximum demand of 50 kw. The sum of their maximum demands would therefore be 100 kw. Suppose, however, these maximum demands do not occur at the same time so that a maximum demand indicator connected to supply both services would indicate a maximum of only 75 kw. The diversity factor would then be 75 kw. divided by 100 kw. or 75 per cent. In other words, the actual maximum demand on a feeder or power plant supplying these two consumers would be only 75 per cent. of their combined maximum demands.

If the consumer's maximum demand is known and the diversity factor for that class of business is also known, the maximum effective demand of the consumer at a given point (such as transformers or power station) is determined by multiplying the consumer's actual maximum demand by the diversity factor (expressed in per cent.) between the consumer and the point under consideration.

The diversity factor is a most important element in central station electric supply; in fact it is one of the economic foundation stones upon which the central station industry is built. But for the fact that the various combined maximum demands of various consumers do not coincide, greater plant capacity would be required to serve them and rates for service would necessarily be high, because of the higher investment required. One hundred per cent. less the diversity factor represents the percentage of apparatus which can be dispensed with by combining the supply of the consumers onto one system.

Thorough study of diversity factors can be made only where maximum-demand meters are used for each consumer. Mr. H. B. Gear, distribution engineer of the Chicago central-station system has reported the results of such investigations at various times as indicated in the Bibliography at the end of this section. The accompanying table gives a summary of Mr. Gear's figures on diversity factors for lighting and power loads (Par. 115).

114. Classification of diversity factor. In an electric light and power distribution system there is first a diversity factor between the individual consumers and the transformer serving a group of such consumers because the maximum demands of the individual consumers do not come at the same time. There is next a diversity factor between different transformers and their feeders for similar reasons. Going back another step there is a diversity factor between various feeders entering a power-house or substation and the bus bars and on large systems there is a diversity factor between various substations, and the power station bus bars.

Par. 115 gives the diversity factor for each step from the consumer to the generating station in the first four items, while the last four items give the diversity factors step by step from consumer to generator.

To combine the demand and diversity factors so as to determine the maximum demand on a transformer, feeder or station, as caused by a given connected load, multiply the diversity factor by the demand factor and multiply their product by the connected load.

The yearly diversity factor between lighting and power load, and electric street and elevated railway loads in Chicago is reported by Mr. Samuel sually the amount of capital, over and above the cost of the physical plant, pon which the property will be permitted to pay common current interest r dividend rates.

120. The market value of such a property, if it has such value over nd above its physical value, is evidently its value to a prospective purchaser, nd the purchaser usually pays a price based on present and prospective arnings. What these earnings will be depends on the possibilities of the erritory served and if there be a rate regulating public service commission, t will also depend on the rate of return on the investment which will be llowed by the public service commission.

121. Central-station operation in connection with ice plant. As nany of the smaller light and power central stations are operated in connecion with ice plants the effect upon the first cost and earnings by adding such plant is given in two cases. The amount of ice manufactured per year, which determines the gross and net income, depends so much on the latitude n which the plant is located that considerable allowance must be made for his fact.

Ice plants, such as are mentioned in cases 4 and 5 (Par. **126** and **127**), night earn double the gross and about double the net earnings if located in he extreme southern part of the United States. The income from ice lepends also a great deal on whether it is sold wholesale or retail, or whether t simply supplies the population in its own town, or in addition ships to ther nearby points.

In comparing the typical cases given for the various sizes of plants, it will e seen that in general the gross earnings per $100 invested are larger in the uccessful small plants than in the large ones, but in the smaller plants the perating expenses are likely to be a larger percentage of the gross receipts. he larger plants can also obtain capital at a lower rate of interest.

The larger the plants the smaller the ratio of gross earnings to capital nvested. This is mainly due to the higher cost of transmission and distriution plants necessary to serve the larger territories supplied from the arger generating stations. In some cases it is also due to the higher cost f underground as compared to overhead distribution, and to a more subtantial character of construction.

