COMPENDIUM IN WIND-TURBINE BLADE THEORY AND PRAXIS

BASED ON EXPERIENCE FROM THE 4th. PERIOD OF WIND

ELECTRICAL POWER GENERATION

The 4th. period was the decade of the re-discovery of wind electrical power generation: 1968 - 1978

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Nothing says more about a wind-turbine than rotor diameter, - Nothing.

Rule nr. 1. For wind-turbines: They must be reliable.

Rule nr. 2. — : They must be cost-effective.

Efficiency is important, but it is not the sole criteria, for judging the performance of a wind-machine.

" Wind Power ", Paul Gipe, USA 1993.
pages 73 and 76. ISBN: 0-930031-64-4.

It is the objective of this compendium to encourage active study and experimentation in wind-turbine blade construction, by technical students, machine and wood-working shops, carpenters, joiners and by other local groups.
The de-centralized local construction of micro and small wind-turbines for electrical power generation, using local resources, and locally available material, such as redundant truck and tractor generators and alternators, will result in accumulation of the expertise and practical knowledge, - [PRAXIS], necessary for the future development of an advanced national de-centralized wind energy program.

Much of the relevant material from the period has been consulted, including German and USSR material, and a small selection has been included in this compendium. Also more modern material is included.
It should be emphasized that careful study of the 4th period of wind-turbine development - [the re-discovery period 1968-1978], which resulted in the development of large-scale production of small and medium, reliable and cost-effective wind-turbines - is most relevant for the accumulation of local knowledge of the different aspects of wind-energy technology.

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Chronology of Wind-turbine Development.

Period nr. 0 Dutch type, F. Nansen, USA 1894

Period nr. 1 La Cour, Denmark 1890 - 1925. La Cour from Askov in Denmark, was the pioneer of modern large-scale wind electrical power generation. - 3kW.- 30 kW. [co-generation systems].

Period nr. 1.5 Lykkegaard, Denmark 30 - 75 kW. 1920 - 1945. Series-production period.

Period nr. 2 F.L. Smidth, Denmark [60 - 70 kW. with effective gear-box developed from cement-ovens], Hütter in Germany, Darrieus in France, Putnam in USA, and especially, very large-scale mass-production in the USSR. 1930 - 1945. [small wind-generators for battery charging, mass-produced in USA].

Period nr. 2.5 J. Juul, Denmark 1950, 13kW.- 45 kW.

Period nr. 3 J. Juul, 200 kW. Gedser wind-turbine, 1955 - 1967, and from 1977 [operated under Danish and USA-NASA research contract]. Plus UK and West-Germany. [Gedser was the first modern, reliable wind-turbine].

Period nr. 4 Re-discovery phase, 1968 - 1978, USA and Denmark. This phase results in 2 different development strategies: - Top-down, and Bottom-up.

a: Mega turbines; Tvind-college in Denmark & official Danish state research program, West-Germany, USA. - [Development of glass-fiber Tvind-wing].

b: The Riisager wind-turbines from Denmark, 10kW.- 30kW. These pioneered the development of the cost-effective wind-turbine

Period nr. 5 Large-scale Danish commercial development and production; - 55kW.- 100 kW. 1978 - 1985.

Period nr. 6 150kW.- 225 kW. 1985.

Period nr. 6.5 300 kW. 1991.

Period nr. 7 Large-scale production of cost-effective 500 kW. units, Denmark and Germany. 1993. Development of wind-turbines without gear-box, [Ring-generator -- Enercon, Germany]

There is at the present time [1997] small-scale production in Denmark of Mega-sized wind-turbines, [between 800 kW. and 1.7 MW.]. However great consideration, must be paid to eventual dis-economies of scale, maintenance, siteing, etc. etc.

" I consider that a Cuban production should commence with the production of small/medium wind-turbines of about 20-55 kW, using generator material already in Cuba, [ex-DDR diesel generators, etc., there is likewise no shortage of tower construction material in Cuba].

Following a successful production of this type, a production development of a 150 kW model should be made. [models similar to the highly successful and very reliable Danish Bonus 55 kW and 150 kW wind-turbines].
There is a potential market in the Caribbean area alone, for these two types of many hundreds of units.

Cuba already produces simple water pump type wind energy machines, the so-called wind mills. This type with a little imagination from the Cuban wind energy specialists, and machine shops, could be used for electrical power generation, as was done in Denmark during both the first and second World Wars, - wind-turbine electrical generation in Denmark, dates from the 1890's.
Large-scale production should also be started of micro and small wind-turbines, using Soviet car and truck generators, [using efficient glass-fiber or wooden airfoil blades of about 2-4 meters in diameter, --- knowledge of wooden airfoil blades is available from CIES in Santiago de Cuba].
These size machines under Cuban conditions could be mounted on simple pipe-type guyed towers of about 10-20 meters height. These machines have a production capacity from 50 watts to about 200-500 watts, and are very useful, not only for electric fences, but also for other rural applications, medical houses, milking stations, etc ".

" The production of wind mills for water pumping is not difficult, however wind-turbine technology for efficient and reliable electrical power generation is based on several unique factors:
1. A high degree of praxis, rather than over-reliance on research; - a " learning by doing " approach.
2. Very high quality fiber technology, and very high quality in fiber-based production.
3. Computer steering programmes.
4. Gearbox design, [not automotive, nor industrial machinery design].
5: A " robust " approach to design, and the total construction.

It should be stressed that wind-turbine units, under normal hard
weather conditions, have an expected life of over 20 years, with regular maintenance ".

" Some Remarks on Energy and Environmental Co-operation Cuba - Denmark ": John Furze.
1991/94 pages 5-6 and, appendex - page 9

WING DESIGN

The length of the wing from root to tip, is based on several different factors:

The size of the energy requirement.

The local wind

What the energy is required for (pumping, grinding, electrical power for local use, or electrical grid energy)

If there are possibilities for energy storage ?

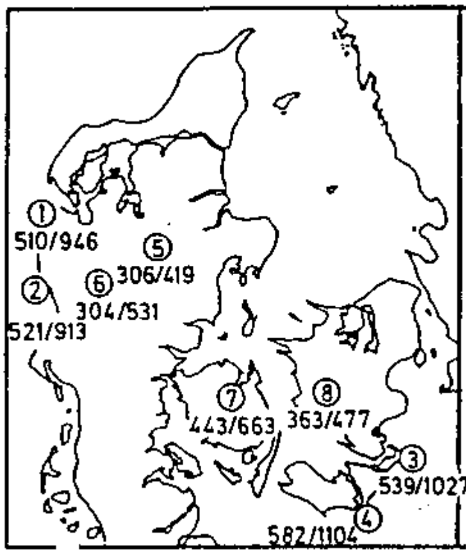
What wind-strength interval will be used (wind speed / height of tower) ?

A wind power system's yearly energy production per sq. meter of the swept propeller (blade / wing) area.

Formula 1.

$$E_p = 0{,}055 \cdot C_p \cdot \Sigma(v_i^3 \cdot q_i) \quad (\mathrm{kWh/m^2/year})$$

Calculated with an effect coefficient c_p of **0.36**, equivalent to a propeller efficiency ηp of **0.6**. Energy production is on the following page, calculated in wind strength intervals 3 - 5 BF, and 3 - 7 BF (Beaufort scale).



0 = Weather Station

3-5 BF / 3-7 BF = wind strength interval

Coast Station	Inland Station
1. 07020 Bovbjerg Fyr	5. 03220 Hald Ege
2. 07420 Lyngvig Fyr	6. 07600 Studsgård
3. 17380 Møn Fyr	7. 11560 Od. Blangstedgård
4. 18700 Gedser Fyr	8. 16100 Sorø
Average: 538/998	Average: 354/523

Figure 1. Energy production in kWh/m/year
Height 10m. c_p = 0.36

Propeller	Coast		Inland	
Radius (m)	3-5 BF	3-7 BF	3-5 BF	3-7 BF
2	6779	12575	4460	6590
3	15225	28243	10018	14801
4	27061	50199	17806	26307
5	42233	78343	27789	41056
6	60794	112774	40002	59099
10	168932	313372	111156	164222
12	243284	451296	160079	236501

Energy Production in kWh/year for different propeller sizes

c_p = 0.36

Figure 2

On the basis of the average values in the diagram (Figure 1).

The tables 2 (Figures 2 and 2.2), show the yearly energy production for propellers of different sizes.

If the length of the wing is dimensioned on the basis of the wind speed, and if the effect coefficient C_p of **0.36**,

(η_p **= 0.6**):

The use of Formula **P.**, for the real rotor effect, will give the results as shown in Figure 2.2

$$P = 0{,}593 \cdot \frac{\varrho}{2} \cdot \eta_p \cdot v^3 \cdot A \quad (W)$$

$$P = 0{,}37 \cdot \eta_p \cdot v^3 \cdot A \quad (W)$$

A = Swept rotor area (m)

THE WIDTH OF THE WING

In calculating the b **max.** , which is the theoretical necessary width in order to obtain the maximum utilization of the available wind energy, the following formula, is used :

Formula 2:

$$b_{max} = 5{,}6 \cdot \frac{R^2}{i \cdot C_L \cdot r \cdot \lambda_N^2} \quad (m)$$

C_L **= coefficient of lift**

Propellens Radius (m)	P_4 (kW) v = 4 m/s	P_6 (kW) v = 6 m/s	P_8 (kW) v = 8 m/s	P_{10} (kW) v = 10 m/s	P_{12} (kW) v = 12 m/s	P_{15} (kW) v = 15 m/s
2	0,2	0,6	1,4	2,8	4,8	9,4
3	0,4	1,4	3,2	6,3	10,9	21,2
4	0,7	2,4	5,7	11,2	19,3	37,7
5	1,1	3,8	8,9	17,4	30,1	58,8
6	1,6	5,4	12,8	25,1	43,3	84,7
10	4,5	15,0	35,7	69,7	120,5	235,3
12	6,4	21,7	51,4	100,4	173,5	338,8

Figure 2.2 Blade radius, Wind speed, Effect.

A large wing width gives a larger friction resistance, and in practice, good results have been obtained with slightly smaller widths.

Hemmingsen and Tvergård suggest the following formula:

Formula 3:

$$b = 4{,}5 \cdot \frac{R^2}{i \cdot C_L \cdot r \cdot \lambda_N^2} \quad (m)$$

The number of blades, and the wing tip speed is chosen, taking into consideration the torque / moment of rotation, and the speed of rotation, while the lift coefficient varies along the length of the wing.

Hemmingsen and Tvergård, suggest that C_L should change from **0.8** at the wing tip to **1.1** at the middle of the wing.

Sødergård suggests a C_L value of **0.6** at the wing tip, with a gradual increase to **1.3** at the wing root.

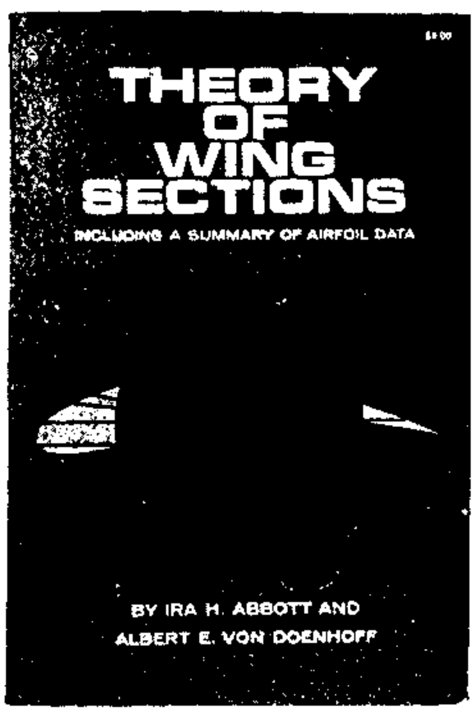
Some very large blades (Tvind glass-fiber wing from 1975) have been built with a C_L value of **1.1** at the wing tip and a linear increase to **1.3** at the wing root.

It is clear from the formulae, that the width of the wing, increases sharply in towards the center. However, 75% of the energy is obtained from the outer section of the wing, and therefore the whole wing is often shaped with a straight rear edge, which also eases construction. The width of the wing is decided at the wing tip and at the middle, following which, the rear edge is a straight line between the two points.

WING PROFILE

Forming of the wing profile is a complicated procedure, that is an inter-relationship between theoretical mathematical models, and pratical wind tunnel testing.

However there is litterature, giving assistance in chosing and dimensioning suitable profiles for smaller wind power systems.



Theory of Wing Sections:
693 pages. Ira Abbot and Albert von-Doenhoff. Dover Publications. New York, USA. 1959.

CHORD

As a measurement for the width of the profile, the term , " Chord " is used. This is the straight line that joins the front edge and the rear edge of the wing / blade.

PROFILE CORDINATES

The profile section, is based on the profile cordinates. Cordinates are procentages (%), of the profile chord. These are calculated with the use of Formula 3 , giving the exact cross section of the profile. Should it be necessary, for reasons of strength, to make the profile thicker, the cordinates are multiplied with a constant.

For example:

A chord length of 10 cms. All the cordinates in the table will therefore be multiplied with this number. Remember that profile cordinates are % : That is: 1,25 % , in reality is 0,0125, etc.

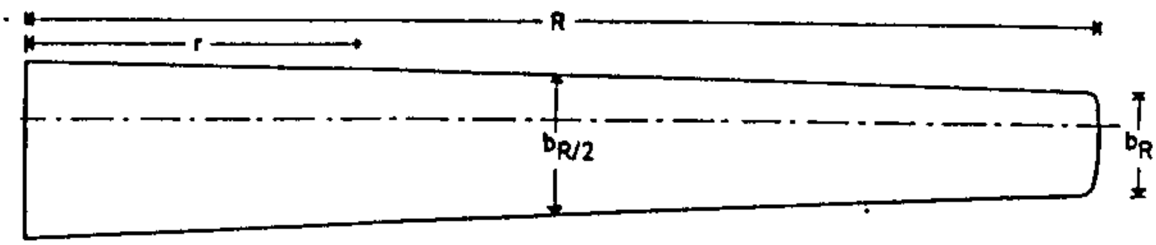


Figure 3. Blade width

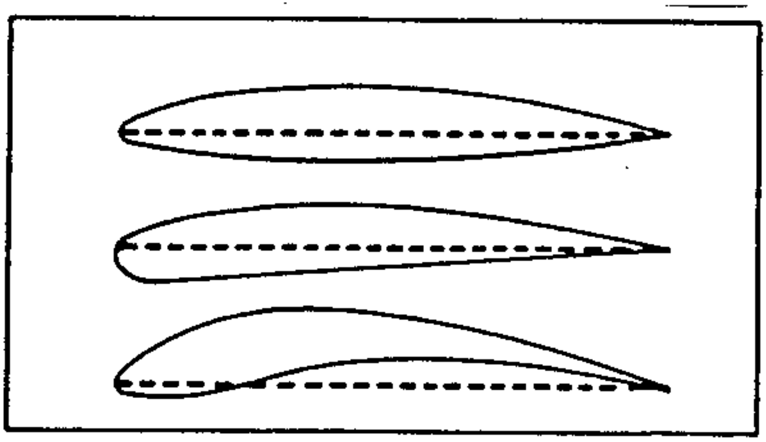


Figure 4. Profile chords

a	b	c
0	0	0
1,25	2,44	− 1,43
2,5	3,39	− 1,95

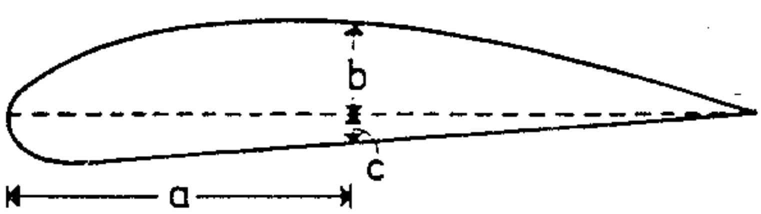


Figure 5. Profile coordinates

Following calculation of the data for every profile cross section, these are drawn on a sheet of paper.

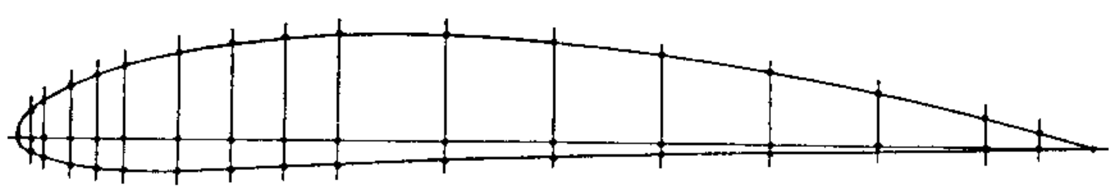
First the " a ", value is marked.

From this obtained fixed point, the " b " value is then marked in the vertical plane, (upwards).

From the same " a " point, the " c " value is finally marked, if this value is a negative number, (minus), it is measured under the chord, otherwise over the chord.

Figure 6

Marking out the **NACA** profile **4412**



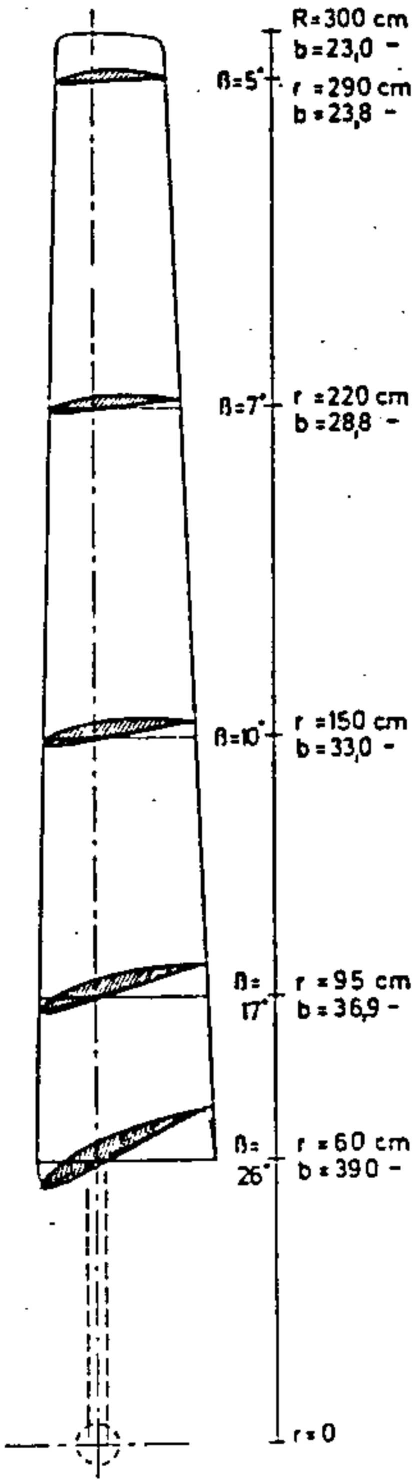


Figure 7. NACA profile: 4412

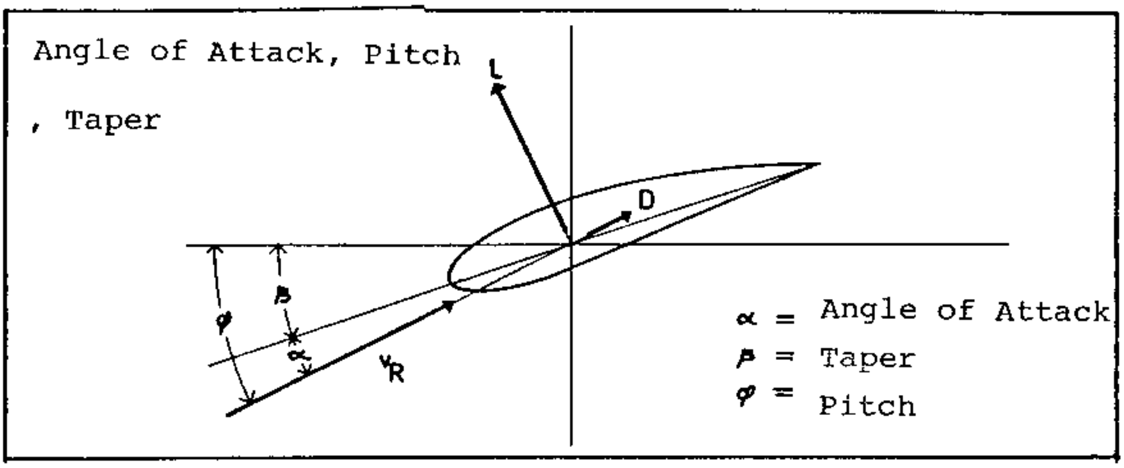
For a 3 blade-propeller

1. ANGLE OF ATTACK

To obtain sufficient lift, it is necessary that the resulting wind, strikes the profile at a certain angle. This is called the profile's , " angle of attack ", α
This is measured as the angle between the resulting wind and the chord.

The diagram, (figure 9) shows the relationship between the angle of attack, and the coefficient of lift, for different profile types. It is shown that lift increases with increased angle of attack. However a point arrives when the angle of attack becomes so great, that the air stream, over the rear of the profile, becomes turbulent, whereupon the lift vanishes, and the wing, " stalls ".

Figure 8.



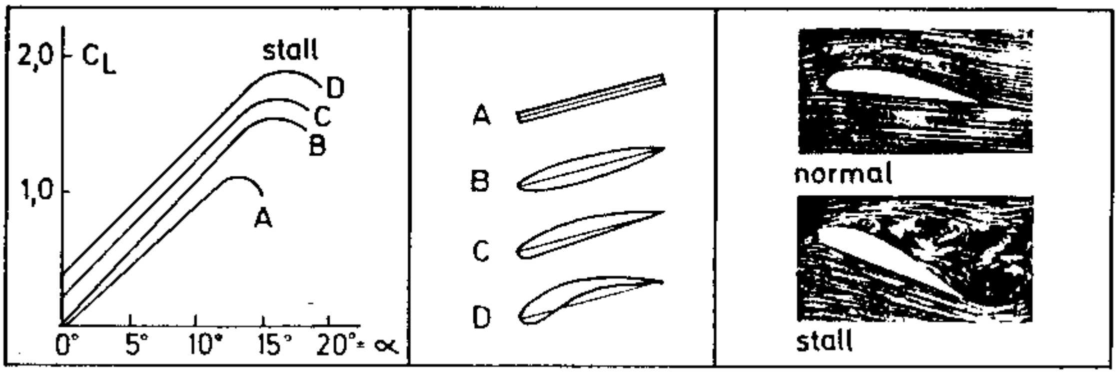


Figure 9. Angles of attack, and Lift-coefficients profile forms.

2. PITCH

The angle between the resulting wind and the plane of rotation, is called the , " profile pitch " φ , this is given by the following formula :

Formula 4:

$$\cot \varphi = \frac{3}{2} \cdot \frac{r}{R} \cdot \lambda_N$$

This is used to calculate the profile taper.