122. Type of plant affecting various items. The typical examples iven are for steam-driven stations where the cost of fuel is near average. Higher fuel cost will, of course, raise the percentage of operating expenses, r, if more expensive machinery is put in to keep the fuel cost down, the apital account will be increased per kilowatt of peak load. Hydroelectric lants operating central-station lighting and power systems frequently nvolve higher first cost per kilowatt of peak load, and a consequent low ratio f gross earnings to capitalization. Such high first cost, of course, can nly be justified by the decreased operating expenses caused by fuel saved y water power operation.

123. Typical earnings of central stations. Case 1.

First cost of physical property		$37,500
Intangible value		12,500
Total capitalization		$50,000
Gross earnings (40 per cent. of capital)	$20,000	
Operating expenses (60 per cent. of gross)		$12,000
Depreciation at 6 per cent. on physical value		2,250
Net earnings for interest or dividends		5,750
	$20,000	$20,000

124. Typical earnings of central stations. Case 2.

First cost of physical property		$75,000
Intangible value		25,000
Total capitalization		$100,000
Gross earnings (33 per cent. of capital)	$33,000	
Operating expenses (58 per cent. of gross)		$19,140
Depreciation at 6 per cent. on physical value		4,500
Net earnings for interest or dividends		9,360
	$33,000	$33,000

Peak load of plant 300 kw.
Gross income per kw. of peak $110

rise to so great abuses in the rates of central station enterprises as might be at first supposed, because, although the central station frequently has a monopoly of electric service in a community, it has on every hand to meet the competition of other methods. Electric lighting comes into competition with gas and oil, and electric power with gas, steam and oil engines. However, as electric service becomes more and more of a necessity and less of the nature of a luxury, the tendency to regulate its rates in accordance with the cost of service to the producer rather than according to the value of service to the more or less helpless consumer, becomes stronger.

130. The cost-of-service theory of rate making is that all rates should be proportioned among the various consumers according to the cost of serving them. The term "Cost" in this case is assumed to include a reasonable profit. The cost-of-service theory is the one now generally used by the various public service commissions intrusted by law with the work of regulating and adjusting the rates of public service enterprises. The theory upon which the majority of such commissions are proceeding is that, on account of the monopolistic character of a public utility, its rates should be regulated in accordance with the cost of service including a fair return upon the capital invested in the public utility.

131. Definitions. The following definitions used in connection with electric central-station rates have been adopted by the Rate Research Committee of the National Electric Light Association. (Examples of all the forms of rates defined are given in Par. **151**.)

Flat rate. The term "Flat rate" is applicable to any method of charge for electric service which is based on the consumer's installation of energy-consuming devices or on a fixed sum per consumer. Meters are not used.

Demand rate. The term "Demand rate" is applicable to any method of charge for electric service which is based on the maximum demand during a given period of time. The demand is expressed in such units as kilowatts or horse-power. Maximum-demand indicators or graphic meters are used.

Meter rate. The term "Meter rate" is applicable to any method of charge for electric service which is based on the amount used. This amount is expressed in units, as kilowatt-hours of electricity. Integrating meters or graphic meters are used.

Consumer's output rate. The term "Consumer's output rate" is applicable to any method of charge for electric service based on the consumer's output. The unit of the consumer's output may, for example, be a gallon of water pumped, a barrel of flour, or a ton of ice made.

Two-charge rate. The term "Two-charge rate" is applicable to any method of charge for electric service in which the price per unit of metered electric energy for each bill period is based upon both the actual or assumed quantity of electric energy consumed and the actual or assumed capacity or demand of the installation.

Three-charge rate. The term "Three-charge rate" is applicable to any method of charge for electric service in which the charge made to the consumer for each bill period consists of, (a) a sum based upon the quantity of electric energy consumed, (b) a sum based upon the actual or assumed capacity or demand of the installation, (c) a charge per consumer.

Straight line. The term "Straight line," as used in connection with and as applied to any method of charge, indicates that the price charged per unit is constant, *i.e.*, does not vary on account of any increased or decreased number of units. The total sum to be charged is obtained by multiplying the total number of units by the price per unit.

Block. The term "Block," as used in connection with and as applied to any method of charge, indicates that a certain specified price per unit is charged for all or any part of a block of such units, and reduced prices per unit are charged for all or any part of succeeding blocks of the same or a different number of such units, each such reduced price per unit applying only to a particular block or portion thereof. The total sum to be charged is obtained by multiplying the number of units in the first block by the price per unit for that block and adding thereto the number of units in the second block times the price per unit for that block, and so on until the sum of the units falling within the different blocks equals the number of units to be charged for.

Step. The term "Step," as used in connection with and as applied to ixed items, such as taxes and insurance, which are dependent entirely upon he size of the plant and which go on continually without regard to the kilo-vatt-hours output of the plant. Such fixed charges are evidently propor-ional to the maximum demand of the customer without any regard to his onsumption of electrical energy. If we find, for example, that the cost of he power station and distribution system per kw. of maximum load is 300, then that consumer who requires 1 kw. maximum should pay ontinuously, per month or per year, the interest, profit, taxes, depreciation, nsurance, etc., upon this $300 investment. This should be paid without egard to whether he uses a large or small amount of electrical energy in ilowatt-hours, because the investment has been made to serve him. In ddition to this he should pay a meter rate or charge per kilowatt-hour. This latter is to pay for the variable cost, principally fuel and labor, which aries according to the output of the station. As a matter of fact there re some labor and fuel costs which are dependent more upon the peak oad of a station than upon the kilowatt-hours output and some authorities vould include some of these costs in the fixed yearly or monthly maximum lemand charge. However these are details aside from the main principle nvolved. Plant conditions change with increasing load and it is more cus-omary to count these fuel and labor items as variable in proportion to the ilowatt-hours output than as charges in proportion to the maximum de-nand. We see then that the cost of serving a customer is divided into two listinct elements, viz., maximum demand, and kilowatt-hours, which hould be combined in making up a rate. The **demand charge** is sometimes alled a **readiness to serve charge.**

Following up our specific example; in the case of the customer making a naximum demand of 1 kw. upon the system at the time of maximum ystem load, the fixed or maximum demand charges against such a customer night then be found to be per year as follows:

Interest and profit on $300 per kilowatt plant and distribution system investment at 8 per cent.	$24.00
Taxes and insurance, 2 per cent. on $300	6.00
Depreciation at 6 per cent. on $300	18.00
Total fixed annual charges per kilowatt demand	$48.00

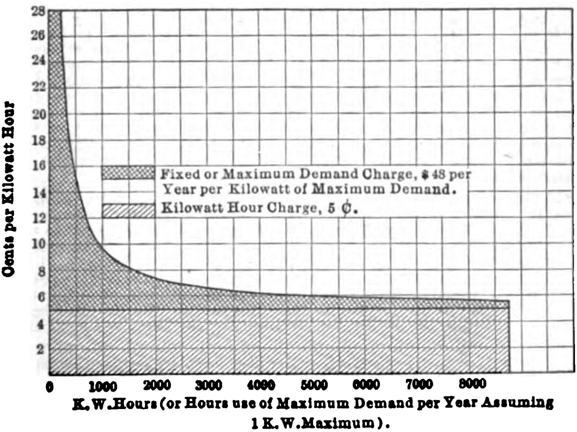

Fig. 5.—Typical form of cost curve for electrical energy supply.

mum load determines the amount of business which can be carried and the consequent gross revenue. A demand rate in effect is very similar to a flat rate. The only difference is that the consumer's maximum demand instead of being contracted for in advance is measured continuously and can be varied by the consumer from time to time without violation of contract.

139. Demand factor or the maximum demand made by the consumer is determined for rate-making purposes in various ways. The most common method with small consumers is to assume the consumer's demand factor or in other words to assume that the consumer's maximum demand is a certain percentage of the connected load. Such demand factors may be determined for different classes of consumers by test of a sufficient number of consumers with maximum demand meters and the results of such tests then taken as the basis of assumptions for all similar consumers. Such a method is of course somewhat inaccurate but it avoids the investment expense of a maximum demand meter for each consumer; which is an important item with small consumers. Demand factors as determined by various authorities for some classes of business are given in Par. **107 to 112.**

With large consumers it is frequently the practice to measure the maximum demand for a comparatively short period of time by means of an indicating instrument inserted at times of greatest load and assume that the maximum demand thereafter is the same as that measured.