3. TAPER

The angle between the chord and the plane of rotation, is called the " profile taper ", β , which is used as a starting point for the construction drawings, and the building of the wing. The taper is calculated using the following formula :

Formula 5:

$$\beta = \varphi \div \alpha + \alpha_{L=0}$$

$\alpha_{L} = 0$ is the " Zero-angle ", that is the angle where no lift is produced. Refering to figure 9, showing stall, it may be accepted that the zero- angle for Type A, and Type B, is 0° degree, for Type C, 2 degrees, and for Type D, 4 - 6 degrees.

ANGLE VARIATION

The wing speed increases proportionally with the distance from the center. At the same time, the resulting wind speed is also increased, and the direction is changed. To insure the best possible angle of attack, the pitch and taper are reduced along the length of the wing.

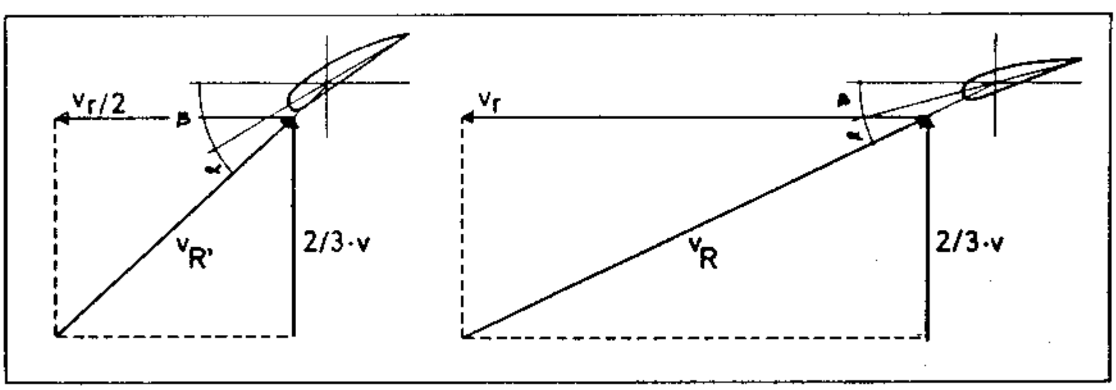
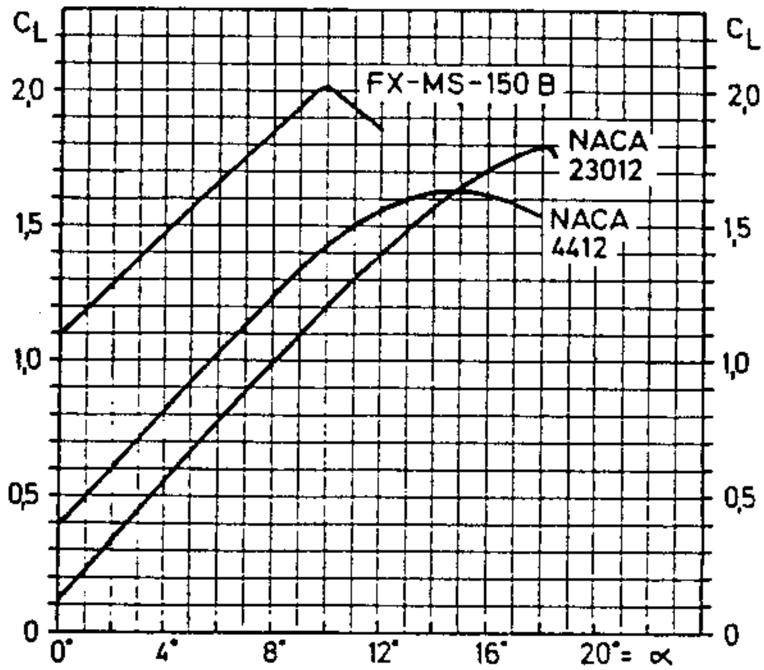


Figure 10.



NACA 4412

a	b	c
0	0	0
1,25	2,44	– 1,43
2,5	3,39	– 1,95
5,0	4,73	– 2,49
7,5	5,76	– 2,74
10	6,59	– 2,86
15	7,89	– 2,88
20	8,80	– 2,74
25	9,41	– 2,50
30	9,76	– 2,26
40	9,80	– 1,80
50	9,19	– 1,40
60	8,14	– 1,00
70	6,69	– 0,65
80	4,89	– 0,39
90	2,71	– 0,22
95	1,47	– 0,16
100	(0,13)	(– 0,13)
100	0	0

Front-edge radius 1.58

NACA 23012

a	b	c
0	0	0
1,25	2,67	– 1,23
2,5	3,61	– 1,71
5,0	4,91	– 2,26
7,5	5,80	– 2,61
10	6,43	– 2,92
15	9,17	– 3,50
20	7,50	– 3,97
25	7,60	– 4,28
30	7,55	– 4,46
40	7,14	– 4,48
50	6,41	– 4,17
60	5,47	– 3,67
70	4,36	– 3,00
80	3,08	– 2,16
90	1,68	– 1,23
95	0,92	– 0,70
100	(0,13)	(– 0,13)
100	0	0

Front-edge radius 1.58

FX 72-MS-150 B

a	b	c
0	0	0
1,7	3,05	– 1,23
2,65	4,01	– 1,24
5,16	6,15	– 1,14
6,69	7,26	– 1,03
10,33	9,43	– 0,72
19,56	13,32	0,13
30,86	16,05	1,16
40,24	16,86	2,09
50,00	16,16	3,27
59,75	14,21	4,25
69,13	11,55	4,64
80,43	7,5	4,07
91,57	3,23	2,21
100	0	0

Figure 11. Data for 3 profile types.

PROPELLER BLADE GEOMETRY

Blade Element Theory, is used to calculate the shape of the blades, the propeller's efficiency, the axial torque, etc. Using the more advanced textbooks, the aero-dynamic relationships of the propeller, can be exactly calculated. Testing a model propeller in a wind tunnel, can further complement these theoretical calculations. There are methods whereby, with good precision, one may calculate the finished propeller's effect in a certain situation. However a simpler form of Blade Element Theory, gives sufficient results with most blade fabrication. Inaccuracies are less than the differences due to un-avoidable surface tolerances under production conditions.

Differences due to both calculation and production, can to a certain extent be eliminated, through minor adjustments of the setting of the smallest blade angle. It is therefore only on wind turbines of power station size, that complicated calculation and testing in a wind tunnel can be effective. In such cases even a small improvement in the propeller efficiency can result in many extra kWh.

In the following section, simple Blade Element Theory (with approximations), will be used in calculating the geometric form of the propeller blades.

The diagram (Figure 1), shows that a blade element is a portion of a propeller blade between radius **r** and **r + Δr.**

Blade width **b** varies along the length of the blade.

At the wing tip, radius **R**, is blade width b_R .

The propeller rotates with angle speed ω radians per second. The blade element has, as a result, a speed in the direction of rotation, **r** $\cdot$ ω . (**r** multiplied by ω).

After passing through the propeller's swept area, the wind speed **v** has been slowed to a lower speed. When the maximun effect is taken from the propeller's swept area, the speed of passage is **2/3** $\cdot$ **v** . The two speeds combined give the following formula:

$$W = \sqrt{(2/3 \cdot v)^2 + (r \cdot \omega)^2}$$

This gives the speed of the wind, before passing through the axis of the blade's rotation. That is, the wind speed that the blade element is swept by.

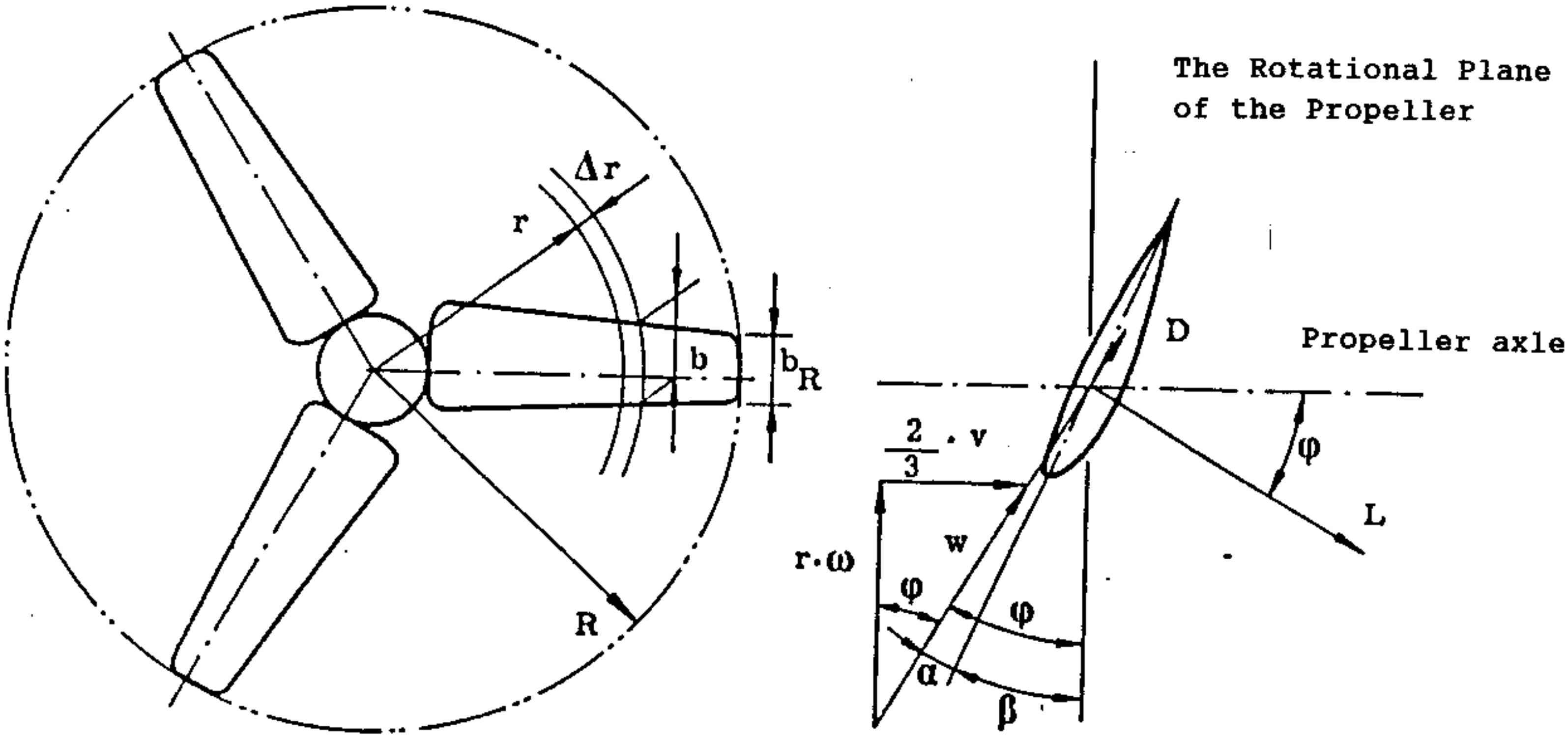


Figure 1. The Coordinates of the Propeller Blade and the Air Forces on a Blade Element

The swept speed w 's direction in relation to the propeller's plane of rotation, is expressed by the pitch angle ϕ .
To make the blade element react to lift, and thereby give the propeller axle a torque effect, it is necessary that the blade element profile has an angle of attack α .
The relationship between the lift coefficient c_L and the angle of attack, is found in a polar diagram for the wing profile, on the following page.

α is a part of angle ϕ .

The other part is the angle β (taper)

Air passing a blade element gives rise to an air force, the two components being ΔD and ΔL . ΔD the drag and friction, and ΔL is the lift. The projection of these two components in the propeller axle direction (wind direction) is called called the axial force (Longitudinal force) ΔT_1.
This is the force, by which, the air flow through the propeller is slowed down. For a propeller with clean surfaces ΔD is small compared to ΔL . For a high-speed rotating propeller the angle ϕ is small. Under projection in the direction of the axle, the influence from ΔD is further reduced, so that, in this relationship, it is of no importance.

Projection of ΔL in the axle direction is $\Delta L \cdot \cos\phi$.

For a high-speed propeller ϕ is small, and consequently; $\cos\phi \cong 1$.

Therefore the usage of $\cos\phi = 1$. It is only for the blade near the wing root that the approximation will give differences in the calculated results. The force ΔL is the product of the lift coefficient c_L , the dynamic pressure $\frac{1}{2} \cdot \rho \cdot w^2$ and the blade element area $b \cdot \Delta r$. The number of the blades are z , and inside a ring element in the propeller disc, the axial force is therefore :

$$\Delta T_1 = z \cdot c_L \cdot \frac{\rho}{2} \cdot w^2 \cdot b \cdot \Delta r$$

The propeller's effect after the formula :

$$p = 0.5 \cdot c_p \cdot \rho \cdot A \cdot v^3$$

is a product of the propellers brakeing power:

$$T_2 = (4/9) \cdot \rho \cdot v^2 \cdot A$$

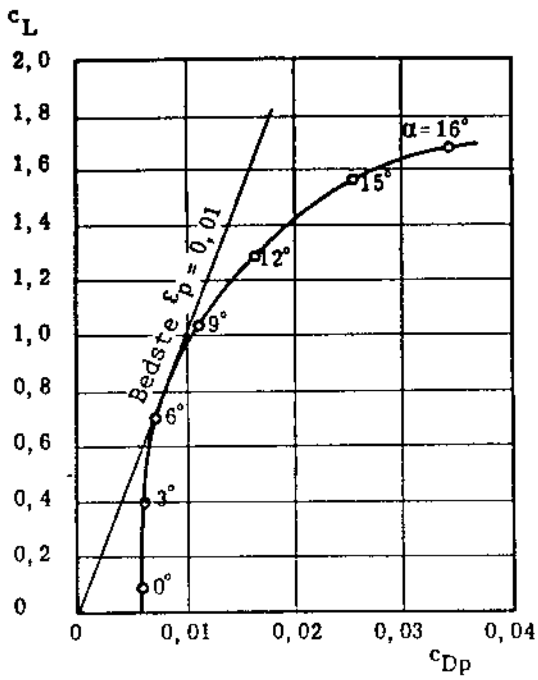
on the air stream passing through, and the speed of the air stream after it has passed the propeller, that is $2/3 \cdot v$ under the maximum effect attainment.

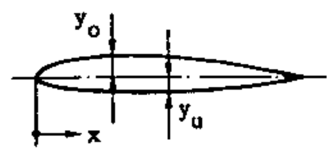
The propeller is designed so that:

The effect is evenly spread over the propeller disc. The proportion of the force that is transfered inside the ring element $\Delta A = 2\pi \cdot r \cdot \Delta r$, is therefore:

$$\Delta T_2 = \frac{4}{9} \cdot \rho \cdot v^2 \cdot 2 \cdot \pi \cdot r \cdot \Delta r$$

Polar Curve





x	y_o	y_u
0	0,00	0,00
1,25	2,67	1,23
2,5	3,61	1,71
5	4,91	2,26
7,5	5,80	2,61
10	6,43	2,92
15	7,19	3,50
20	7,50	3,97
30	7,55	4,46
40	7,14	4,48
50	6,41	4,17
60	5,47	3,67
70	4,36	3,00
80	3,08	2,16
90	1,68	1,23
95	0,92	0,70
100	0,00	0,00

Profile Coordinates

Figure 2. NACA 23012 Wing Profile

ε_p = profile glide number

c_{D_p} = profile drag

Formula: $\Delta T_1 = 0.5 \cdot z \cdot c_L \cdot \rho \cdot w^2 \cdot b \cdot \Delta r$
Axial-force

is based on the aero dynamic properties of a blade element.

In the formula :

Axial-force $\Delta T_2 = \frac{4}{9} \cdot \rho \cdot v^2 \cdot 2\pi r \cdot \Delta r$

The starting point is the optimal energy transfer between the propeller and the air stream. These are in two different ways, expressions for the same force. One can therefore set

$\Delta T_1 = \Delta T_2$. If in addition:

$$w^2 = \left(\frac{2 \cdot v}{3}\right)^2 + (r \cdot \omega)^2$$

$$\lambda_{\hat{}} = \frac{R \cdot \omega}{V}$$ (the nominal speed of the propeller)

Will these lead to the following formula:

$$z \cdot \frac{b}{R} = \frac{16 \cdot \pi}{9 \cdot c_L} \cdot \frac{1}{\left(\frac{r}{R}\right) \cdot \lambda_{\hat{}}^2}$$

This formula is used to calculate the blade width b , which is necessary to fully utilize the wind energy.

The lift coefficient c_L varies along the length of the blade. How large c_L becomes, depends on how great an angle of attack α, the blade is constructed with. A relativly low value for c_L for the outer portion of the blade makes turbulence losses at the blade tips small. This is an advantage for propeller efficiency. It is also advantageous with regard to to the flexation forces in the blade. It is suitable to chose $c_L = 0.6$ at the outer section of the blade. The coefficient can be gradually increased to $c_L = 1.3$, at the blade root.

It may be noticed that the factor λ_λ^2 on the right hand side of the formula, has a dominating infulence on the blade width. If, for example, the speed relationship changes from 5 to 7, the necessary blade width is reduced 50%.

This means that less raw material is used to manufacture the blades, if the speed relationship is high. However the higher the speed relationship, the smoother the surface must be, otherwise the efficiency will suffer. Small blades, have a low start moment, but there can also be a problem concerning the strength of small blades. The most economical result is obtained with a speed relationship of about 7 - 8.

The blade shape is decided by the the factor (**r / R**) in the denominator in the formula for the optiminal blade-width **b:** (**z** = number of blades).

$$z \cdot \frac{b}{R} = \frac{16\pi}{9 \cdot c_L} \cdot \frac{1}{\left(\frac{r}{R}\right) \cdot \lambda_{\wedge}^{2}}$$

The denominating infulence is only partly countered by the lift coefficient c_L , that increases towards the root. This results in the blade width increasing from the wing tip in towards the root. As a rule the trapezium shape with it's straight lines, will be equivlent to the calculated blade shape.

With the assistance of the first diagram (figure 1), the following formula is obtained :

$$\cot\phi = \frac{r \cdot \omega}{\frac{2}{3} \cdot v} = \frac{3}{2} \cdot \frac{r \cdot \omega}{v} = \frac{3}{2} \cdot \left(\frac{r}{R}\right) \cdot \lambda_{\wedge}$$

The angle ϕ is calculated for a number of the values of the cordinate **r / R** . From the angle ϕ the angle of attack α is drawn, chosen with regard to the necessary lift. This is done with assistance of the second diagram.

Following this, one can for the same cordinates **r / R** ,

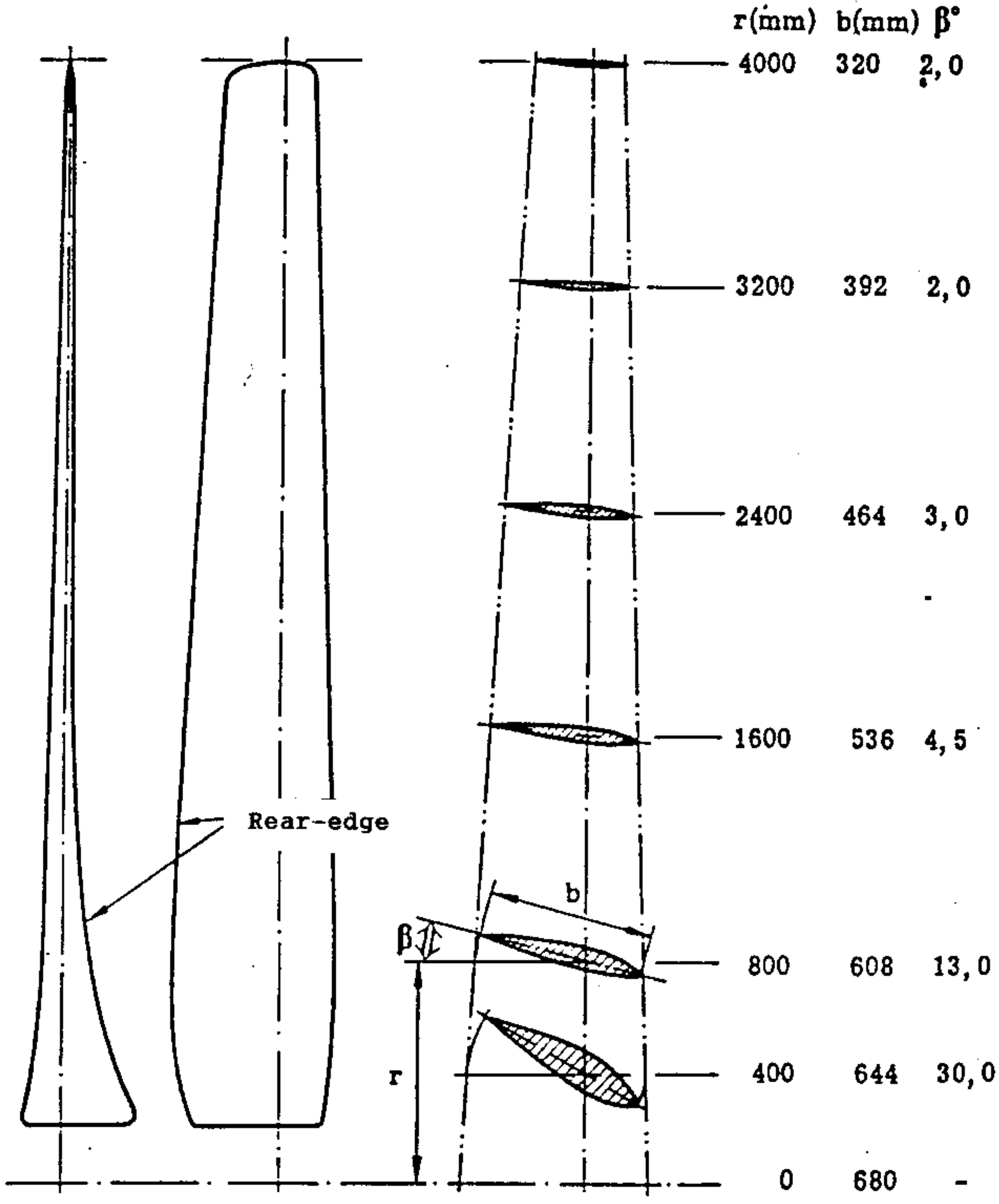
calculate $\beta = \phi - \alpha$ = blade angle (taper).

The blade angle is the angle between the blade profile's angle in relation to the plane of rotation of the propeller.

The angle β is used in marking up the measurements of the propeller blade.

The blade cross section profile is also part of the blade profile. A suitable profile for a propeller blade is the blade profile **NACA 23012** . The table with fgure 2. shows the cordinates for this profile. In towards the wing root, it may be necessary with a thicker profile for reasons of strength. If one multiplies the profile cordinates for the basis profile, as listed in the table, with a constant then the profile cordinates for the thicker profile will be the result.

The geometry for a propeller blade for a three-blade propeller with a speed relationship **7** is shown in the following diagram (figure 3).