140. Maximum-demand meters. In the Wright demand system of charging (Par. **136**) the maximum demand is determined by **a Wright demand meter** kept continuously in circuit alongside the kilowatt-hour meter. The Wright demand meter is an instrument for recording the maximum current which has passed and operates by the expansion and pouring over of a liquid by the heating effects of the current. It measures maximum amperes, not kilowatts.

A printing attachment on a recording watt-hour meter can be arranged to print at regular intervals the reading of the meter at that instant. The difference between two succeeding readings divided by the hours elapsed between readings gives the average demand in kilowatts between readings. By arranging the instrument to print at intervals of a few minutes, peak loads of very short duration can be measured. Such an instrument also shows the time at which the maximum demand is taken, thus showing whether at the time of the maximum load on the system or not; which in some cases is important as explained later in connection with off peak or limited hour rates. The paper rolls need be removed but once a month.

Watt-hour meters with attachments for recording maximum demand are available, such attachments depending upon the torque exerted upon the meter at any instant; this torque being proportional to the maximum demand.

A curve-drawing watt-meter which draws a curve of the load upon a roll of paper is sometimes used for determining maximum demand where the meters can be looked after with sufficient frequency. It is usually considered practicable only in large installations.

141. The maximum demand in the case of residences is sometimes assumed to be proportional to the room area or to the number of certain kinds of rooms in a house. This is sometimes called the **Detroit system,** having been first used in America at Detroit. Under this system the residence consumer's maximum demand is assumed to be a certain number of watts for each different kind of room. Not all rooms are counted as only those rooms termed active are included and the number of watts per room is varied according to a schedule believed from experience to correspond to the average actual demand of such rooms. While such a method of figuring maximum demand would appear peculiar at first sight it is nevertheless probably as fair as an assumption that the maximum demand is a certain proportion of the connected load. Basing assumed maximum demand upon connected load in a residence has the serious drawback that it practically puts a penalty on the wiring of a house with a large number of closet lights and similar conveniences. These have but little influence upon the maximum demand but are nevertheless very convenient for the consumer and have much to do in persuading him to use electric light. Basing the maximum demand upon the active rooms in a house or upon the size of the house eliminates this unfairness and helps to cultivate the residence business.

from. It is not however customary to attempt to charge each consumer with the exact feeder investment necessary to serve him. Some consumers are a considerable distance from the power station and others are near, and making an exact analysis would complicate matters to such an extent that it is customary to take the complete feeder and pole-line equipment reduced to a cost per kw. of demand basis and to charge this investment equally among all consumers.

145. Off-peak rates, sometimes called limited rates are sometimes made for classes of business where the maximum demand of the consumer is limited to certain hours of the day so that all or a large portion, of the consumer's load is turned off during the hours of maximum central station load. In this way the power station and distribution system investment which is installed to provide for the demands of ordinary consumers can be made to do double duty and the demand charge is considerably reduced. There is a difference of opinion among rate experts as to how much of the demand charge should be borne by the off-peak consumer in such cases. Some argue that, inasmuch as the station and meter capacity are already installed for serving the peak-load consumer, it is proper to eliminate a considerable percentage of the demand charge for the off-peak consumer, because the power-station capacity service supplied to such a customer is in the nature of a by-product which would not otherwise be utilized. The general practice is to divide such charges between the peak and the off-peak consumers. However, in cases where it is necessary for competitive reasons to remove the demand charge of the off-peak consumers in so far as it applies to investment already made for peak consumers, and allow it to be borne altogether by the peak consumers, the by-product theory offers an excellent argument. Further, the taking on of such off-peak business, even though it bears but a small percentage of the maximum-demand charge, increases the net income of the company and assists in a more economical production, so that ultimately reduced rates can be instituted for all consumers. As a general policy the leaders of the central-station industry as well as public service commissions recognize fully that any rates which help to increase and build up the volume of central-station business help ultimately to reduce the cost of service to all consumers.

146. The practical deviations of rates from the cost-of-service theory are necessarily numerous. It is not feasible to determine the exact investment required to serve each consumer. Consumers must rather be taken by classes. Furthermore, the rate per kw-hr. to each consumer using electricity but a few hours per month based upon the cost of service, would be astonishingly high. If the rates charged on this business were based strictly on cost of service, there would be so much public protest that both central-station companies and rate-regulating commissions apparently have concluded that it is best to allow this class of business to be taken at a loss and let the losses be made up by other consumers, inasmuch as the gross revenue from such business is a small proportion of the whole.