Propeller Axle

Figure 3. Propeller blade for a 3-blade propeller

(Speed relationship 7).

EFFECT. EFFICIENCY. MOMENT

A wind turbine with a high efficiency can be replaced by a wind turbine with a lower efficiency, but with a larger propeller. **The best wind-turbine is the one that produces energy at the lowest cost.** For a wind machine efficiency has not quite the same clear meaning for economy as is, for example, the case with a petrol or diesel engine. However a smaller propeller with a high efficiency has a lower weight. If this efficiency is not achieved by dependence on extremely smooth surfaces, or expensive materials, then this is, from an economic point of view preferable. A high efficiency means that the forces on the blades are reduced.

Axial, (longitudinal) forces are transferred to the tower and other parts of the wind turbine's structure. With a high efficiency, many of the wind turbine's components, can therefore be constructed with smaller dimensions, therefore giving lower total construction costs. So although the wind is a free resource, there are strong motives to construct wind turbines with a high useful effect/efficiency .

Following from formulae:

$$P = 0.5 \cdot c_p \cdot \rho \cdot A \cdot v^3$$

Effect coefficient c_p

$$\eta_p = c_p / 0.592$$

the wind turbine effect will be:

$$P = c_p \cdot (\rho/2) \cdot (\pi \cdot R^2) \cdot v^3$$

and the efficiency :

$$\eta_p = c_p / 0{,}592.$$

The limits- curve for the highest propeller efficiency, follow from the relationship:

$$\eta_p = 1 - \frac{3}{2} \cdot \varepsilon \cdot \lambda_\wedge$$

for speeds greater than $\lambda_\wedge = 3$. This curve is reproduced in the diagram, figure 4. High efficiency is obtained with many-bladed propellers with small blades and smooth surfaces.

The " glide number " : ε , is the sum of the glide numbers ε_p and ε_i . The blade profile's glide ratio is the relationship between the coefficients of profile drag c_{D_p} and lift c_L , therefore, $\varepsilon_p = c_{D_p} / c_L$

Coefficients are dependent on the angle of attack and are characteristic for the specific blade profile. The relationship between the three variables is given in a polar diagram for the profile, (see diagram, figure nr. 2). A straight line from the zero point, tangents the polar curve at the value for the relationship c_{D_p} / c_L , that gives the best (= least) profile glide number ε_p . It is found, that the best glide number for the blade profile **NACA 23012** according to the diagram is ε_p = **0.01** . The glide number's other sum ε_i , is dependent on the induced resistance at the wing tips. This resistance is low for a free-running propeller. However when the propeller is braked by the transfer of energy to an electrical generator, the induced resistance is increased, and thereby also ε_i . Therefore a propeller blade's glide number is greatly reduced by the braking effect of an electrical generator. The sum of the two glide numbers for a high efficiency propeller under full load is: ε = **0.025** .

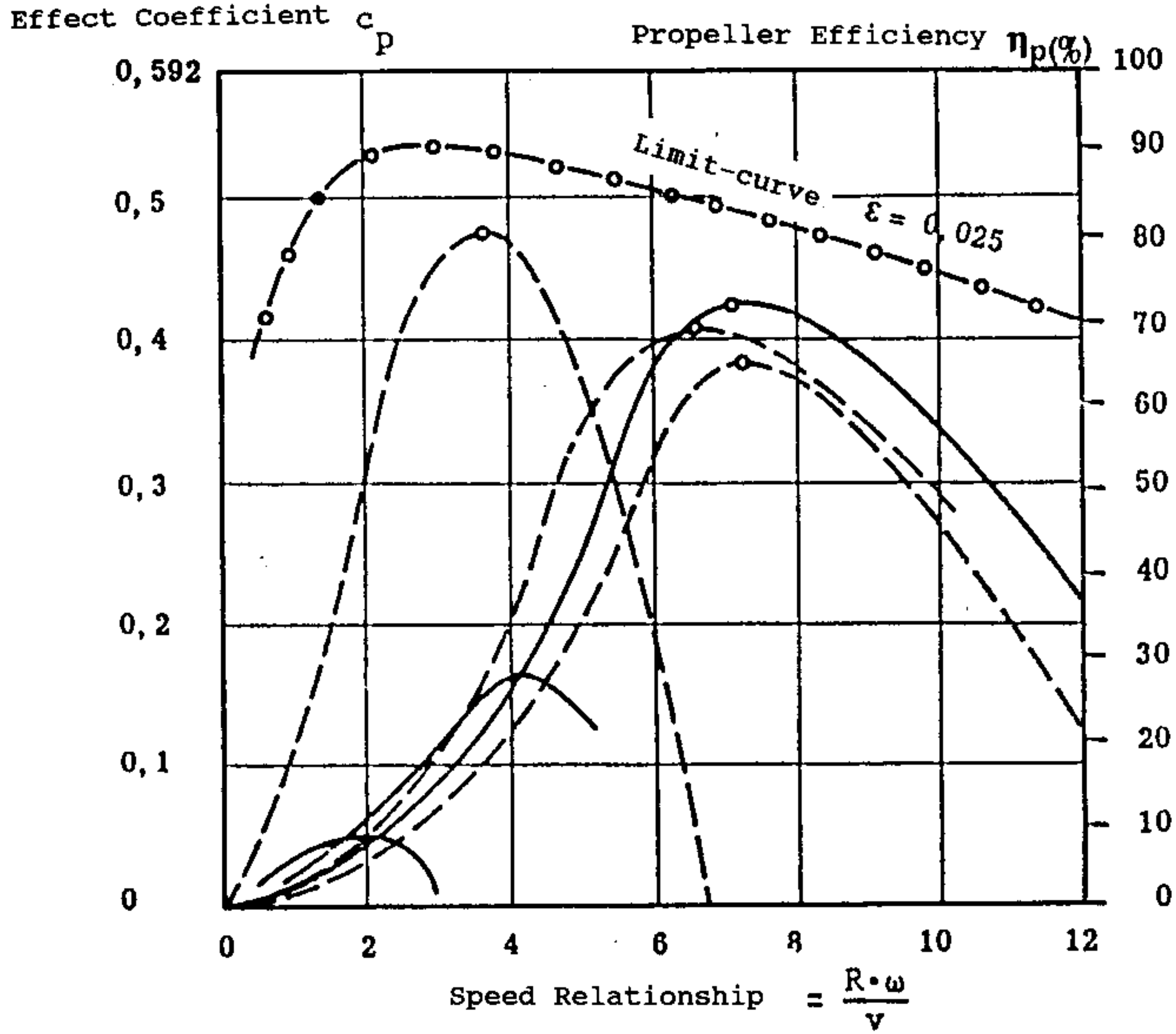


Figure 4. Effect coefficient for different propeller types

o = Best efficiency (=)

From wind-tunnel tests, for 3-blade pitch regulated / adjustable, blades.

The best efficiency is achieved with a propeller with low value, (about 3) for speed relationship's $\lambda_{\wedge} = R \cdot \omega / v$. However such propellers must have many blades, to fully utilize the wind energy. It is complicated to construct a blade angle changing device. Blade pitch regulation can be necessary for the regulation of effect under high wind speeds, and to avoid strong forces during storms. A propeller with a greater speed relationship, and a somewhat lower efficiency is therefore better suited for modern wind turbines. Material usage in blade manufacture is also much less for the high-speed propeller. This is of decisive importance for large wind-turbines.

The diagram (figure 4), shows the curve for the propeller efficiency and effect coefficient for 3 wind tunnel tested wind turbine blades, with speed relationships $\lambda_{\wedge} = 3.5$, 6.5 , and 7. Propellers with the larger speed relationships can obtain propeller efficiencies of about 70 % .

For wind speeds, lower than the wind speed for full effect, the wind turbine is constructed in such a way that the propeller works with the greatest possible efficiency. If the turbine has a generator that permits variable rotational speeds, the rotation speed is allowed to follow the wind speed. The relationship $R \cdot \omega / v = \lambda$ therefore becomes a constant $= \lambda_{\wedge}$, and the wind turbine can therefore operate with maximun efficiency with wind speeds up to full effect.

However if the turbine has a generator type, that only allows a constant speed of rotation, (constant $R \cdot \omega$), the normal working level lies to the right of the top of the efficiency curve during wind speeds lower than the nominal. The efficiency is therefore lower than the maximum.

In both generator types the gear ratios in the gearbox between the propeller axle and the generator must be as described in the following :

Under the nominal wind speed $v_{\wedge}$, the given propeller axle effect is sufficient to give the generator full effect.

The gearbox's gear ratio j , is calculated, so that the propeller acheives the best efficiency at this point, following the formula :

$$j = \Omega / \omega = \Omega \cdot R/\lambda_{\wedge} \cdot v_{\wedge}$$

(the generator's nominal speed of rotation is $\Omega / 2 \cdot \pi$ Hz that is, Ω radians per second).

Under wind speeds higher than $v_\wedge$, a propeller with a fixed blade angle gives a higher effect than the generator can accept. With blade angle changing (pitch regulation),

-- the fully drawn line in figure 4, --

propeller efficiency is sufficiently reduced. An increase of wind speed to $2 \cdot v$ requires on the grounds of strength that the propeller efficiency reduces to **1/8 th.** This is roughly the reduction that is achieved as shown by the bottom small curve for the adjustable pitch propeller in the diagram.

The transfered effect P in an axle is the product of the axle's torque Q and it's angle speed ω , $P = Q \cdot \omega$ and the moment $Q = P / \omega$.

With the use of the formula:

$$P = 0,5 \cdot c_P \cdot \rho \cdot A \cdot v^3$$

for the effect, the moment will be :

$$Q = P/\omega = \frac{1}{\omega} \cdot c_P \cdot \rho/2 \cdot A \cdot v^3$$

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for the effect, the moment will be :

$$Q = P/\omega = \frac{1}{\omega} \cdot c_P \cdot \rho/2 \cdot A \cdot v^3$$

However $\omega = \lambda \cdot v / R$, which therefore gives :

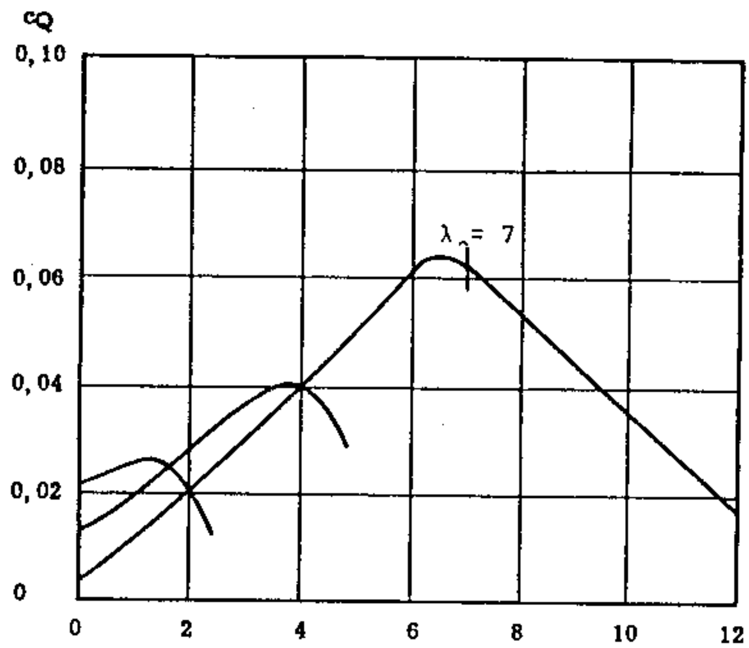
$$Q = c_Q \cdot \frac{\rho}{2} \cdot A \cdot R \cdot v^2$$

The effect coefficient c_P is the product of the moment coefficient c_Q and the speed relationship λ . Under wind tunnel tests c_Q is measured and from these measurements c_P is calculated. Figure nr. 5 is a diagram of the moment coefficient of the adjustable blade in the diagram, figure nr. 4. The maximum moment is not obtained at the same time as the maximum effect. When the propeller is working with maximum effect, it can further be braked with a some-what larger moment.

The diagram also shows, that when $\lambda = 0$ the moment is small, if the blade is set with a smaller blade angle. (when $\omega = 0$, that is when the propeller is not rotating, the relationship is also $\lambda = R \cdot \omega / v = 0$) The propeller has therefore a poor start moment with a small blade angle. However if the blade angle is increased up to 30 or 40 degrees the moment for the stationary blade is increased many times. With blade angle changing / adjustable pitch blades, the wind-turbine's start capability is improved greatly.

Changing the blade angle / pitch may therefore be necessary, both , for regulating the surplus-effect, and to enable the wind-turbine to more easily start during low wind speeds.

Moment Coefficient

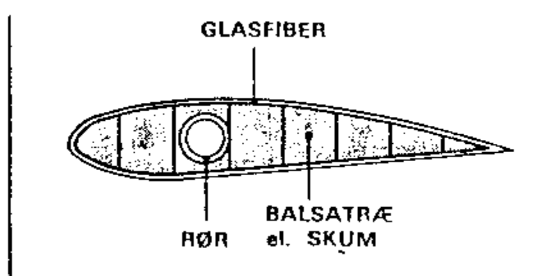


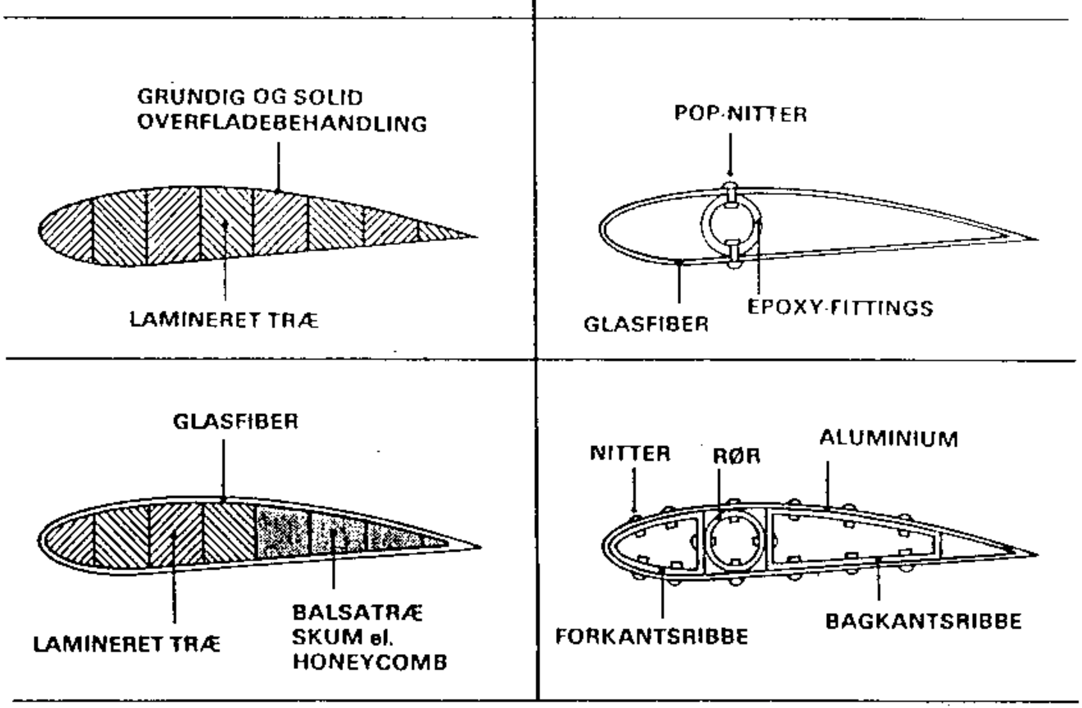
Speed Relationship

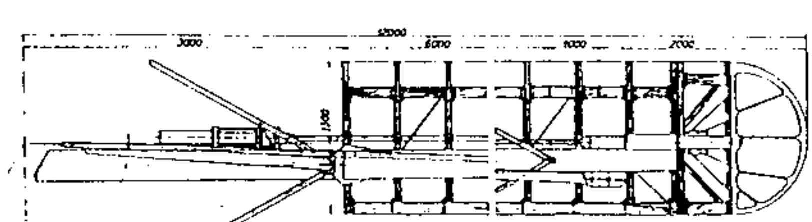
Figure 5. Moment coefficient for 3-blade adjustable pitch, propeller

CONSTRUCTION PRINCIPLES

The most used materials in wing construction are :
Canvas; Wood; Glas-fiber; and Aluminium.
Normally it is important to obtain as low a weight as possible, resulting in lower demands on the strength of the construction.
It is important to obtain as high a kW as possible, for the invested money. As a, " perfect " wing demands great precision, and therefore is highly labour-intensive, for smaller units, a rectangular wing is often chosen. If the wing is made slightly larger, this compensates for the lower efficiency.







GEDSERMØLLENS RIBBEKONSTRUKTION

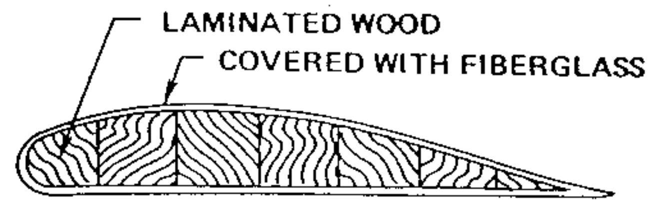
The structural design of a blade, and the materials with which it is made determine blade strength. The blade must be designed to take centrifugal tension and bending. It must retain the airfoil shape and twist, and remain firmly attached to the hub. Several ways exist to accomplish all of these design tasks. Here are a few of them.

First, the carved wood method uses construction skills which are not new to experimenters. Carving wood is easy, fun, and very rewarding. Wood, however, is not necessarily the best material with which to build a windmill. It's true that wood is the most readily-available, replaceable resource, but wood soaks up moisture and it is mighty difficult to prevent this from happening. If one blade soaks more water than another, it's easy to see that an out-of-balance condition will result. You can calculate the result of this by changing the weight of one blade in your practice calculations for centrifugal force. In the overspeed condition, out-of-balance is liable to cause the windmill to shake itself to death. If, on the other hand, you will take care to keep the wooden blades sealed, this is a great way to build a windmill.

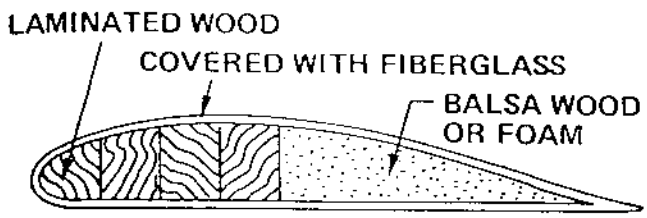
As a result of the Hans Meyer plans for a windmill printed in POPULAR SCIENCE, lots of people are building windmills with Method 2, a tube spar inside a paper honeycomb filler, skinned with fiberglass. While honeycomb is somewhat expensive this method is an easy way to build experimental blades. The skills required to work with honeycomb and fiberglass are easily learned and the results of your efforts are strong, high-performance blades.

The rivetted aluminum structure yields a blade which is strong, light weight, and which will last a long time. The skills of rivetting, drilling, metal forming and bonding are easy to master.

1. Solid, or partially solid carved wooden blade with bolted steel or aluminum hub attachment. Wooden blades can be "skinned" with fiberglass and resin for improved protection.

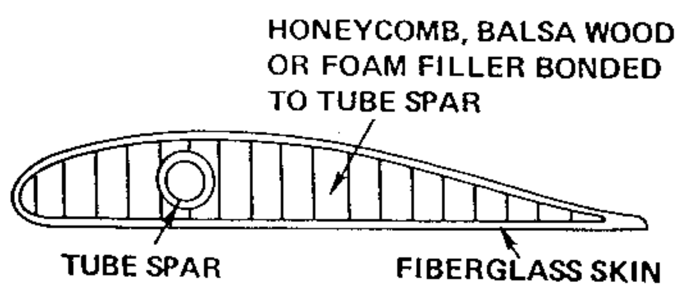


SOLID WOOD BLADE

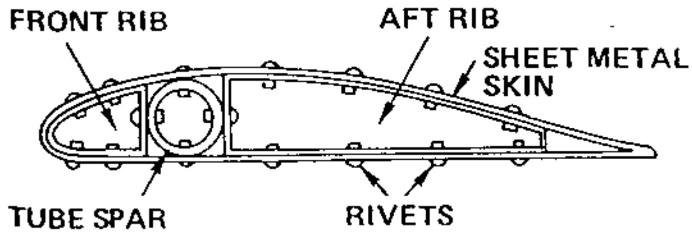


PARTIALLY SOLID BLADE

2. Tubular spar, with foam, balsa wood, or honeycomb, or other filler, covered with fiberglass and resin. The spar can be made of aluminum, steel, or stainless steel.

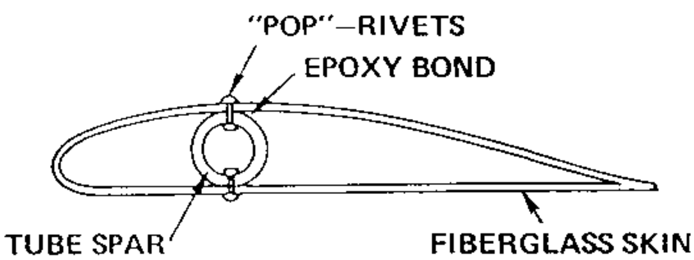


3. Tubular spar, with metal ribs and skin.



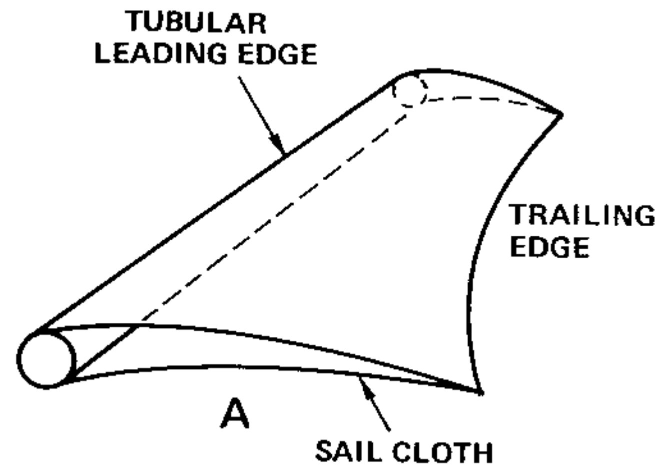
The usual material for this design is aluminum, but you will have to be careful in planning this type of blade to get the skin to take both the curvature of the airfoil, and blade twist. Try constructing a test blade with paper. Rivets and epoxy bonding will attach the skin, ribs, and spar together. Rivets may be aircraft aluminum, or steel "pop-rivets".