147. Limited-demand flat rates are sometimes used for small residence lighting where it is desired to cut out the expense of meter investment, meter readings and bookkeeping. Such rates also appeal to a certain class of small consumers who wish to know definitely what their lighting bills will be per month without the uncertainty of a meter. One trouble with flat rates has been that consumers put in larger lamps or other devices than they contract to pay for. Under the limited-demand flat rate system the consumer is served through a limiting device of some sort which periodically interrupts the current and flickers the lamps whenever the contracted maximum demand is exceeded. The consumer is thus warned to turn off one or more lamps and prevented from using an excess demand over that contracted for.

The limited-demand flat rate has some of the disadvantages of all flat rates namely that consumers waste electrical energy by keeping lights on when not needed. Where such rates are in use, however, this tendency is somewhat restricted by making the consumer pay for lamp renewals, and if lamp renewals are sufficiently expensive there is some incentive to turn out lamps when not needed in order to save renewal costs. However such flat rates must always be made high enough to allow for considerable waste on the part of the consumer. The principal use for such a rate is in the supply of very small residences where the cost of bookkeeping, meter reading and than the first 30 hr. use per month of the active connected load. Secondary rate, 8 cents per kw-hr. for additional energy used. (In this case the active connected load is the assumed maximum demand.)

Where the active room plan is used as a basis of estimating maximum demand of residences, the following is an example of one method of estimating: multiply the number of rooms in the house by 0.04 kw., but do not count bathrooms, basements, cellars, porches, stairways, attics, store rooms, small halls, entrances, woodsheds, or barns.

Three-charge rate. Six dollars per year per consumer (as a consumer charge) plus $30 per year per kw. of maximum demand (as a demand charge sometimes called a readiness to serve charge) plus 6 cents per kw-hr. for electrical energy used.

Block meter rate. For the first 250 kw-hr. monthly consumption, 10 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 9 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 8 cents per kw-hr.

Step meter rate. For the first 250 kw-hr. of monthly consumption 12 cents per kw-hr.; for a monthly consumption between 250 and 500 kw-hr., 11 cents per kw-hr.; for a monthly consumption between 500 and 750 kw-hr., 10 cents per kw-hr. (Note that under the foregoing schedule a consumer of 249 kw-hr. per month would pay more than a consumer of 251, in actual dollars and cents. There is evident injustice in this and also in the fact that the discount is applied in sharp steps rather than gradually.)

152. Discounts for prompt payment are sometimes allowed and as the majority of consumers will take advantage of such discount the rate should be adjusted so that they will yield the owners of the property a fair profit after the discount is taken off. In order that a discount for prompt payment may be legally sustained it is necessary that it should not be a very large discount. About 10 per cent. is common. Discounts in excess of this are in danger of being set aside by courts or commissions as being unfair to the consumer who does not take advantage of the discount.

VALUATIONS FOR RATE-MAKING PURPOSES

153. Classification of purposes for which valuations are made. The laws of many states where public service or public utility commissions have been created for the purpose of public-utility regulation, provide for the valuation of public utility properties for purposes of establishing reasonable rates. The theory upon which these laws are based (although it is not always expressly so stated) is that of allowing the investor in public utility properties a fair and reasonable rate of return (interest and profit) upon his investment.

Valuations made for rate-making purposes may be very different from valuations made for other purposes. If a property is to be appraised or valued for the purposes of an ordinary business purchase, the fundamental question to be solved is the probable earning power of the property both present and prospective. In valuations for rate making, however, the earning power of the property should receive no consideration, because the earning power is dependent upon the very rates which it is proposed to regulate, and to value a property on its earnings would defeat the entire end in view.

154. The purpose of a valuation to be used in rate making, should be to determine as nearly as possible the actual fair investment in the property to the end that rates may be so adjusted that a fair annual return (interest and profit) will be made to the investor upon the amount invested in the property after all expenses are paid. If this end were kept constantly in view many of the disputes and discussions in connection with such valuations would be obviated.