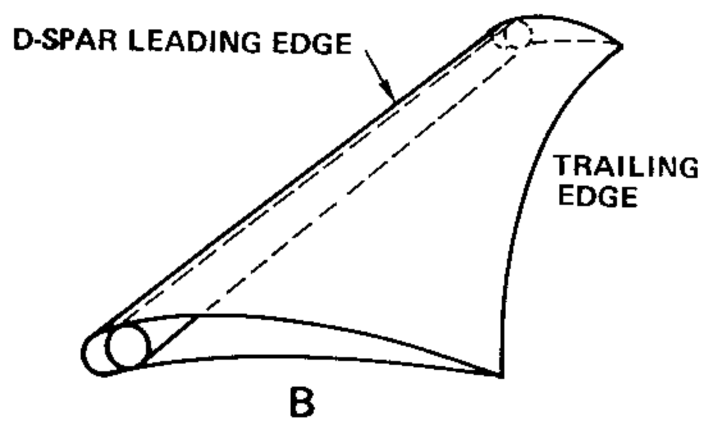
4. Tubular spar, with molded fiberglass skin.



A few foam ribs may be bonded inside the fiberglass, but in any case, the fiberglass skin will be four to eight laminations thick, and must be strong enough to avoid flexing in strong winds.

5. Sailwing construction will make fine, economical blades.





These blades are easily made with a tube spar, a stretched cable trailing edge, and a plasticized fabric (the fabric pores are sealed against air leakage) membrane. The membrane changes curvature in response to changing airflow, and thus generates high lift quite efficiently. The membrane must be stretched fairly tight for best performance. An ideal membrane can be made from the light weight nylon fabric that backpacking tents are made with, or extra light sail cloth, as used on hang gliders.

§ 8. Use of Nonmetallic Materials

Plastics and reinforced concrete are ever more widely used as construction materials in wind machines for manufacture of blades, towers, bushings and bearings. Along with a reduction in metal consumption and labor consumption of manufacturing parts and improved operational indices, with the use of these materials, the attainment of simple methods for identical blades which are resistant to atmospheric phenomena and mechanical defects is made easier. In connection with the operating conditions of wind machines, which make organization of constant servicing more difficult, it is necessary to move away from frequent lubrication of supporting devices and use self-lubricating bearings. For pasture machines, use of reinforced concrete towers, which during the periods when the watering points are not functioning are not dismounted while the basic components and mechanisms of the wind machine are subjected to preserving, is frequently justified.

Blades of pressed fiberglass are used in domestic and foreign machines. The load-bearing elements of the blade are the fiberglass skins or box longerons. Plastic foam is usually used as the filler. The absence of metal spars and ribs simplifies manufacture of the blade. Abroad, fiberglass is reinforced with steel or aluminum wire, and is also fitted with a metal load-bearing longeron (spar).

Plastics reinforced with fiberglass on polyethyl resins possess high mechanical characteristics. The tensile and cross breaking strength of fiberglasses on a base of PN-1 resin reaches 0.2 kn/mm^2; they are resistant to the effect of repeated loads. The strength of fiberglass under low frequency cyclic loads with the asymmetrical cycle taking place in blades is close to the strength of aluminum alloys and reaches 0.13 kn/mm^2. Blades of fiberglass are not very sensitive to cuts or the action of abrasive particles. Considering, however, that the windmill is a responsible component, the lowest fatigue limits (up to 0.07 kn/mm^2) should be selected when calculating blades.

The use of fiberglasses decreases the weight of the windmill, increases reliability, simplifies servicing, since the blades are less damaged during work and transportation, and does not need painting. Pressed blades have higher quality surface and coefficient ξ by comparison with blades having a metal skin. Of the two methods for pressing blades: 1) under high pressures and temperatures using hot setting resins and 2) under normal temperatures using cold setting polyester resins (PN-1, PN-4), the most preferred is the second, in which time and expenses on manufacture are reduced. However, with the second method for pressing, the strength characteristics and resistance of the blade against the effect of moisture and temperature jumps are somewhat reduced (by 12-15%0.

Of the two typical blade designs (Fig. 137, a and b) of machines having a power of 1.5 kW, the first (Fig. 137, a) does not have a longeron, and its load-bearing skin is made of changing thickness, decreasing from 10 mm at the hub to 2 mm at the periphery; the inner hollow is filled with plastic foam. This blade design is preferable for relatively thin blades and is convenient in that one molding press is required for manufacture of the blade. Blades of constant width (Fig. 137, b) have a load-bearing longeron, which is also obtained by the cold pressing method. This allows the skin thickness to be decreased, but the technology of manufacturing the blade was made more complex. Blades of larger machines are fastened to the hub with universal tips, which are connected to the blade with bolts.

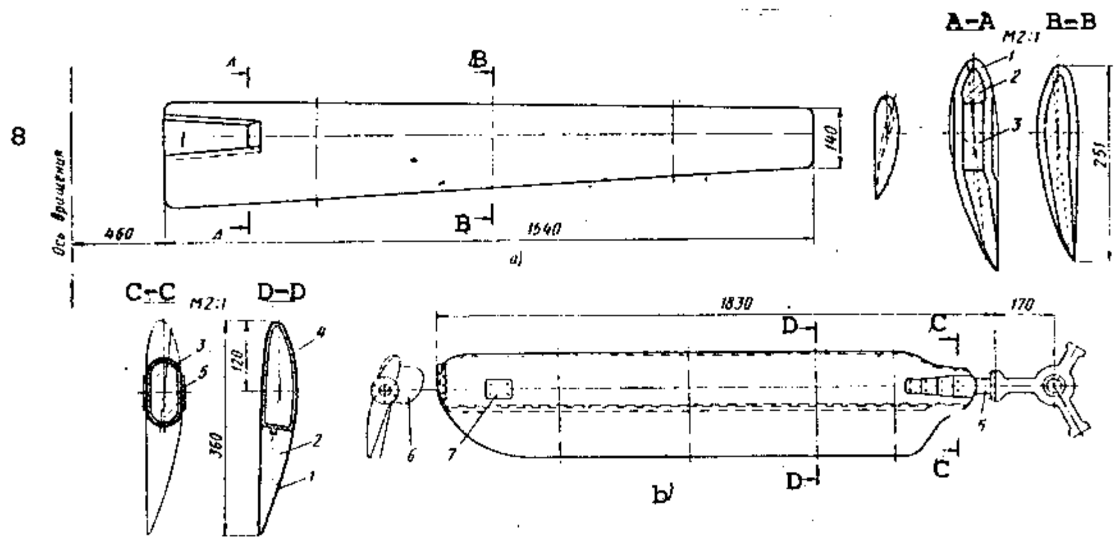


Fig. 137. Blades of fiberglass: a. without longeron; b. with longeron; 1. skin of glass fabric; 2. plastic foam filler; 3. textolite insert beneath connector; 4. longeron; 5. connector; 6. tab; 7. balancing weight; I. slot for fastening connector; 8. axis of rotation.

Under strict observation of the engineering process, the difference in the weight of pressed blades going into a set is relatively small. Thus, with D_{wm} = 4 m, it does not exceed 2%, and deviation in the value of the static moment is no greater than ± 0.7 n·m. For hot pressing, this deviation is still smaller. Selective choice of blades during formation of sets allows their balancing to be avoided.

Testing of blades and accumulated experience allows their incorporation to be recommended. With an identical volume of space, the cost of manufacturing blades of fiberglass is 15-20% lower than metal ones.

A wind machine has many bushings and sliding bearings, for which thermoplast polymers with a low specific weight and coefficient of friction, and which do not require lubrication, are relatively cheap and easily machined, are effectively used. Some of their deficiencies (low heat conductivity and heat resistance, high coefficient of linear expansion) are not essential for the working conditions in wind motors. The most long-lived of these polymers is fluoroplast-4: it is not wetted by water, and when filled with graphite, has a coefficient of friction of $f = 0.02$ (the coefficient of dry friction on steel is equal to 0.04-0.07). It is used for regulator bushings and in the supports of the water lift and drive. In more difficult conditions (at high temperature and dynamic forces) AG-1500 stannic graphite works best.

Replacing the metal support with reinforced concrete reduces expenditure of metal by four times and greater. Depending on the purpose and layout of utilization, the tower can be made tubular with one or two bracing guys and a hinged device in the lower part; free-standing with its section changing with height and a rigidly fastened foundation part or a frame type with reinforced concrete elements fastened together with bolts. The strength of supports made of prestressed reinforced concrete can be significantly increased by centrifuging.

Supports of the first type can be recommended for machines of medium power. The expenditure of metal on manufacturing these supports is reduced by 6-7 times by comparison with the expenditure of metal for manufacturing a metal support. Supports of the second type are expedient to use for small electrical and pumping machines. For conservation of the motor, these supports are not dismantled. Supports of the third type are universal, although their assembly is complex. With an output of 3-4000 per year, the cost of this support is equal to the cost of a metal one or somewhat lower.

AERODYNAMIC FORCES AND OTHER TRANSFERS OF ENERGY

In any airflow, there are important changes of energy that occur throughout the air itself, and between the flow and solid surfaces. There are three main classes of energy transfer: mechanical forces (pressures), heat and electromagnetic forces.

Aerodynamic pressures and forces

Interest in the pressure of the air on a small region of a solid surface arises for four reasons:

(i) Such information is directly relevant to the lifting force of an aeroplane wing.
(ii) The surface must be strong enough to withstand the pressure without collapsing or distorting.
(iii) A definite amount of air may have to be removed from the outside flow either to measure its characteristics, to ventilate a building, or to feed a fan or an engine.
(iv) Gas may be ejected from that point, e.g. an exhaust or a petrol jettison vent.

The surface pressure results from the speed and density of the main flow, and from the speed changes and energy losses which have occurred while the flow has been passing over the surface up to the point in question. It will thus depend on the state of the boundary layer and the angle of the surface to the main flow. If there is a large intake at the point, as in a jet engine, this inward flow will appreciably change the airflow round the body. Local roughness or bending of plates on the surface will also considerably modify the pressures. Pressures can be steady or may vary with time. In the latter case, the oscillations can be large and slow, such as an eddying flow, or small and rapid as in the high frequency sound vibrations created by jet engines or rocket exhausts.

A pressure coefficient is defined thus:

$$C_p = \frac{\text{pressure}}{\text{dynamic pressure}} = \frac{P}{\frac{1}{2}\rho V^2}.$$

Figure 8 shows the pressure at various points on a roof in a wind. The C_p values are roughly independent of the wind speed, so that at 50 m.p.h. the peak suction at point A would be 3·8 lb/sq ft and at 100 m.p.h., 15·3 lb/sq ft. If the wind direction changes, the flow alters and the C_p values will alter too.

Pressure distributions can be drawn for aeroplane wings, space vehicles, rockets, motor cars, etc. The total aerodynamic force on a body or surface is formed by adding together the pressures, allowing for variations in magnitude and direction. Forces are conventionally measured as in Fig. 8. The resultant force is

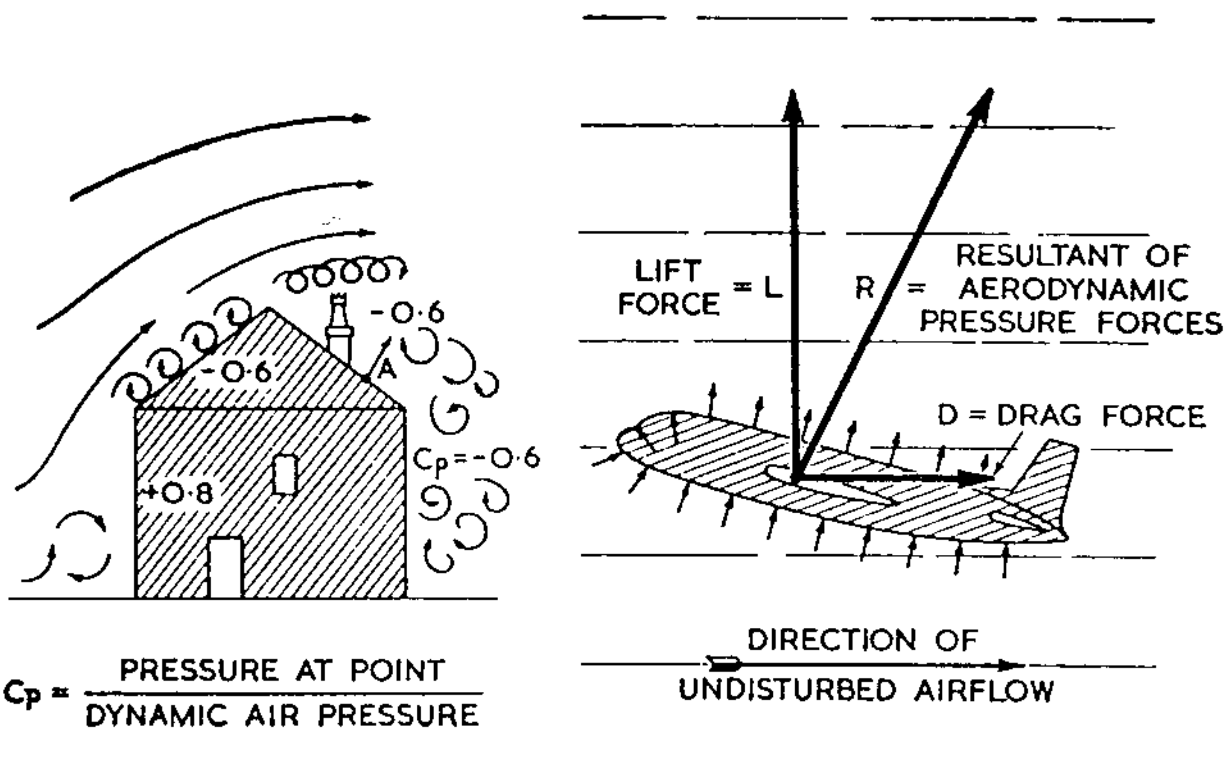


Fig. 8. Aerodynamic pressures and forces

divided (resolved) into a drag force parallel to the main airflow, and a lift force perpendicular to it. The corresponding non-dimensional coefficients are the drag coefficient and the lift coefficient.

$$C_D = \text{drag force}/\tfrac{1}{2}\rho V^2 S \qquad C_L = \text{lift force}/\tfrac{1}{2}\rho V^2 S$$

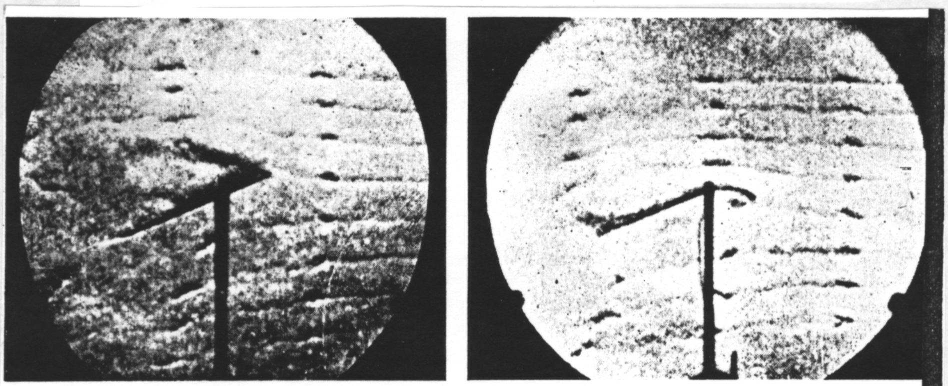
where S is a representative surface area of the body.

LIFT AND DRAG

The leading edge of an aeroplane wing was originally known as the 'Phillips entry'. The best shape for the rest of the top surface has been found to be a curve rising to its highest point at about one-third of the width from back to front, or 'chord', of the wing and with a gradual 'run-home'—to adopt a boat-building expression—to the trailing edge. This form of wing gives a smooth entry for the air and carries it away with the least amount of turbulence at the back (Plate IV.).

But the aerofoil shape not only reduces the 'drag' of the wing, compared with a flat plate, but it also increases the lift—a very important point, because the efficiency of a wing depends, naturally, upon its having the maximum possible lifting effect while at the same time causing as little resistance as possible; or, in other words, upon its having the highest possible 'lift to drag ratio'. The effect of the dipping front edge is to smooth the path of the accelerated air along the top surface and so increase the partial vacuum effect of the lower pressure and increase the circulation round the wing.

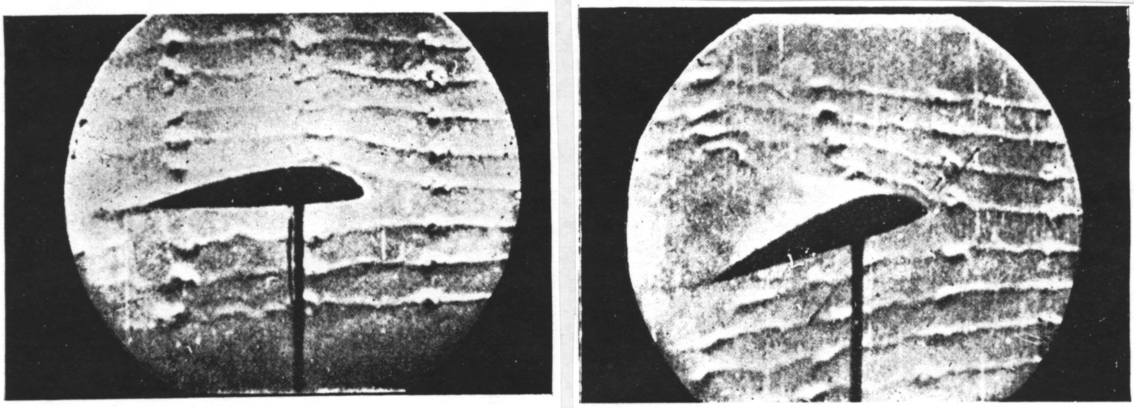
The combined effect of the reduction in drag and increase in lift of the cambered aerofoil is, in a wing of good average shape, to give a 'lift to drag ratio' of about 17 to 1 compared with the 7 to 1 of a flat plate at its best angle. At the same time, the lift alone of a cambered aerofoil may be nearly three times as great as that of a flat plate.



Improvement in flow over the top surface of a flat plate obtained by adding a dipping front edge

THE AEROFOIL

An interesting and important effect of the dipping front edge is that it also makes a cambered aerofoil begin to give lift at a very much flatter angle to the horizontal than a flat plate. It is easy to understand that if a flat plate is mounted absolutely horizontally it will produce no lift at all, the air simply flowing past it above and below with no 'reaction' of any sort vertically—like the board in the bath. A cambered aerofoil on the other hand has quite a considerable lifting effect when placed absolutely parallel to the air stream. Not only so but it begins to lift when it is actually pointing downwards—or 'at a negative angle of incidence' as it is



The flow round a cambered aerofoil at normal angle of incidence and above the stalling angle—or 'burble point'

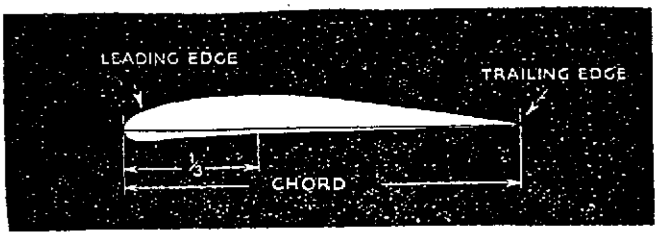


Fig. 4. Aerofoil features

called. The 'angle of incidence' is the angle made by the 'chord' of the aerofoil with the relative wind (the 'chord' being a straight line drawn from the leading to the trailing edge) (Fig. 4.). It is not strictly accurate to describe the angle of incidence as the angle between the chord and the horizontal, because if an aeroplane happens to be flying in an up current of air ir may be pointing downwards when it is actually perfectly parallel to the current of air it is flying through. For this reason the angle is always spoken of with reference to the 'relative' wind, or air flow (Fig. 5.). (The point becomes of practical importance when dealing with engineless gliders which can only remain in the air by taking advantage of an upward current on the windward side of a hill or ridge (Fig. 6.). A cambered aerofoil begins to develop lift when it is set at a negative angle of two or three degrees below the path of the air stream in which it is placed; which gives it, as it were, a considerable 'start' over a flat plate which would be developing 'negative lift', or a tendency to dive downwards, at such an

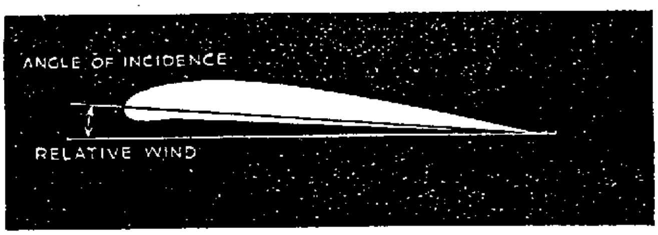


Fig. 5. Aerofoil in lifting attitude

angle. The amount of lift will progressively increase until the angle of incidence is about 15 degrees. But at such large angles —15 degrees is equivalent to a 'rise', of a road on a hill, for example, of 1 in 6—the drag has also begun to go up to a very high figure, and as the ratio of lift to drag is the real measure of the efficiency of an aerofoil in normal flight, its angle will in practice be confined to between -2 or -1 degrees to about $+4$ degrees, when the lift-drag ratio is at its best. It is easy to see why this should be so, when one considers what happens to the air flowing past the wing as the angle of incidence is increased. An aerofoil is, as has been explained, so designed as to upset the flow of air as little as possible. But this is, naturally, when the aerofoil is at, or approximately at, no angle of incidence, lying flat or parallel to the general trend of the air stream. If it is set at an angle much above or below this, it is clear that conditions will be changed and become less favourable to the steady, placid flow of the air, which at once causes an increase of resistance, or drag. The best angle is then necessarily a compromise representing the position at which the ratio of lift to drag is at its highest, though this is by no means necessarily the angle of greatest lift.

It may be wondered why the course taken by the air over the top surface of an aerofoil has been described in some detail, while that taken by the air following the lower surface has been ignored. This is because the shape of the top surface of an aerofoil is of very much greater importance than the underneath. This arises mainly from the fact that the air, as has been shown already, begins to take an upward trend before it actually reaches the leading edge of the aerofoil, or flat plate. In fact, roughly 75 per cent of an aerofoil's lift comes from the top surface, while only the remaining 25 per cent is caused by the direct positive pressure of the air on the under side. It is therefore clear that much more attention need be paid to the precise shape and curvature of the top. This becomes perhaps more easy to understand if it is realized that when an aerofoil is set at an angle to the wind its upper surface is the back, while the lower surface is the face actually receiving the wind direct on it. This will at once become clear if the aerofoil be imagined set up on its edge at right angles to the wind in the same position as we first considered the flat plate. That is, of course, the extreme case, but the effect is the same at all angles down to zero. Now the wind striking against and meeting the lower surface, or front face, of the aerofoil can, at any rate at small angles, do little else but follow along the surface. There is little opportunity for it to form the eddies and vortices that are set up, as the angle is increased, along the top surface. The top surface is, therefore, not only the chief cause of lift but the most potent cause of the setting up of the eddies that mean increased drag. It is therefore the most important both from the point of view of obtaining the greatest lift and of reducing the resistance to the minimum. For this reason quite a number of efficient aerofoils have top surfaces of carefully calculated camber, while their under sides are perfectly flat chords.

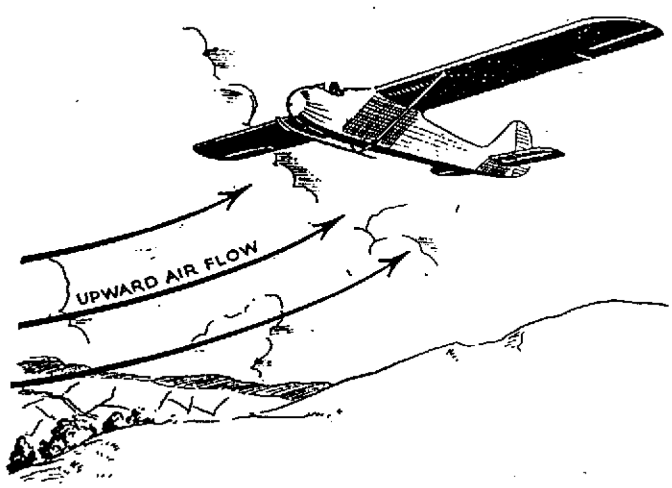


Fig. 6. Glider borne on a wave-crest

Flight Manual: W.K.Kershner. Iowa State Univ. Press USA. 1973. ISBN 0 8138 1610 6

2. *The Airplane and How It Flies*

THE FOUR FORCES

Four forces act on an airplane in flight: *Lift, Thrust, Weight* and *Drag* (Fig. 2-1).

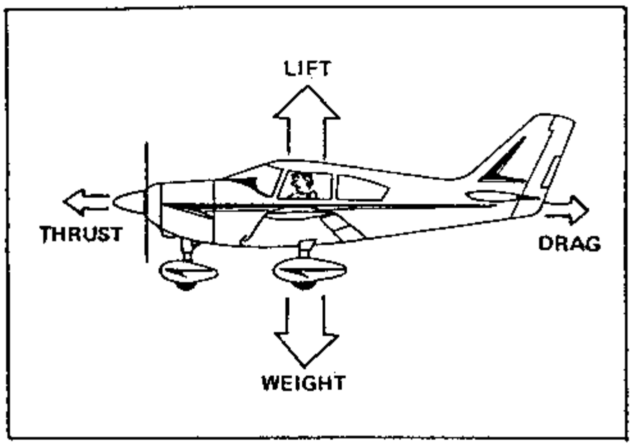


Fig. 2-1. The Four Forces.

LIFT

Lift is a force exerted by the wings. (Lift may also be exerted by the fuselage or other components, but at this point it would be best just to discuss the major source of the airplane's lift, the wings.) It is a force created by the "airfoil," the cross-sectional shape of the wing being moved through the air or, as in a wind tunnel, the air being moved past the wing. The result is the same in both cases. The

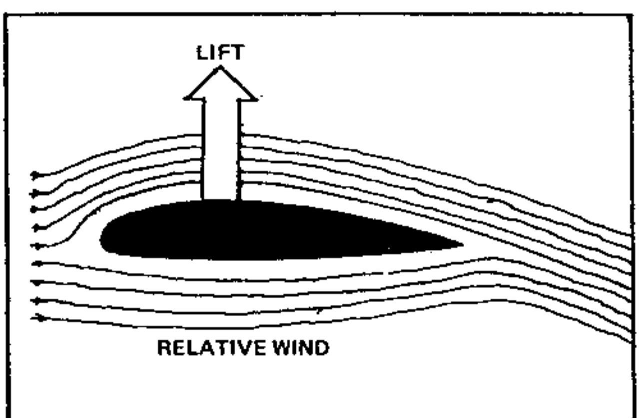


Fig. 2-2. The airfoil.

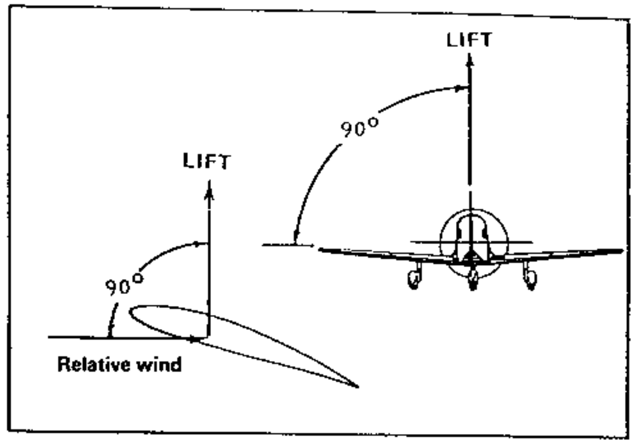


Fig. 2-3.

"relative wind" (wind moving in relation to the wing and airplane) is a big factor in producing lift, although not the only one (Fig. 2-2).

Lift is always considered to be acting perpendicularly both to the wingspan and to the relative wind (Fig. 2-3). The reason for this consideration will be shown later as you are introduced to the various maneuvers.

As the wing moves through the air, either in gliding or powered flight, lift is produced. How lift is produced can probably be explained most simply by Bernoulli's theorem, which briefly puts it this way: "The faster a fluid moves past an object the less sidewise pressure is exerted on the body by the fluid." The fluid in this case is air; the body is an airfoil. Take a look at Figure 2-4, which shows the relative wind approaching an airfoil, all neatly lined up in position (1). As it moves past the airfoil (or as the airfoil moves past it — take your choice),

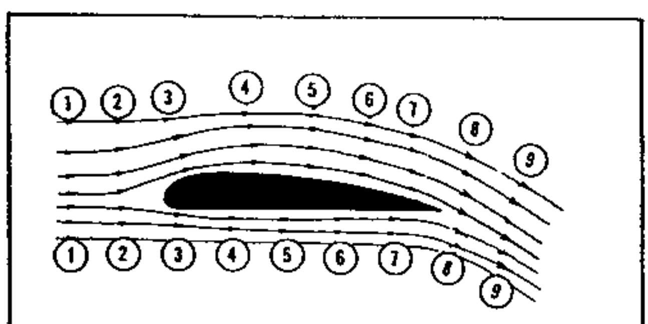


Fig. 2-4.

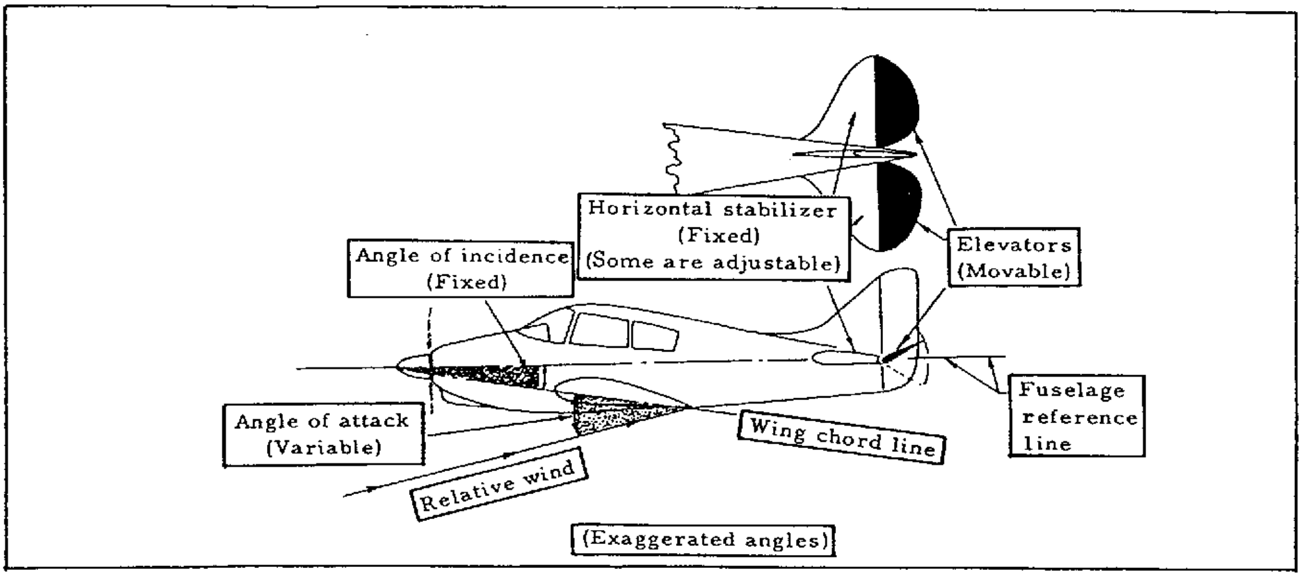


Fig. 2-5. Nomenclature.

things begin to happen, as shown by the subsequent numbers.

The distance that the air must travel over the top is greater than that under the bottom. As the air moves over this greater distance it speeds up in an apparent attempt to reestablish equilibrium at the rear (trailing edge) of the airfoil. (Don't worry, equilibrium *won't* be established.) Because of this extra speed, the air exerts less sidewise pressure on the top surface of the airfoil than on the bottom, and lift is produced. The pressure on the bottom of the airfoil is normally increased also and you can think that, as an average, this contributes about 25 per cent of the lift; this percentage varies with "angle of attack" (Fig. 2-5).

Some people say, "Sure, I understand what makes a plane fly. There's a vacuum on top of the wing that holds the airplane up." Let's see about that statement:

The standard sea level air pressure is 14.7 pounds per square inch (psi), or 2116 pounds per square foot (psf). As an example, suppose an airplane weighs 2000 pounds, has a wing area of 200 square feet and is in level flight at sea level. (The wing area is that area you would see by looking directly down on the wing.) This means that for it to fly level (lift = weight), each square foot of wing must support 10 pounds of weight, or the wing loading is 10 pounds per square foot (2,000 divided by 200). Better expressed; there would have to be a difference in pressure of 10 pounds per square foot between the upper surface and the lower surface. This 10 psi figure is an average; on some portions of the wing the difference will be greater, on others, less. Both surfaces of the wing can have a reduced sidewise pressure under certain conditions. However, the pressure on top still must average 10 psi less than that on the bottom to meet our requirements of level flight for the airplane mentioned. The sea level pressure is 2116 pounds per square foot, and all that is needed is an average difference of 10 psf for the airplane to fly.

Assume for the sake of argument that in this case the 10 psf is obtained by an *increase* of 2.5 psf on the bottom surface and a *decrease* of 7.5 psf on the top (which gives a total difference of 10 psf). The top surface pressure varies from sea level pressure by 7.5 psf, and compared to the 2116 psf of the air around it, this is certainly a long way from a vacuum, but it produces flight!

Note in Figures 2-2 and 2-4 that the airflow is deflected downward as it passes the wing. Newton's Law: "For every action there is an equal and opposite reaction," also applies here. The wing deflects the airflow downward with a reaction of the airplane being sustained in flight. This can be easily seen by examining how a helicopter flies. Some engineers prefer Newton's theory over the Bernoulli theory. But the air *does* increase its velocity over the top of the wing (lowering the pressure), and the downwash also occurs. You'll meet proponents of both views as you progress in aviation. The downwash idea and how it affects the forces on the horizontal tail will be covered in Chapters 9 and 23.

ANGLE OF ATTACK

The angle of attack is the angle between the relative wind and the chord line of the airfoil. Don't confuse the angle of attack with the angle of *incidence*. The angle of *incidence* is the *fixed* angle between the wing chord line and the reference line of the fuselage. You'd better take a look at Figure 2-5 before this gets too confusing.

The pilot controls his angle of attack with the elevators (Fig. 2-5). By easing back on the control wheel (or stick) the elevator is moved "up" (assuming the airplane is right-side-up). The force of the relative wind moves the tail down, and because the wings are rigidly attached to the fuselage (you hope), they are rotated to a new angle with respect to the relative wind, or new *angle of attack*. At this new angle of attack the apparent curvature of the airfoil is greater, and for a very short period lift is increased. But because of the higher angle of attack more drag is produced, the airplane slows and equilibrium exists again. (More about drag later.)

If the pilot gets too eager to climb and *mistakenly* believes that the reason an airplane climbs is because of an "excess" of lift (and so keeps increasing the angle of attack), he could find that he's made a mistake. He finds that as he increases the angle of attack the airplane slows and attempts to reestablish equilibrium, so he continues to increase it in hopes of getting an "excess" of lift for more climb. He may make the angle of attack so great that the air can no longer flow smoothly over the wing, and the airplane "stalls" (Fig. 2-6).

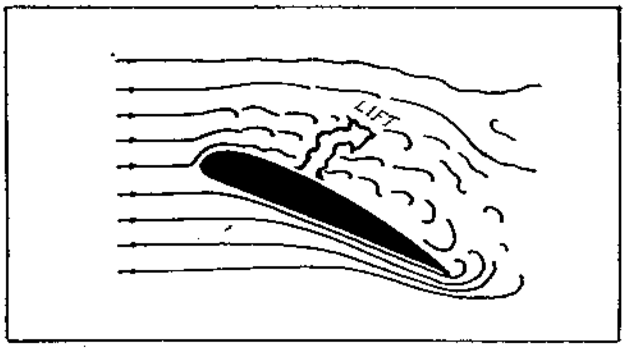


Fig. 2-6. The stall.

It's not like a car stalling, in which case the engine stops; the airplane stall is a situation where the lift has broken down and the wing, in effect, is no longer doing its job of supporting the airplane in the usual manner. (The engine may be humming like a top throughout the stall.) There is still some lift, but not enough to support the airplane. The pilot has forced the airplane away from the balanced situation he wants it to maintain. For the airplane to recover from a stall, the pilot must decrease the angle of attack so that smooth flow again occurs. In other words, point the plane where it's going! This is done with the elevators, the angle of attack (and speed) control (Fig. 2-5). For most light plane airfoils the stalling angle of attack is in the neighborhood of 18 degrees. Stalls will be covered more thoroughly in Chapters 12 and 14.

At first, the student is also confused concerning the *angle of attack* and airplane *attitude*. The attitude is how the plane looks in relation to the horizon. In Figure 2-7 the plane's attitude is 15 degrees nose up, but it's climbing at an angle of 5 degrees so the angle of attack is only 10 degrees.

In a slow glide the nose attitude may be approximately level and the angle of attack close to that of the stall. Later in your flying you'll be introduced to the attitude of the wings (wing-down attitude, etc.) but for now only nose attitudes are of interest.

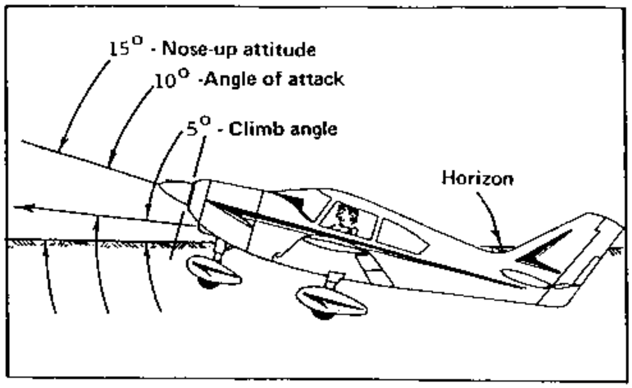


Fig. 2-7.

The coefficient of lift is a term used to denote the relative amounts of lift at various angles of attack for an airfoil at a given speed and altitude. The plot of the coefficient of lift versus the angle of attack is a straight line, increasing with an increase in the angle of attack until the stalling angle is reached (Fig. 2-8).

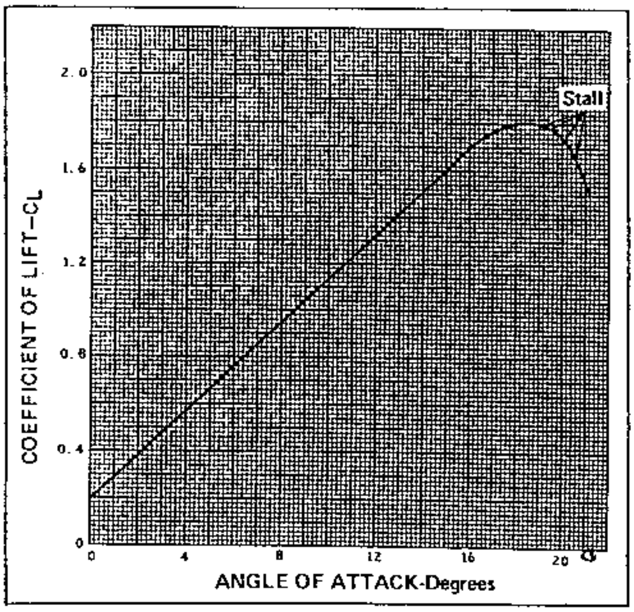


Fig. 2-8.

Lift depends on a combination of several factors. The equation for lift is:

$$L = C_L S \frac{\rho}{2} V^2 \text{ or } L = C_L \times S \times \frac{\rho}{2} \times V^2$$

Where L = Lift, in pounds.

C_L = Coefficient of lift. (Varies with the type of airfoil used and the angle of attack.)

S = Wing area in square feet.

$\frac{\rho}{2}$ = The air density (ρ) divided by 2. Rho (ρ) is air density, which for standard sea level conditions, is 0.002378 slugs per cubic foot. If you want to know the mass of an object in slugs divide the weight by the acceleration of gravity, or 32.2. (The acceleration caused by gravity is 32.2 feet per second per second at earth's surface.)

and V^2 = Velocity in feet per second squared.

When you fly an airplane you'll be working with a combination of C_L and velocity; but let's talk in pilot terms and say that you'll be working with a combination of angle of attack and airspeed. So lift depends on angle of attack, airspeed, wing area and air density. For straight and level flight, lift equals weight. Assuming that your airplane weighs 2000 pounds, 2000 pounds of lift is required to maintain level flight. This means that the combination of the above factors must equal that value. The wing area (S) is fixed, and the air density (ρ) is fixed for any one time and altitude. Then C_L (angle of attack) and velocity (airspeed) can be worked in various combinations to maintain the 2000 pounds of lift required. Flying at a low airspeed requires a high angle of attack, and vice versa. As a pilot you will control angle of attack, and by doing so, will be controlling the airspeed. You'll use power (or lack of power) with your chosen airspeed to obtain the desired performance.

While the factors of lift are being discussed it might be well to say a little more about air density (ρ). The air density decreases with increased altitude and/or temperature increase. Airplanes require more runway to take off on hot days or at airports of high elevation because of decreased air density. You can see in the lift equation that if the air is less dense the airplane will have to move faster through the air in order to get the required value of lift for flight—and this takes more runway. (The airspeed mentioned is called "true airspeed" and will be discussed in more detail in the next chapter.) Not only is the lift of the wing affected, but the less dense air results in less power developed within the engine and, as the propeller is nothing more than a rotating airfoil, it also loses "lift" (or more properly, "thrust"). Taking off at high elevations or high temperatures can be a losing proposition, as some pilots have discovered after ignoring these factors and running out of runway.

Interestingly enough, you will find that lift always tends to remain at a constant value during climbs, glides or straight and level flight. *Don't start off by thinking that the airplane glides because of decreased lift or climbs because of excess lift. It just isn't so.*

Gliding: D.Piggot. A. & C. Black. London UK. 1958.

The gliding angle is measured as a ratio of the distance travelled for the height lost, e.g. 30 : 1. It varies considerably at different flying speeds and depends upon the ratio of the lift and drag. The best gliding angle occurs when the lift/drag ratio (L/D) is at a maximum. This is usually about 15 m.p.h. above the stalling speed. The best gliding angle for a particular type of glider can only be increased by improving the lift or by reducing its drag. (Fig. 45.)

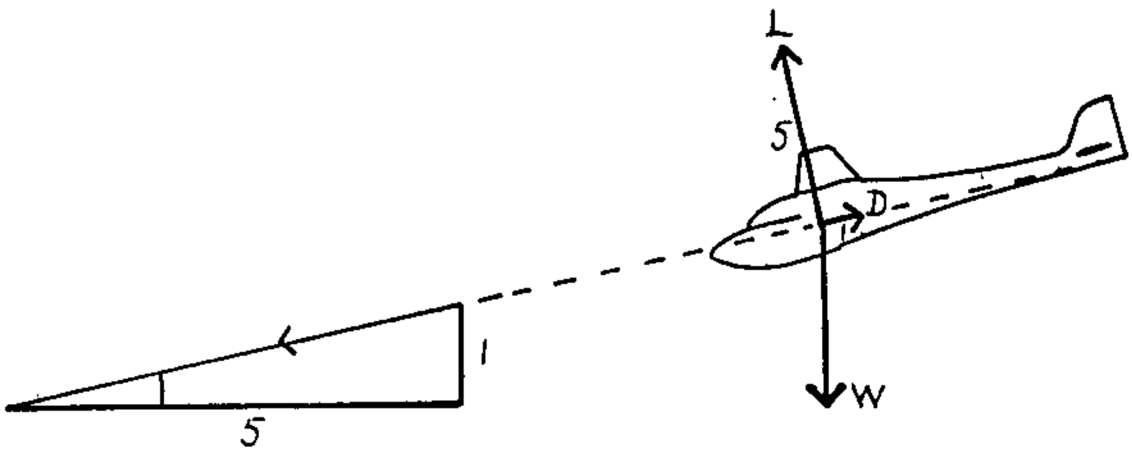


Fig. 45. The gliding angle and the lift/drag ratio. In a steady straight glide the gliding ratio is equal to the ratio between the lift and drag of the glider (5 : 1).

The rate of descent depends on the gliding angle and the flying speed.

3 Flight Mechanics

THIS CHAPTER has nothing to do with the people who work on aircraft; *flight mechanics* are the forces and moments acting on the airplane in flight. While the Four Forces are fresh in your mind from the last chapter it would be well to see how they act on the airplane.

The term *force* was covered in the last chapter, and you've used moments in computing Weight and Balance problems. A moment normally results from a force (or weight) acting at the end of an arm (at a 90° angle to it) and is usually expressed as pound-inches or pound-feet (Fig. 3-1).

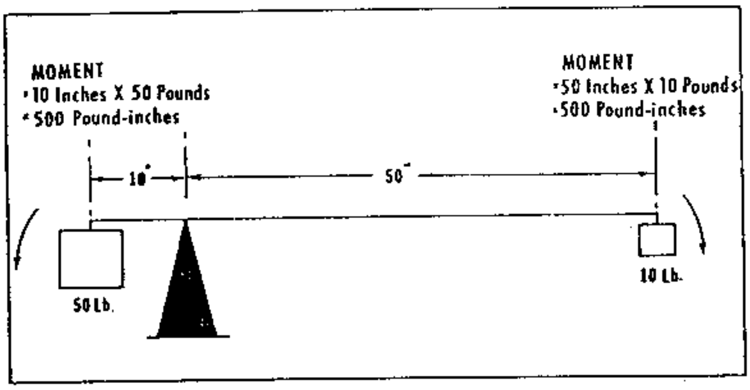


Fig. 3-1. A system of moments in equilibrium.

The airplane in steady-state flight—that is, in a steady climb, a glide, or in level unaccelerated flight (this includes steady level turns)—must be in *equilibrium*, that is, the forces acting in opposite directions on the airplane must cancel each other out. (The same thing goes for the moments.)