If the actual cost of a public-utility property could always be obtained from the construction or property accounts, the problem would be simple. However, it is frequently the case that construction costs are not kept in such shape that they can be accepted unquestionably by the appraiser. It may also happen that part of the books and records of the enterprise is destroyed or unavailable. In any case the engineer making the valuation must be prepared by knowledge of other plants to check the accuracy of any figures submitted to him or even to value a plant entirely in accordance with costs of similar plants elsewhere if no figures whatever are available on the actual cost of the plant under consideration. The value of a public utility property is usually classified under two heads, tangible and intangible.

payable until some time in the future (see Par. 42). If the earnings in the past have not been sufficient to pay all such expenses and a loss has resulted from operation, such losses should be included in intangible or going value after making the proper deductions as stated.

158. The per cent. upon the investment which a public utility is allowed to earn as a fair and reasonable annual interest and profit upon its value as taken for rate-making purposes is a matter for commissions and courts to decide in accordance with the prevalent or market interest rate upon investments in similar securities. Public utility securities must compete in the financial market with other securities or they will not be sold. These are financial rather than engineering questions, but, since the engineer must frequently deal with them in the course of his business, the following points are given as presenting current practice.

Where part of the money to pay for the construction of a plant is raised by a bond issue, it is customary to sell the bonds at a discount below par, a part or all of which discount is taken by the bond broker as his commission for finding purchasers for the bonds. As the bonds must be redeemed at par when they are due, the discount upon the bonds must be added to the total annual interest paid on the bonds, in order to determine the actual annual cost to the public utility for the use of the money. This is a point sometimes overlooked in figuring the fixed charges which a public utility must carry. The principal question is to determine what rate of interest and profit a public utility must pay after discounts or commission on sale of securities are included. It is not a question of theory but of market conditions.

Mr. Halford Erickson member of the Railroad and Public Service Commission of Wisconsin in a public address 1914 (see Bibliography) gives the following figures as to rates actually paid by public utilities for money: Ten representative first mortgage bond issues covering electric-lighting and street-railway plants, brought out in 1913 and bearing interest at 5 per cent. on par value, were placed on the market at prices at which they would yield the investor an income of from 5 to 6 per cent. The cost to the issuing company of obtaining this capital amounted to from 1 per cent. minimum to over 11 per cent. maximum for discount and about 3 per cent. for selling expenses. The total average was about 6.2 per cent. During the same period 10 representative second mortgage bond issues covering gas, electric-lighting, and railway plants, bearing interest at 5 per cent., were offered at prices that would net investors an income of 5 to 6.2 per cent. On these issues the discount varied from 1 to over 12 per cent. and the selling expense stood at about 3 per cent. The total cost to the companies for this financing ranged from 5.2 to about 7 per cent., the average being about 6.4 per cent. Twelve note issues were offered to the public at prices which placed them upon a 6.2 per cent. income basis to the investors. When the discounts and selling expenses were taken into account, the cost to the companies of the bonds thus obtained was found to be about 9.4 per cent. per annum. In this case the discounts ranged from less than 1 to about 2.34 per cent. The selling costs, however, were rather heavy since they appear to have ranged from about 5 to over 8 per cent. Five preferred-stock issues were sold on a basis whose average yield to the investor was about 7.3 per cent. Since the discounts varied from 3 to 12.5 per cent. and the selling expense also had to be met, the cost to the companies was, of course, much greater than the price to the public. For about 40 plants in Wisconsin whose appraised value varied from about $20,000 to about $2,000,000 per plant, the bonds, when discounts and selling expenses are included, have of late years been selling at prices under which the cost of financing on the plant ranges from about 5.5 to fully 6.5 per cent. per annum. In these cases the bonds covered from 50 per cent. to more than 85 per cent. of the values of the plants and their business, while the net earnings of the plant did not amount to less than twice as much as the interest on the bonds.

In further explanation of Mr. Erickson's figures it should be said that this is in a state where most of the public utility companies are protected from competition as a recompense for commission regulation of rates and service, and that such securities, therefore, would present to the investor the minimum amount of hazard to be found in public utilities of any given size. Mr. Erickson's figures probably represent minimum interest rates obtainable by the public-utility properties in the United States of the kind and at the times stated.

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