A *vector* is an arrow used to represent the direction and strength of a force. You've had experience with vectors in working out wind triangles in navigation and also unconsciously discuss vector systems when you talk about headwind and crosswind components for takeoffs and landings (Fig. 3-2). As a pilot you use the runway centerline as a reference and consciously (or unconsciously) divide the wind into components acting along and perpendicular to this reference axis.

You are interested in the component of wind acting across the runway (for example, 15 K) and, if you were interested in computing the takeoff run, you would use the headwind component, or the component of the wind acting down the runway (say, 26 K). You usually don't go so far as to figure out the exact crosswind component but note the wind velocity and its angle to the runway and make a subconscious estimate of how much trouble it might give you on takeoff or landing. You set up your own axis and work with what would seem a most complicated system if people started talking about axes, vectors, and components. What you do is break down the wind's vector into the two components of most interest to you, as was done in Chap. 1. The same general idea will be used here for the forces acting on the airplane.

The reference axis for operating the airplane is the flight path or line of flight, and the forces are measured as operating parallel and perpendicular to it (Fig. 3-3). For an airplane in a *steady-state condition* of flight such as straight and level unaccelerated flight, a constant-airspeed climb or glide, or a constant-altitude balanced turn of a constant rate, the forces acting parallel to the flight path must be balanced. The same thing applies for those forces acting perpendicular, or at 90°, to the flight path—they must cancel each other. Each of the vectors shown in Fig. 3-3 may represent the total of several forces acting in the direction shown.

The following must be realized in order to see the mechanics of flight:

1. *Lift* always acts perpendicular to the relative wind (and, hence, perpendicular to the flight path). This is the *effective* Lift discussed in the last chapter, or the Lift acting perpendicular to the actual path of the airplane.
2. *Drag* always acts parallel to the relative wind (and flight path) and in a "rearward" direction.
3. *Weight* always acts in a vertical (down) direction toward the center of the earth.
4. *Thrust*, for these problems, always acts parallel to the centerline of the fuselage. (In other words, at this point we'll assume no "offset" thrust line and that Thrust is acting parallel to the axis of the fuselage.)

This chapter will take a look at the Four Fundamentals of flight—*straight and level, climbs, descents, and turns*—and analyze the factors in each.

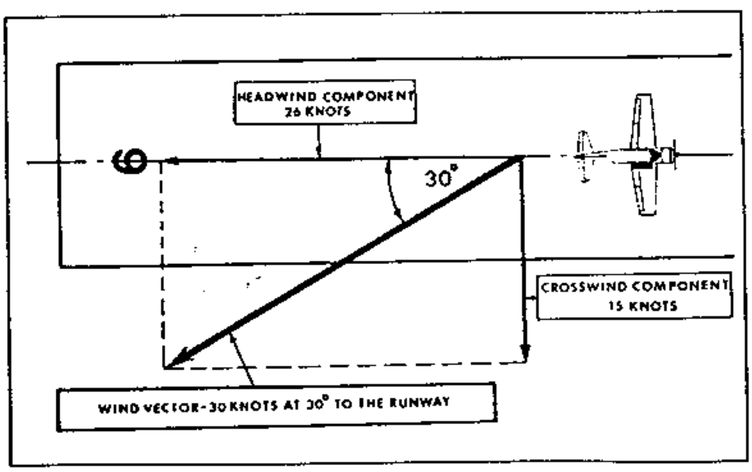


Fig. 3-2. A vector system as faced by the pilot during a takeoff or landing in a crosswind that is 30° to the runway at 30 K (Chap. 1).

THE FORCES AND MOMENTS IN STRAIGHT AND LEVEL FLIGHT

Take an airplane in straight and level *cruising* flight: The average airplane in this condition has a tail-down force because it is designed that way (the need for this will be covered in Chap. 10). Let's examine the forces and moments acting on a typical four-place airplane in straight and level flight at a constant speed at *cruise*.

For simplicity, rather than establishing the vertical acting forces with respect to the center of gravity (CG), which is the usual case, these forces will be measured fore and aft from the center of Lift. Assume at this point that Lift is a string holding the airplane up; its value will be found later (this is legal). The airplane in Fig. 3-4 weighs 3000 lb, is flying at 154 K CAS, and at this particular loading the CG is 5 in. ahead of the "Lift line."

Summing up the major moments acting on the airplane (check Fig. 3-4 for each):

1. *Lift-Weight moment*—The Weight (3000 lb) is acting 5 in. ahead of the center of Lift, which results in a 15,000-lb-in. *nose-down* moment (5 in. × 3000 lb = 15,000 lb-in.).

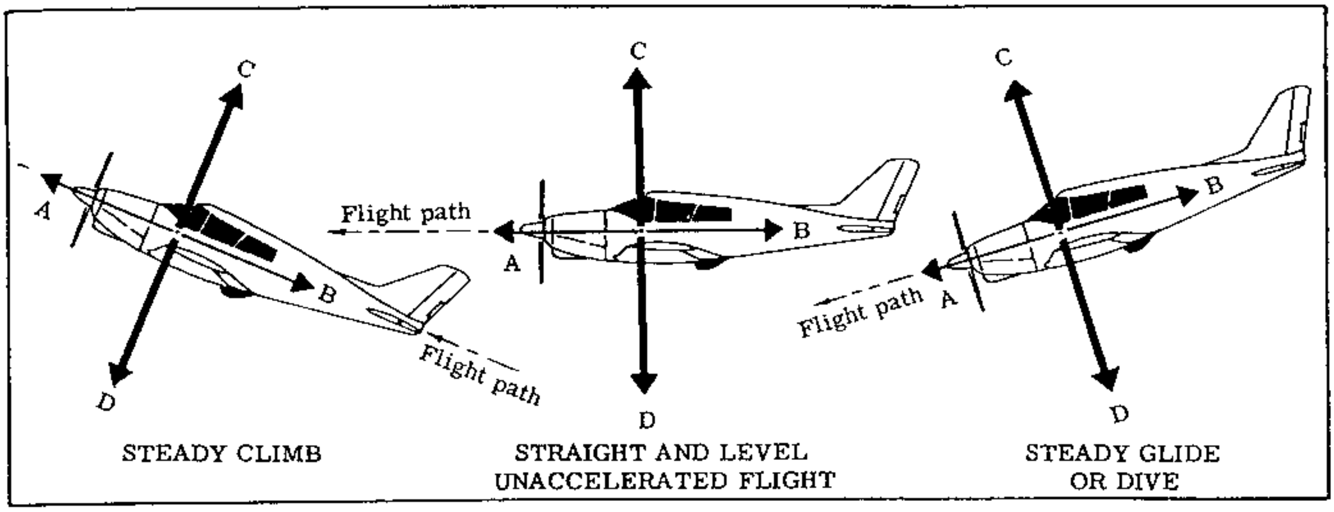


Fig. 3-3. In steady-state flight the sum of the forces acting parallel to the flight path (A-B) must equal zero; the same applies to those acting perpendicular. Minus signs may be given to forces acting in a "downward" or "rearward" direction.

2. *Thrust moment*—Thrust is acting 15 in. above the CG and has a value of 400 lb. The *nose-down* moment resulting is 15 × 400 = *6000 lb-in.* (The moment created by Thrust will be measured with respect to the CG.) For simplicity it will be assumed that the Drag is operating back through the CG. Although this is not usually the case, it saves working with another moment.

3. *Wing moment*—The wing, in producing Lift, creates a nose-down moment, which is the result of the forces working on the wing itself. Fig. 3-5 shows force patterns acting on a wing at two airspeeds (angles of attack). These moments are acting with respect to the aerodynamic center, a point considered to be located about 25% of the distance from the leading to the trailing edge for all airfoils.

Notice that as the speed increases (the angle of attack decreases) the moment becomes greater as the fôrce pattern varies. If the airfoil is not a symmetrical type the nose-down moment created by the wing increases as the *square* of the airspeed. (There is no wing moment if the airfoil is symmetri-

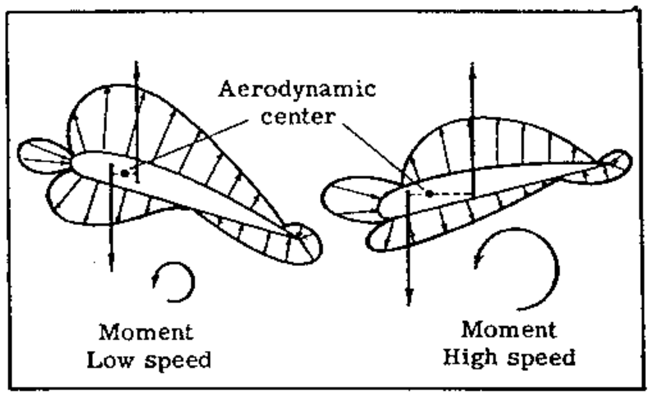


Fig. 3-5. The moments created by the unsymmetrical airfoil at two different airspeeds. The angles of attack and pressure patterns around the airfoil have been exaggerated.

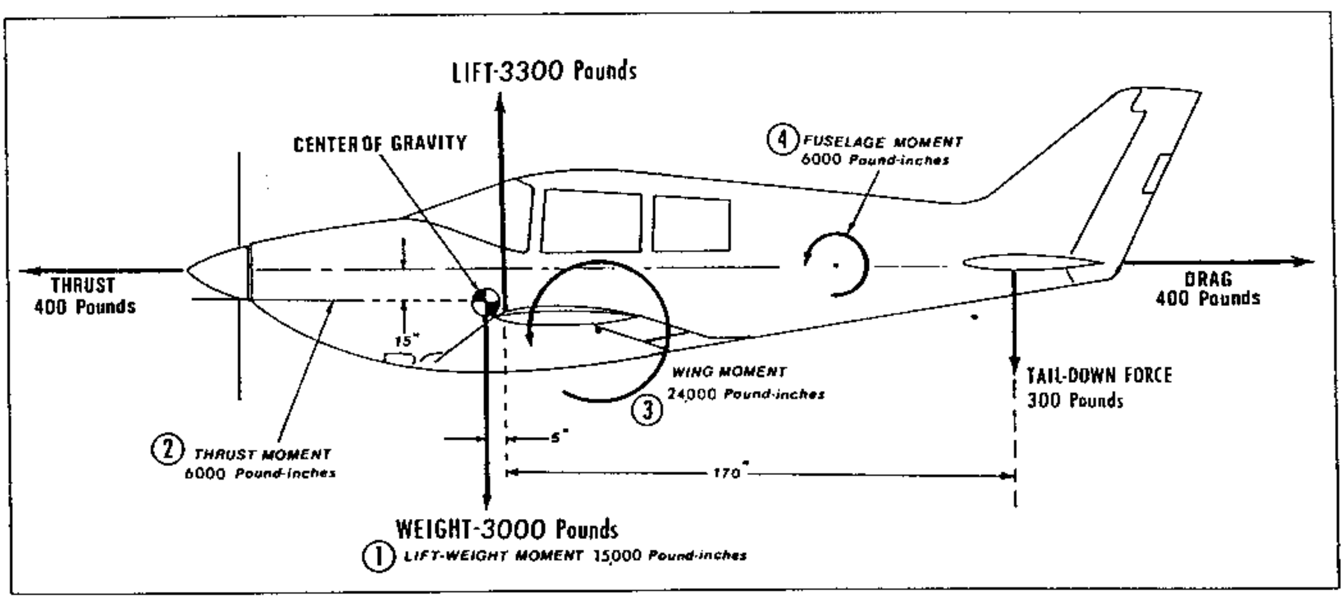


Fig. 3-4. Forces and moments acting on an airplane in steady straight and level flight.

cal because all of the forces are acting through the aerodynamic center of the airfoil.)

For an airplane of the type, airspeed, and Weight used here, a nose-down moment created by the wing of 24,000 lb-in. would be a good round figure. Remember that this would vary with indicated airspeed. *Nose-down moment created by wing = 24,000 lb-in.*

4. *Fuselage moment*—The fuselage may also be expected to have a moment about its CG because it, too, has a flow pattern, which, for the airplane type and airspeed in this example, would be about *6000 lb-in. nose-down.* (This is not always the case.)

Summing up the nose-down moments:

Lift-Weight moment	= 15,000 lb-in.
Thrust moment	= 6,000 lb-in.
Wing moment (at 154 K)	= 24,000 lb-in.
Fuselage moment (at 154 K)	= 6,000 lb-in.
Total nose-down moment	= 51,000 lb-in.

For equilibrium to exist there must be a *tail-down* moment of 51,000 lb-in., and this is furnished by the tail-down force. Fig. 3-4 shows that the *arm* (the distance from the Lift line to the center of the tail-down force) is 170 in. So, the moment (51,000 lb-in.) and the arm (170 in.) are known; the force acting at the end of that arm (the tail-down force) can be found: 51,000 lb-in./170 inches = 300 lb. The airplane nose does not tend to pitch either way.

The *forces* must also be balanced for equilibrium to exist. Summing up the forces acting perpendicular to the flight path (in this case because the flight path is level, it can be said also that the *vertical* forces must be equal—in a climb or glide the forces acting perpendicular to the flight path will not be vertical) (Fig. 3-3). The "down" forces are the Weight (3000 lb) and the tail-down force (300 lb). The "up" force (Lift) must equal the down forces for equilibrium to exist so that its value must be 3300 lb. Now the moments *and* forces acting perpendicular to the flight path are in equilibrium. As can be seen, Lift is not normally the same as Weight in straight and level unaccelerated flight. Of course, the CG can be moved back to a point where no nose-down moment exists and no tail-down force is required. This, however, could cause stability problems, which will be covered in Chap. 10.

In the situation just discussed it was stated that the airplane was at a *constant cruise* speed so that the force (lb) acting rearward (Drag) and the force (lb) acting forward (Thrust) are equal. (It is assumed that at higher speeds the Thrust line is acting parallel to the flight path so it can be considered to be equal to Drag.)

Thus it can be said without too much loss of accuracy that in the cruise regime Thrust equals Drag and normally Lift is slightly greater than Weight when the forces are balanced.

But what about a situation where the airplane is flying straight and level at a constant airspeed in *slow flight*? Again the forces must be summed as shown in in Fig. 3-6. Now the Thrust line is *not* acting parallel to the flight path (and opposite to Drag); for purposes of this problem it will be assumed that it is inclined upward from the horizontal by 15°.

As a pilot, for straight and level slow flight you set up the desired airspeed and use whatever power is necessary to maintain a constant altitude; you don't know the value of Drag, Thrust, or Lift (and may have only a vague idea as to what the Weight is at that time, but for this problem it's 3000 lb, as before). The tail-down force will be assumed to be 200 lb. (At this high angle of attack it likely will be less than for cruise.) In the problem of straight and level *cruising* flight it was just assumed that Thrust equaled Drag and we weren't particularly interested in the values. Look at Fig. 3-7 for a typical Drag versus airspeed curve for the type of airplane being discussed.

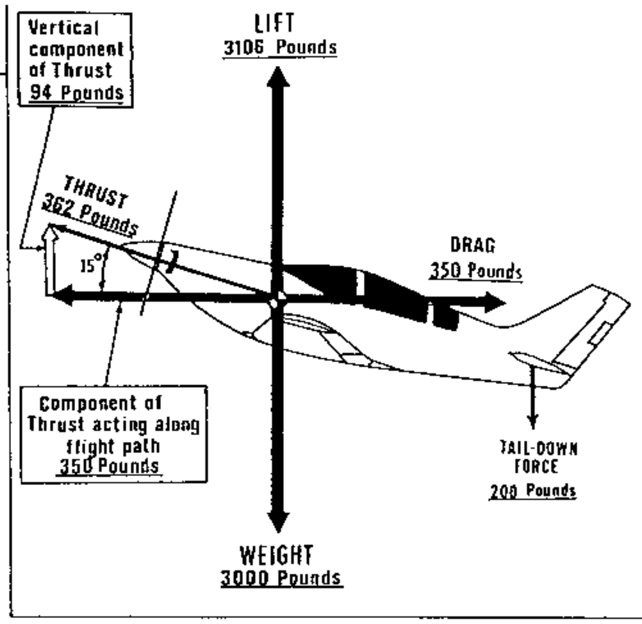


Fig. 3-6. The forces at work on the airplane in straight and level slow flight just above the stall. The vertical component of Thrust has been moved out ahead of the airplane for clarity. Because of the placement of the various forces it would appear that the moments are not in equilibrium. They will be assumed to be so for this problem.

In summing the forces parallel to the flight path in slow flight with this airplane, Drag is 350 lb; the component of Thrust acting opposite Drag must be 350 lb also. No doubt you are already ahead of this in your thinking and realize that because it is inclined at an angle, the actual Thrust must be greater than Drag if its "forward" component along the flight path is equal to Drag. You could look in a trigonometry table and find that at a 15° angle, the *actual* Thrust must be about 3½% higher, or about 362 lb compared with 350 lb of Drag.

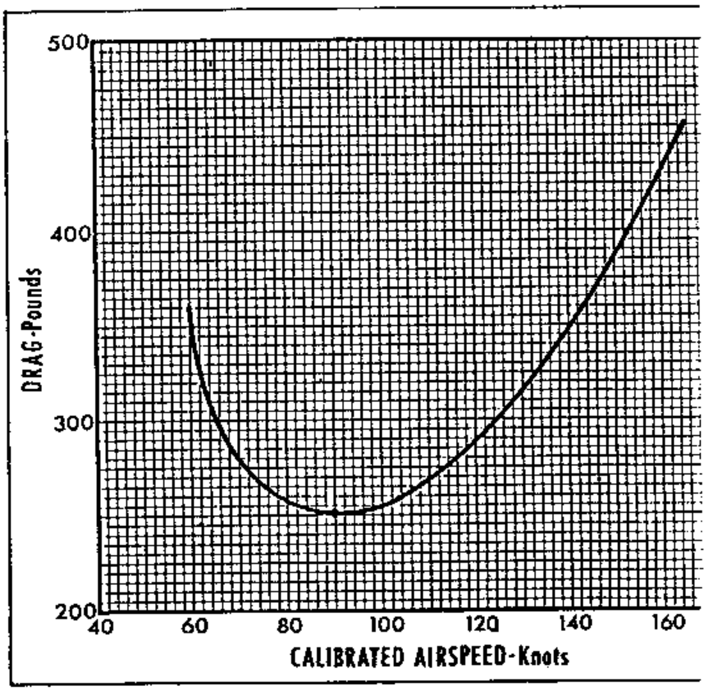


Fig. 3-7. A Drag versus airspeed curve for a fictitious, four-place, high-performance, single-engine airplane at gross Weight. The values are in the area currently expected of that type of airplane.

Thrust also has a component acting at a 90° angle to the flight path parallel to Lift. A check of a trigonometric table would show that this force is 26% of the actual Thrust and has a value of about 94 lb (which is a fair amount).

Now, summing the forces perpendicular to the flight path (the "up" forces must equal the "down" forces):

Forces "down" = Weight + tail-down force = 3000 + 200 = *3200 lb*
Forces "up" = Lift + vertical component of Thrust = Lift + 94 lb = *3200 lb*

Lift, of course, is found as 3200 − 94 = 3106 lb, using our arbitrary values. So Lift is less at low-speed level flight (3106 lb) than at cruise (3300 lb), if you are talking strictly about each of the Four Forces. You don't worry about this in practical application but fly the airplane and set the power and airspeed to get the desired result.

As the vertical component of Thrust helps support the airplane, the wings only have to support 3106 lb rather than the full 3200 lb (Weight plus tail-down force) in slow flight and therefore the wing loading is less than would be expected. The airplane always stalls at a lower airspeed with power on (for the same flap setting and Weight) than in the power-off condition. The effect of the slipstream across the wing helps lower the stall speed, too.

The greater that Thrust is in proportion to Weight, the greater this effect. For instance, if the airplane had an engine-propeller combination capable of producing 3000 lb of Thrust the airplane would be capable of "hanging on its prop" and in theory the power-on stall speed would be zero.

So, in summary, in straight and level flight in the *slow flight regime* it may be expected that (1) the actual Thrust exerted by the propeller (lb) is greater than the Drag of the airplane and (2) Lift is less than at higher speeds. The location of the CG, the angle the Thrust line makes with the flight path, and other factors can have an effect on these figures, of course.

FORCES IN THE CLIMB

To keep from complicating matters, the tail-down force will be ignored for the first part of each section of flight mechanics. It exists, of course, and varies with CG and angle of attack (airspeed) but is comparatively small in most cases so Lift will be considered equal to Weight, at least at the beginning. We'll also assume that all moments are balanced and won't have to consider them further, and the Four Forces will be drawn as acting through a single point (the CG) of the airplane to avoid complicating the drawings.

One of the biggest fallacies in pilots' thinking is believing that the airplane climbs because of "excess Lift." For purposes of this problem the Drag (lb) of the example airplane will be 250 lb at the recommended climb speed of 90 K (Fig. 3-7). The figures for the values for Drag have been rounded off.

Again, remembering that all forces (and moments) must be in balance for such equilibrium to exist, the following is noted. Because the flight path is no longer level, Weight, for the first time, is no longer operating in a direction 90° to the flight path. As the forces must be in equilibrium both parallel and perpendicular to the flight path, Weight must be broken down into the components acting in these directions (as you do with the wind when it is neither right down the runway nor straight across it) (Fig. 3-8).

Fig. 3-9 shows the forces acting on the airplane in a steady-state climb of 90 K (CAS). The airplane has an angle of climb of 8° to the horizontal and requires an angle of attack of 6° to fly at the climb airspeed of 90 K. We are assuming that the angle of incidence is zero (the wing chord line is exactly parallel to the fuselage centerline) and that the Thrust line is offset "upward" from the flight path by 6° in this climb. In the following drawings the angles will be exaggerated and a simplified airplane silhouette used for clarity.

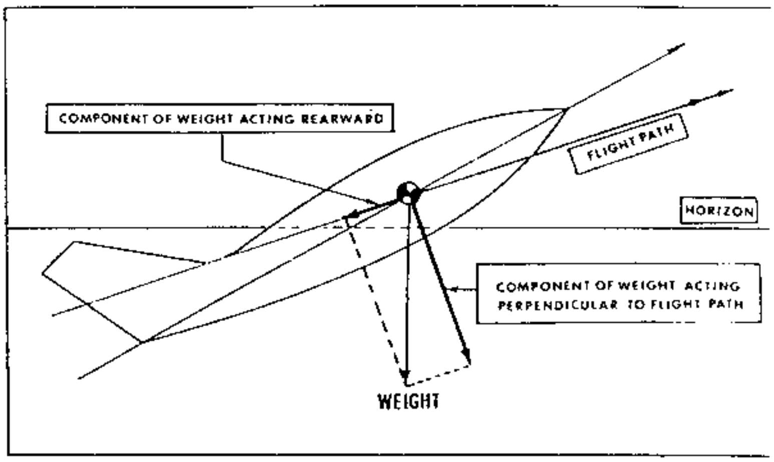


Fig. 3-8. As Weight is no longer acting perpendicular to the flight path it must be broken down into components as shown.

To sum up the forces *parallel* to the flight path:

The forces acting rearward along the flight path are aerodynamic Drag (250 lb) (see Fig. 3-7 again) *plus* the rearward component of Weight, which by checking a trigonometric table for the 8° angle of climb (in round numbers) is found to be 417 lb. The *total* rearward acting force is aerodynamic Drag (250 lb) plus the rearward acting component of Weight (417 lb), or *667 lb*.

For the required equilibrium (steady-state climb condition) to exist, there must be a balancing force acting forward along the flight path; this is furnished by Thrust. The fact that the Thrust line is offset upward from the flight path by 6° further complicates the problem. Because of its inclination the actual Thrust produced by the propeller must be greater than 667 lb in order to have that force acting along the flight path. The actual Thrust, you will note, is the hypotenuse of a right triangle, and you remember from your geometry (and Chap. 1) that the hypotenuse of a right triangle is always longer than either one of its sides; the longer of the two other sides is the

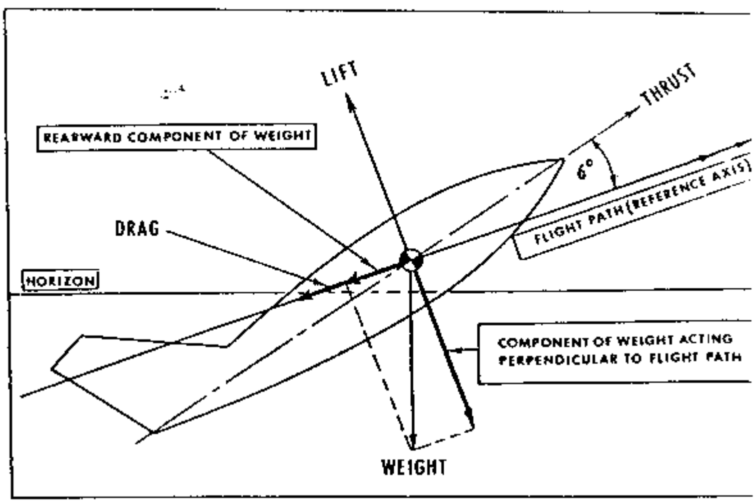


Fig. 3-9. The forces acting on an airplane in a steady climb.

component of Thrust acting along the flight path, which must be equal to the rearward acting force(s). The sum of the forces equals zero.

Again, a check of a trigonometric table shows that to have 667 lb along the flight path the *actual* Thrust must be about 0.55% greater (a little more than one-half of 1%) so that its value is 3 lb greater, or about 670 lb (a nit-picking addition, to be sure). The forces acting *parallel* to the flight path at the climb speed of 90 K and Weight of 3000 lb are balanced (Fig. 3-10).

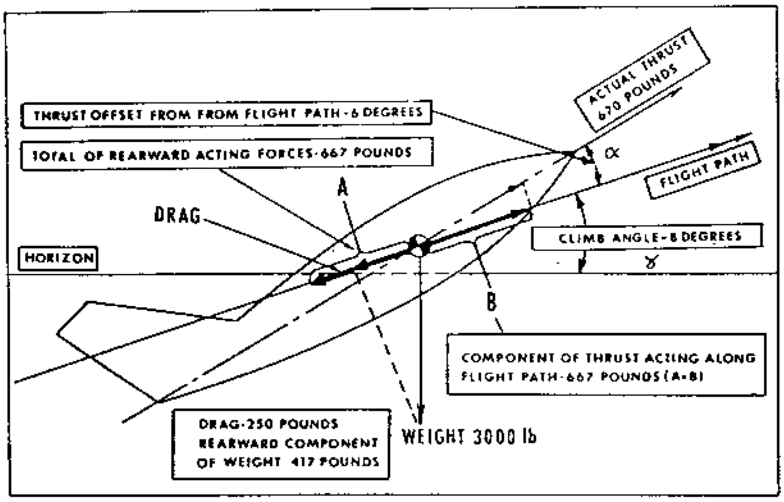


Fig. 3-10. A summary of the forces acting *parallel* to the flight path in the steady-state climb.

To sum the forces acting *perpendicular* to the flight path:

The component of Weight acting perpendicular (more or less "downward") to the flight path at the climb angle of 8° turns out to be 2971 lb according to the trigonometric table (the cosine of 8° is 0.9902). As this is considered to be the only force acting in that direction (now that the tail-down force is being neglected) it must be balanced by an equal force (or forces) in the opposite direction. The two forces acting in that direction are (1) Lift and (2) the component of Thrust acting at 90°, or perpendicular, to the flight path (Fig. 3-11).

As Thrust is now a known quantity, we can solve for that component acting in the same direction as Lift. For a 6° angle of inclination the component for 670 lb of Thrust is 70 lb (rounded off). This means that Lift must have a value of 2901 lb in this case (2971 − 70 = 2901 lb), or Lift (2901 lb) + Thrust component (70 lb) = Weight component (2971 lb). The forces acting perpendicular to the flight path are balanced.

Lift (2901 lb) is found here to be *less* than the airplane's Weight (3000 lb) in the steady-state climb. Thrust (670 lb) is *greater* than aerodynamic Drag (250 lb).

What happened to the idea that an airplane makes a steady climb because of "excess" Lift? Even considering the tail-down force, which for this airplane's airspeed, Weight, and CG location could be expected to be about 250 lb, Lift is hardly greater than Weight. In any event, there is no "excess Lift" available—it's all being used to balance the tail-down force and the component of Weight acting perpendicular to the flight path. (Lift would have to be 2901 lb plus 250 lb, or 3151 lb.)

You remember from the last chapter that the Thrust horsepower equation is THP = TV/325 (the 325 is for the airspeed in knots) so that the THP power being developed along the flight path is (667 × 90)/325 = 185 THP. The "V" in the equation is *true* airspeed; it will be assumed that the airplane is operating at sea level at this point so that the calibrated climb airspeed of 90 K equals a TAS of the same value.

The rate of climb of an airplane depends on the amount of *excess* THP available at a particular airspeed. This excess THP means the horsepower that is working to move the airplane vertically. The recommended best rate of climb speed is that one at which the greatest amount of excess THP is available. The following equation may be used to determine the rate of climb in feet per minute:

$$\frac{\text{excess THP} \times 33{,}000}{\text{airplane Weight}}$$

Power is *force* times *distance per unit of time* and 1 HP is equal to 550 ft-lb per second or 33,000 ft-lb per minute. That's where the 33,000 in the equation comes in; it's set up for a rate of climb (RC), or vertical displacement, in feet per minute. Going back to the original idea for horsepower (in this case THP), the equation for the THP (excess THP) used to climb would be as follows:

$$\frac{\text{airplane Weight} \times \text{RC (fpm)}}{33{,}000}$$

The THP required to climb is that raising a certain Weight (the airplane) a certain vertical distance in a certain period of time.

But to find the rate of climb for the example airplane it would be well first to find out how much THP is required to fly the airplane *straight and level* at a constant altitude at sea level at 90 K. As Weight in *level flight* will not have a component acting rearward to the flight path, the only retarding force is aerodynamic Drag, which was found to be 250 lb. The

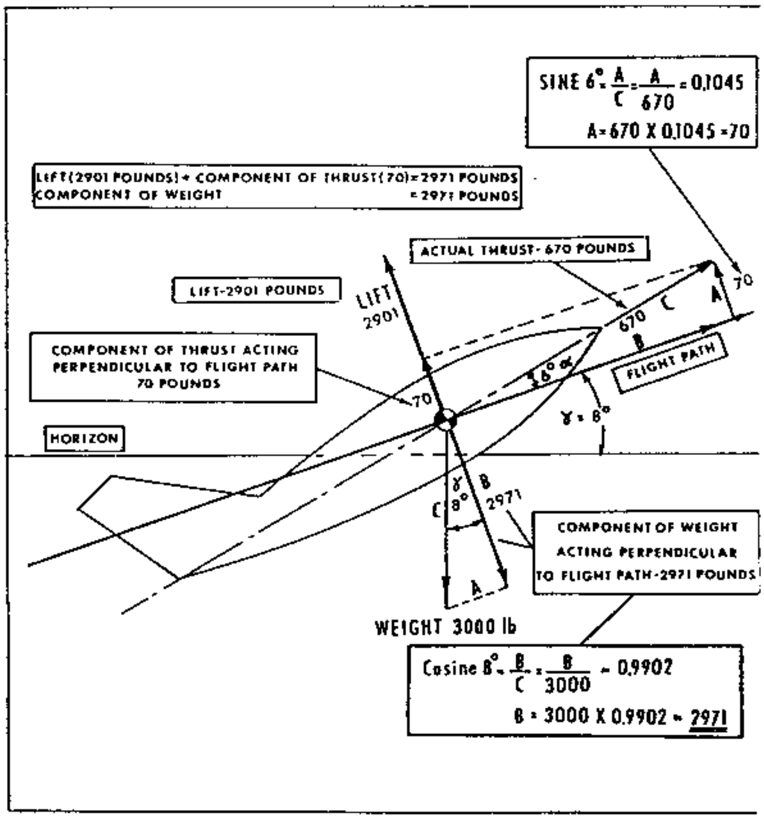


Fig. 3-11. A summary of the forces acting *perpendicular* to the flight path in the climb.

Thrust component acting along the flight path must be equal to this, or 250 lb. Assuming that the angle of attack and the angle Thrust makes with the flight path is 6°, to get this value the actual Thrust would be about 251 lb (rounded off to the 250) (Fig. 3-12).

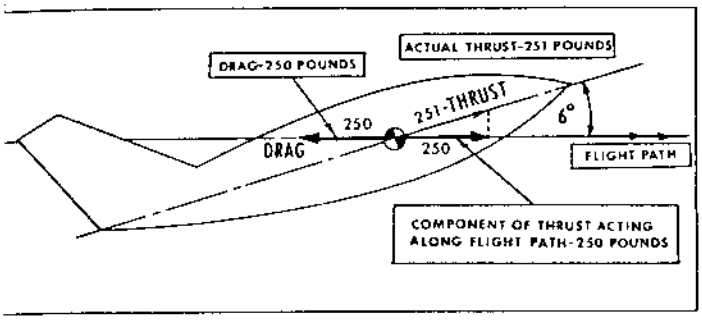


Fig. 3-12. The forces acting parallel to the flight path for the airplane flying *straight and level* at the recommended climb speed of 90 K.

In the earlier look at the climb at 90 K, 667 lb of Thrust was being exerted along the flight path. This is 417 lb more than required for level flight and is, in effect, the "excess Thrust" needed for a climb angle of 8° at 90 K. (The rearward component of Weight was 417 lb.)

Solving for excess Thrust horsepower (ETHP):

$$\text{ETHP} = \frac{\text{excess Thrust} \times \text{velocity (K)}}{325}$$

$$\text{ETHP} = \frac{417 \times 90}{325} = 115 \text{ THP}$$

Solving for rate of climb:

$$\text{RC} = \frac{\text{ETHP} \times 33{,}000}{\text{Weight}}$$

$$\text{RC} = \frac{115 \times 33{,}000}{3000} = 1265 \text{ fpm}$$

The brake horsepower (BHP) required to get such performance for a 3000-lb airplane with the described characteristics could be estimated. It can be assumed here that at the climb speed the propeller is 74% efficient (efficiency varies with airspeed, you remember from Chap. 2) and that the THP being developed is 74% of the BHP being developed at the crankshaft. The *total* THP being used in the climb is THP = (T × V)/325 = (670 × 90)/325 = 185 THP (rounded off). The Thrust acting along the flight path was 667 lb, but the *total* Thrust exerted was 670 lb; this is what must be used to work back to the BHP requirement.

This, then, is approximately 74% of the horsepower developed at the crankshaft, so the BHP required to get this performance for the fictitious airplane would be 185/0.74, or approximately 250 BHP (0.74 × 250 = 185).

The rate of climb found is in the ball park for current four-place retractable-gear airplanes ("our" airplane may be cleaner or dirtier aerodynamically than others). All of this resulted from our arbitrarily selecting an aerodynamic Drag (250 lb), an angle of attack in the climb (6°), and a climb angle of 8° at a climb speed of 90 K. The figures were picked to give a reasonable idea of how such airplane types get their climb performance. The 74% used for propeller efficiency is also arbitrary, although the figure is close to that expected for the airplane type and speed discussed.

The more practical aspects of the climb will be covered in Chap. 6.

FORCES IN THE GLIDE

As you have probably already reasoned, anytime the flight path of the airplane is not horizontal, Weight has to be broken down into two components. The glide or descent at an angle of 8° to the horizontal would have the same percentages of Weight acting perpendicular and parallel to the flight path as for the 8° angle of climb just mentioned—except that in the glide the component of Weight parallel to the glide path is not a retarding force but is acting in the direction of flight.

For this situation it is assumed that the power is at idle and *no Thrust exists*. The tail-down force will be neglected at first. The forces acting parallel to the flight path are (1) the component of Weight, which must be balanced by (2) aerodynamic Drag in order to keep the airspeed constant in the descent. For an 8° angle of descent the component of Weight acting along the flight path would be 417 lb, as for the climb—except that it's now working in the direction of motion. The aerodynamic Drag must equal the component of Weight acting along the flight path for a steady-state condition to exist. Looking back to Fig. 3-7, you see that for an 8° angle of descent this value of Drag (417 lb) exists at about 157 K.

The more usual situation would be to use the power-off glide speed recommended by the manufacturer. For this example 90 K will be used as the recommended (clean) glide speed. We'll also ignore the effects of power decrease or windmilling prop on the Drag curve and say that aerodynamic Drag at 90 K is 250 lb as it was for the power-on climb. The speed of 90 K may or may not be the best one for maximum glide efficiency (it depends on the airplane), but the niceties of that will be covered further on.

Illustrating the same reasoning as in the other steady-state flight conditions, Fig. 3-13 shows the forces acting parallel to the flight path in a power-off glide. (Again, the tail-down force is neglected for simplicity.)

Realizing that the component of Weight acting along the flight path must have a value equal to the 250 lb of aerodynamic Drag, the glide path will be of a certain angle for this

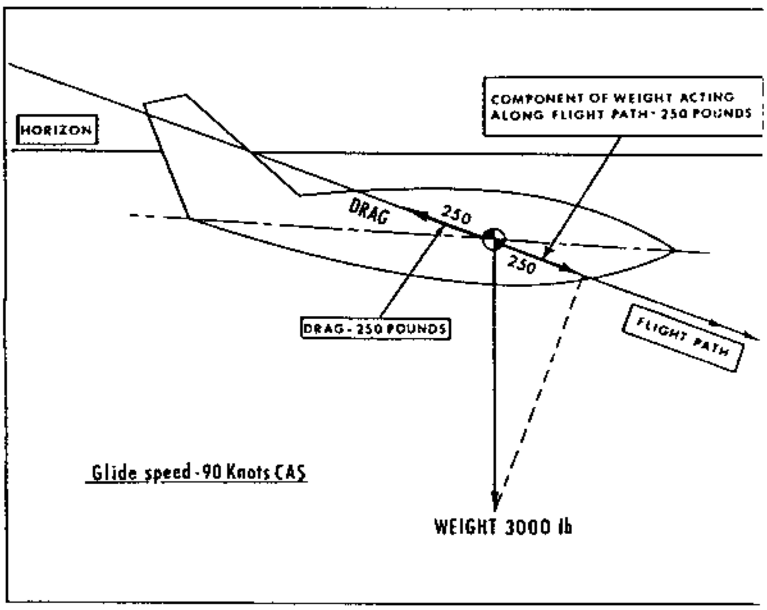


Fig. 3-13. The forces acting parallel to the flight path in the power-off glide at 90 K.

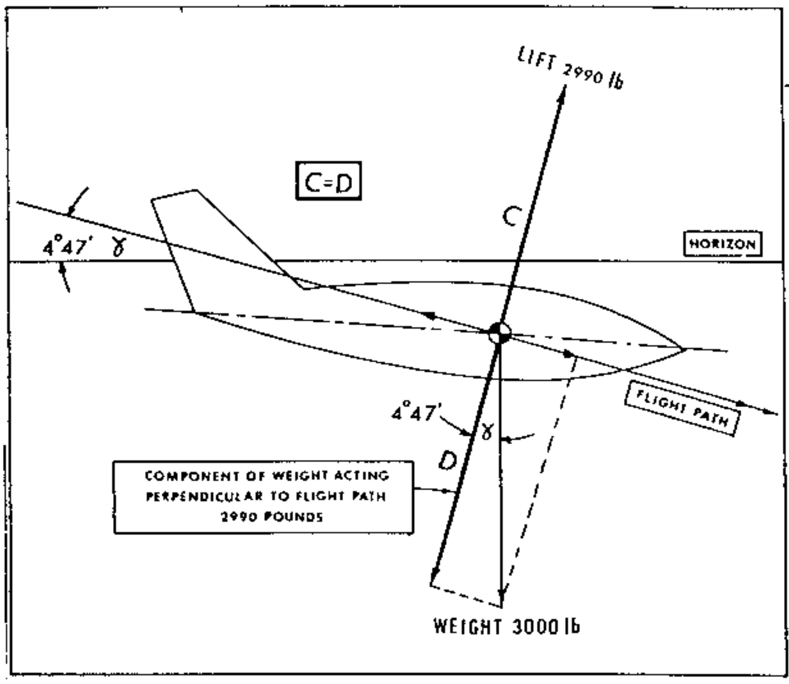


Fig. 3-14. The forces acting perpendicular to the flight path in the glide.

condition to occur; a check of a trig table shows this to be 4°47′ (4 degrees and 47 minutes), or nearly a 5° angle downward in relation to the horizon. Knowing the glide angle, the forces acting 90° to the flight path (Lift and the component of Weight acting perpendicular to the flight path) can be found (Fig. 3-14).

That Weight component, which can be found by reference to a trig table, is 2990 lb, so Lift must also equal this value for a steady-state (or constant) glide under the conditions of ignoring the tail-down force.

For shallow angles of glide the variation of Lift from Weight is usually ignored. In this case, Lift is 2990 lb to a Weight of 3000 lb, a variation of about one-third of 1%.

In the climb a final figure for Lift required at 90 K (considering the tail-down force) was 3151 lb. For the glide the tail-down force for this airplane would be in the vicinity of 225 lb because of the lack of a moment created by Thrust. The component of Weight acting perpendicular to the flight path at the 90-K glide was 2990 lb and Lift required to take care of this would be 2990 + 225 or *3215 lb. There are 64 more pounds of Lift in the glide than in the climb, or Lift would be greater in the glide than in the climb under the conditions established!*

The angle that Weight varies from being perpendicular to the flight path is also the angle of glide or descent. *If aerodynamic Drag is cut to a minimum, the components of Weight acting parallel to the flight path can also be a minimum for a steady-state glide.* In other words, if the aerodynamic Drag could somehow be halved for this airplane the angle of glide would be halved; the airplane would descend at an angle of about 2.5° to the horizontal *and would glide twice as far for the same altitude.*

As the airplane's Weight is considered to be constant for a particular instant of time the solution is that the farthest distance may be covered with the airplane flying at the angle of attack (or airspeed) with the minimum aerodynamic Drag. For instance, assuming that at small angles of descent Lift equals Weight (3000 lb), the angle of glide of the example airplane is 3000 lb (Lift or Weight)/250 lb (aerodynamic Drag) = 12. The glide ratio for our example airplane at 90 K is 12 to 1, or 12 ft forward for every 1 ft down. And as the point of minimum aerodynamic Drag (250 lb at 90 K CAS) was determined from Fig. 3-7 this would be the minimum glide angle (or *maximum distance* glide) for the example airplane. Anytime Drag is increased, the efficiency of the glide is *decreased.* With a faster or slower glide speed than the 90 K chosen, a check of Fig. 3-7 shows that Drag will increase—and the glide ratio will suffer.

One method of increasing Drag would be to glide with the landing gear extended (an increase in parasite Drag, which would result in an increase in total Drag). With the gear down a typical figure for Drag for an airplane of this type at 90 K would be 300 lb. The glide angle would be greater and the glide ratio would suffer.

Assume that the pilot starts gliding "clean" and the glide ratio is 12 to 1. The nose is at a certain attitude to get the 90 K (and the 4°47′ angle of descent); for most airplanes of that type the nose will be approximately level.

The gear is extended and suddenly the forces acting parallel to the flight path are no longer in balance; Drag is greater than the component of Weight and the airplane would start slowing if the nose were kept at the same position. Deciding to glide at 90 K as before, the pilot must drop the nose and change the flight path so that the component of Weight acting along the flight path would equal the 300 lb of aerodynamic Drag. The new glide ratio at 90 K with the gear down would be Lift (3000 lb)/Drag (300 lb), or about 10 to 1; the glide angle would be about 6° relative to the horizon.

The method of finding the rate of sink of the airplane can be compared to that of solving for the rate of climb. The rate of sink, however, is a function of the *deficit THP* existing at the chosen airspeed:

$$\frac{\text{deficit THP} \times 33{,}000}{\text{airplane Weight}}$$

The aerodynamic Drag for the airplane is a force of 250 lb acting rearward along the flight path at the airspeed of 90 K (the airplane is clean and weighs 3000 lb). The equivalent THP required to be acting in the direction of flight to equal the effects of Drag at 90 K would be THP = DV/325 = (250 × 90)/325 = 69. The combination of Thrust and velocity would have to equal 69 THP for level flight at 90 K, or TV/325 = 69 THP. However, in this case Thrust is zero and, as you know, zero times any number (90 K in this case) is still zero. So, there's no THP being developed by the engine; the airplane is 69 THP in the hole, or there is a deficit of 69 THP. The rate of sink can be calculated: (69 × 33,000)/3000 = 760 fpm (rounded off).

This could be checked by looking at the situation in Fig. 3-13 again. The airplane is descending down a path inclined at an angle of 4°47′ at 90 K forward speed. Converting the 90 K to feet per minute it can be said that the airplane is moving down the path at a rate of 9130 fpm. It was already found that the glide ratio was 12 to 1 so that the feet down per minute would be one-twelfth that traveled along the glide path, or about 760 fpm.

Estimation of Wind Resources

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General Considerations

The knowledge of occurring wind conditions is important for many human activities. The old sailors' knowledge of large wind systems like the trade winds, and of treacherous local winds was not only a matter of life and death, but of daily income as well. Nowadays, by making modern technology, we have learned to avoid many of the hazards of the weather. The use of this technology requires in many cases a detailed knowledge of the strength and probability of occurrence of the various weather conditions. Safe transport at sea, in the air and on land calls for good weather predictions.

The collected experience with the weather over many years is termed climatology. Averaged yearly rainfall, amount of snow, early frost, maximum and minimum temperatures, wind directions, strongest occurring winds and other elements form the climatology of a place or a geographical area. Many activities depend on climatological knowledge, an example is the design of large building structures to withstand extreme wind conditions. Whereas many applications of climatology call for statistics on extreme weather events only, there are two major areas where a rather precise knowledge of the statistics over a long timespan is necessary: Air pollution and wind energy. The height of a chimney must be designed to ensure that the concentrations of effluent at the surface are below certain limits (Fig. 1). The mean annual energy production of a wind turbine must be estimated in connection with economical assessments of the utilization of wind energy. Both calculations require knowledge of the wind speed and wind direction at an essential height, the stack height and the hub height.

Wind energy calculations are special in two aspects. Firstly, the accuracy of mean wind speed needs to be high. Just a 10% uncertainty gives rise to approximately 30% uncertainty in the mean energy production, a problem which makes economic predictions difficult. Secondly, once a wind turbine is erected at the site for which the wind energy potential was calculated, the turbine acts as a measuring device that checks these calculations. In a year or two, it will be known how good or poor the estimate was.

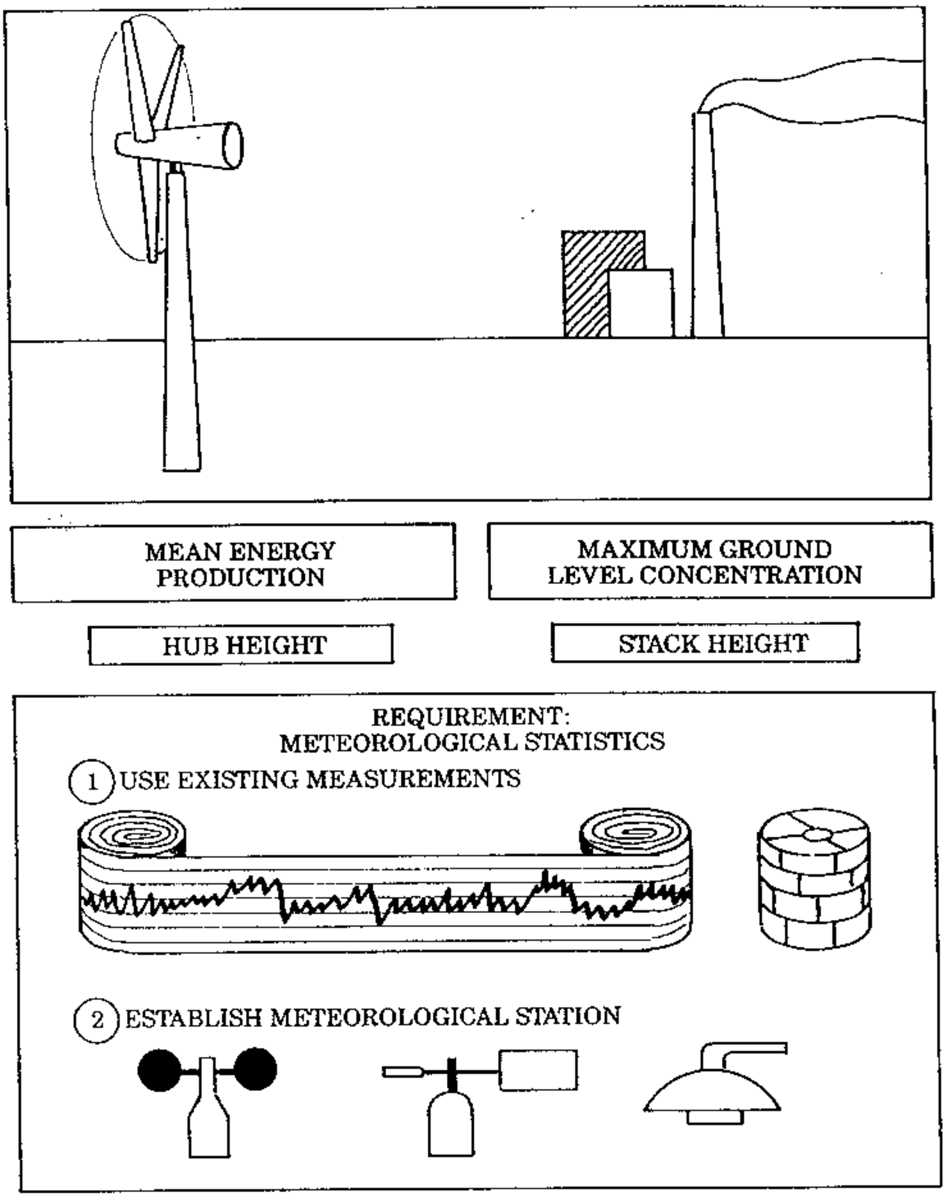


Figure 1. Meteorological statistics and two areas of application: Air pollution and wind energy.

Thus it is important to have an accurate determination of wind conditions at a given wind turbine site. In Fig. 1 (lower part) the means for getting wind statistics are sketched. Data might already be available for a sufficient period of time. However, this is almost never the case and to obtain the wind statistics at the wind turbine site one has to make measurements over three to five years. This is a long period to wait and we must therefore search for other possibilities to get the wind statistics. We have to rely on measurements made at nearby meteorological stations, nearby typically meaning a distance of 50 km or more. A common and general problem in wind resource evaluations now arises, namely that of horizontal and vertical extrapolation of mean wind statistics.

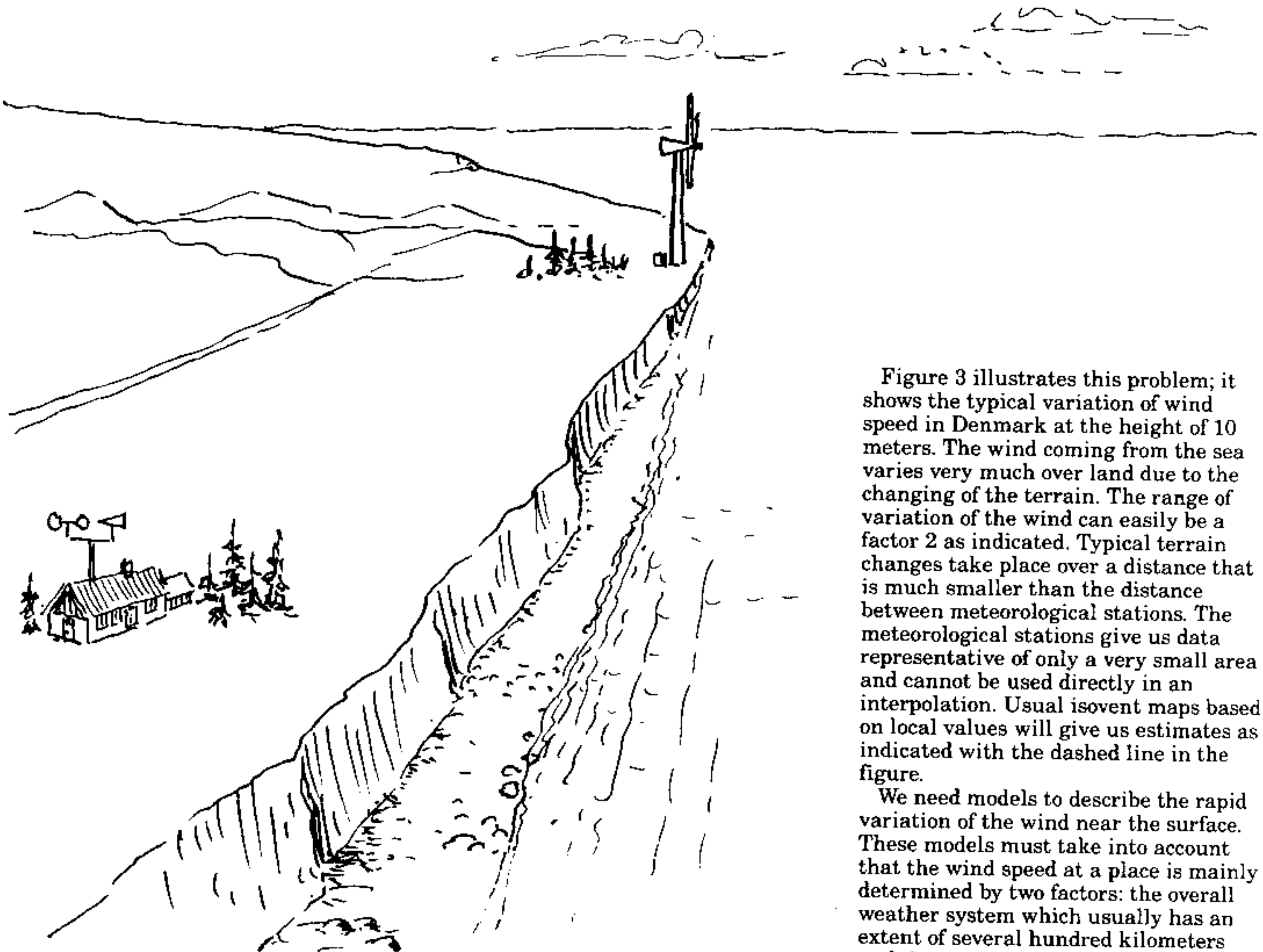


Figure 2. Wind turbine siting and the available meteorological measurements.

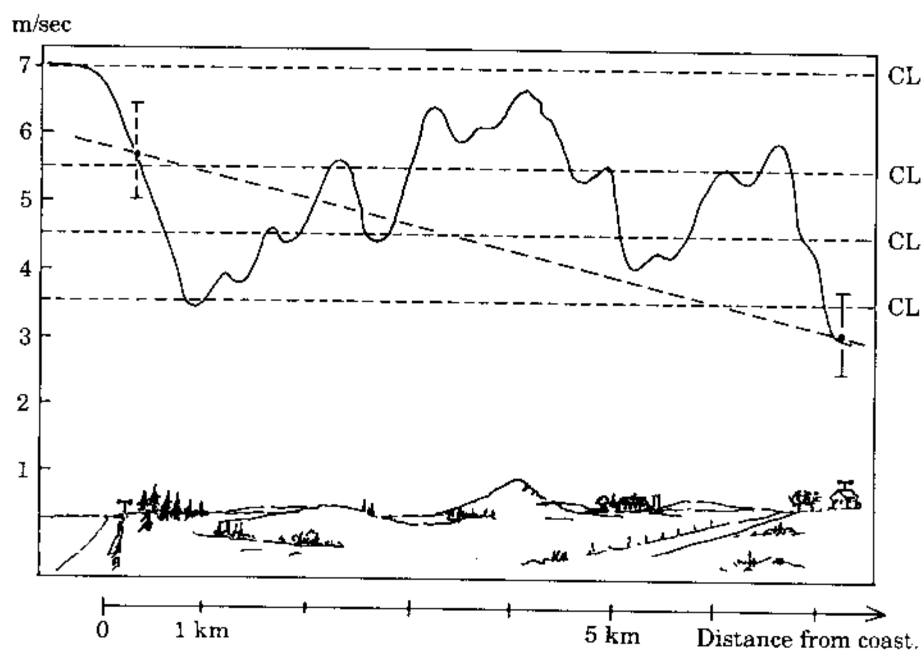
Figure 2 illustrates a common situation: a wind turbine is to be sited at a coast, but wind data are available only from a climatological station some kilometers away, and the wind there is influenced by nearby terrain conditions, in this case trees and a cliff. Further, the placement of the anemometer and wind vane at the top of the building, has a strong influence on the measurements, an influence which is difficult to correct for. If we want to use the wind statistics from the station we first have to correct them for the influence of the house and terrain. At the turbine site we have to determine how the surrounding terrain influences the wind at hub height. Finally, we must introduce this into the wind statistics in order to make it representative for the wind conditions at the site. Obviously a difficult task.

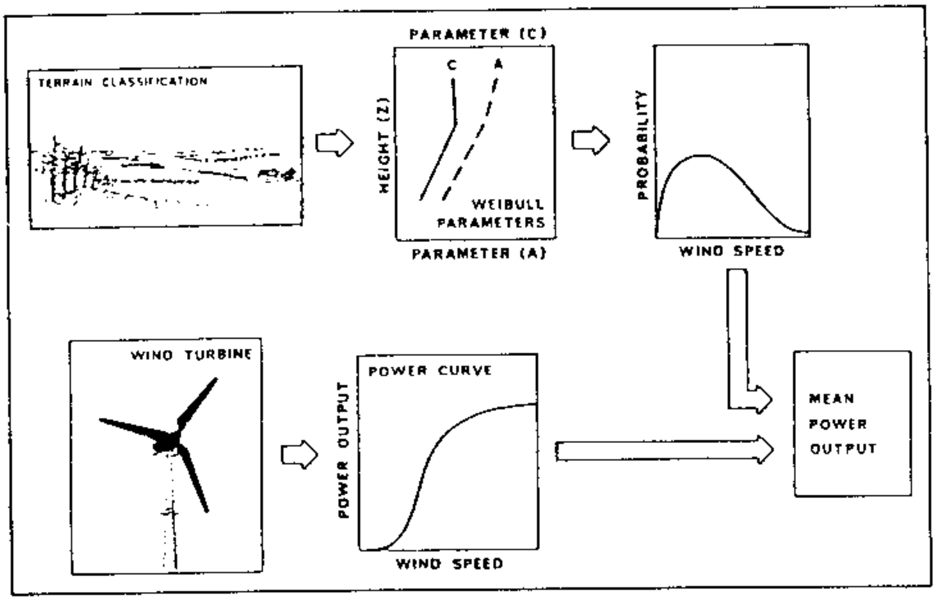
This discussion leads us to pinpoint a difficulty with most wind resource investigations. It is costumary to make isovent maps, i.e. maps for larger areas with lines of equal wind speed. Usually these maps are drawn without considering the terrain inhomogeneities in the area covered. Also quite generally the wind data are used without correcting for imperfect placement of measuring devices.

Figure 3 illustrates this problem; it shows the typical variation of wind speed in Denmark at the height of 10 meters. The wind coming from the sea varies very much over land due to the changing of the terrain. The range of variation of the wind can easily be a factor 2 as indicated. Typical terrain changes take place over a distance that is much smaller than the distance between meteorological stations. The meteorological stations give us data representative of only a very small area and cannot be used directly in an interpolation. Usual isovent maps based on local values will give us estimates as indicated with the dashed line in the figure.

We need models to describe the rapid variation of the wind near the surface. These models must take into account that the wind speed at a place is mainly determined by two factors: the overall weather system which usually has an extent of several hundred kilometers and the nearby terrain, say out to five kilometers from the site. The Danish wind resource work which took place in the years 1978-79 leading to »Wind Atlas for Denmark« was an attempt to solve the problem of taking into account both the large-scale statistics of the weather and the effects of local terrain.

Figure 3. The variation of the wind speed with the type of terrain at a height of 10 m.





The Danish Wind Atlas

The objective of the Danish Wind Atlas was to evaluate the wind resources for the purpose of locating wind power plants in Denmark. The investigations were carried out jointly by Risø National Laboratory and the Danish Meteorological Institute under the sponsorship of the Wind Power Programme of the Danish Ministry of Energy and the Danish utilities.

The investigation led to a method for the determination of the variation (frequency distribution function) of the wind speed at a given height over a specified terrain. The method was developed, described, exemplified, and verified in the Wind Atlas. The contract report »Vindatlas for Danmark« was published in Danish in a limited edition in May 1980. It was especially intended for a government investigation into the possibility of placing many large wind turbines in Denmark. In the following years a large number of private people were interested in investing in their own small wind turbines, and this gave rise to a growing demand for a »user's guide« type of report. Such a report was then published in August 1980, and finally an English edition became available by January 1981.

The Wind Atlas has been widely used in Denmark since it was published and a major part of the 1400 wind turbines now operating in Denmark including those in all the wind farms have been sited according to the method given in the report. All the licensed turbines are sold with a documentation of production based on the method and it is used in the central, regional and local authority wind energy planning. The methodology developed has influenced similar studies in other countries, and in 1981 Risø was asked to act as the main contractor and coordinator of the work towards a »Wind Atlas for the European Community Countries«.

Despite its title, the Danish Wind Atlas is not a collection of wind maps. It supplies the necessary statistical data

Figure 4. Sketch of procedures in calculating the mean energy production from a given wind turbine at a specific site by means of the "Wind Atlas Method".

and describes how to perform mean production calculations using these data. The calculations use a classification of the terrain around the turbine. The use of the Wind Atlas is schematically shown in Fig. 4. The Atlas can be used to estimate the energy production of a single turbine at a specified site, or the siting possibilities and wind power potential at a specified area and for different types of turbines. Using topographical maps the Atlas enables a user to produce maps showing the geographical variation of the wind energy production.

The necessary statistical wind data supplied in the Atlas were calculated using a method illustrated in Fig. 5. The method implies a calculation of the statistics of the free wind (the geostrophic wind[1]) at a height of approximately one kilometer. The term »free wind« indicates that the wind at this height is not directly influenced by the character of the earth's surface. The free wind was calculated from 13 years of atmospheric pressure measurements taken every three hours at 55 meteorological stations in Norway, Sweden, West Germany, East Germany, Poland, and Denmark.

The statistics of the free wind were calculated for a number of grid points distributed over Denmark. One result was that the statistics of the free wind varies only slightly over an area the size of Denmark. This variation could be neglected in the further part of the procedure. The second step used the time sequence of the free wind and a stability index[2] in calculating wind speeds at several heights from 10 to 200 meters and over four different types of terrain. The calculated time sequences of wind speed were then used to estimate the frequency distribution of the wind speed as function of height, direction and type of terrain. These frequency distributions were found to be adequately described by so-called Weibull distributions. The distributions are dependent on two parameters: a scale parameter A, and a shape parameter C. These parameters are given in the Wind Atlas as a collection of charts from which it is possible to determine the parameters corresponding to a given terrain and a given height, and hence (see Fig. 4) the mean energy production of a wind turbine, provided the power curve is known.

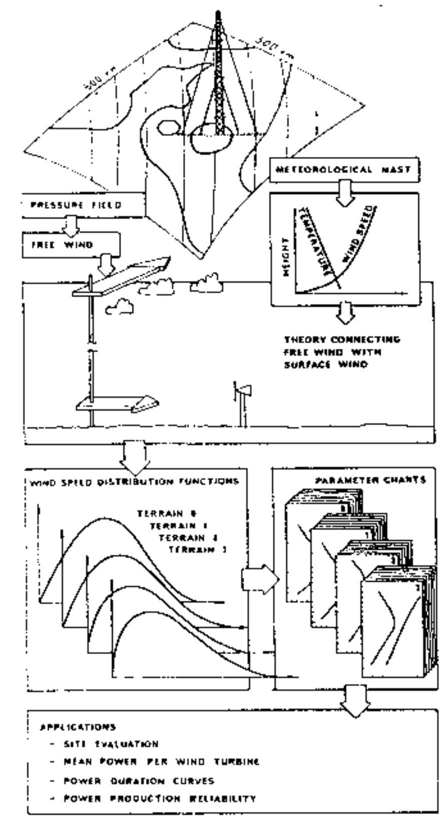


Figure 5. The four major steps in the construction of the Danish Wind Atlas: pressure analysis, the free (geostrophic) wind, the surface, wind over four terrain classes; the Weibull parameter charts.

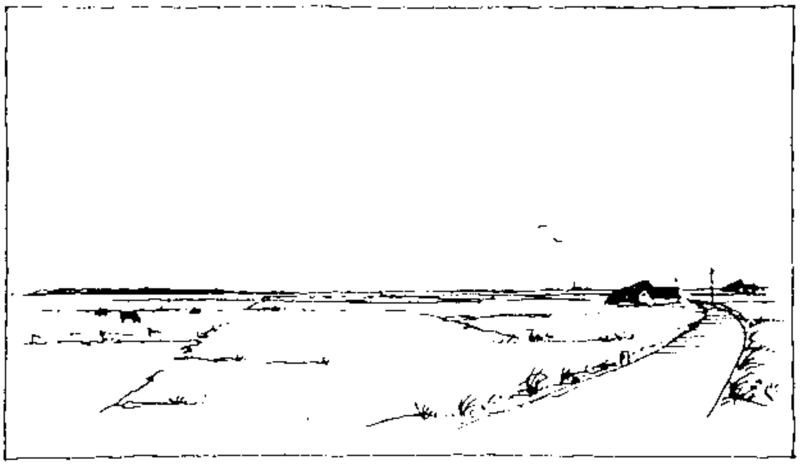
1) The velocity that can be calculated under the assumption of equilibrium between the Coriolis and pressure-gradient forces. The geostrophic wind is often a very good approximation to the velocity observed at a height of one kilometer above the terrain.

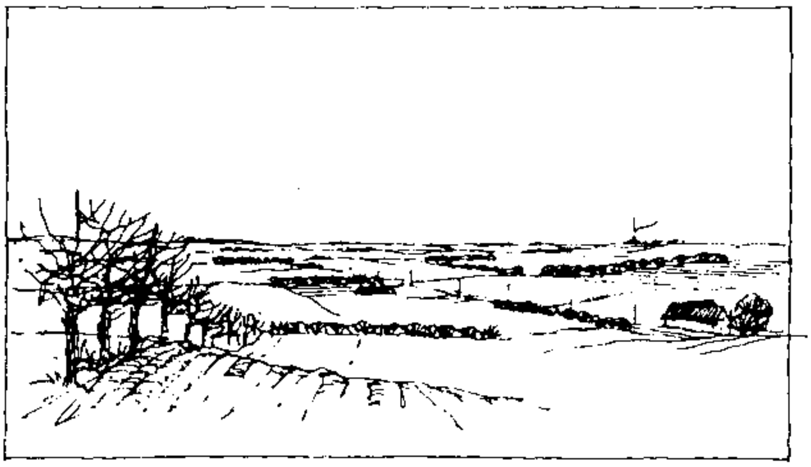
2) The stability index indicates, roughly speaking, whether the atmosphere is stable, unstable, or neutral which are typical conditions for night-time, mid-day and under strong wind conditions, respectively. Stability in that portion of the atmosphere closest to the ground has a strong influence on wind conditions. For a given geostrophic wind, unstable conditions will cause increased wind speeds relative to those expected in neutral conditions, while stable conditions normally give rise to relatively smaller wind speeds.

Before the appropriate Weibull parameter can be chosen it is necessary to conduct a terrain classification for the selected site. For that purpose the Danish landscape has been classified into four terrain types or roughness classes as shown in Table 1 and Fig. 6.

In Table 1 the importance of the terrain roughness for the wind energy potential is illustrated by showing the variation of the calculated wind energy at a height of 50 m above surface. The numbers are relative and the energy for water areas is arbitrarily chosen as 10. Also shown in Table 1 is the so-called roughness length which is a length scale ascribed to the corresponding terrain and used in the mathematical expressions for the connection between the free wind and the wind at low heights over the surface.

The terrain classification is performed for each of eight direction sectors. A problem which then often occurs is the change of terrain class at some distance from the site. A typical example is a site near a coast. Other complications are nearby sheltering objects such as houses, trees, and shelter belts, or hilly terrain. The Wind Atlas contains graphs, charts, and calculational procedures that can take such complications into account in estimating the frequency distribution of the wind speed.





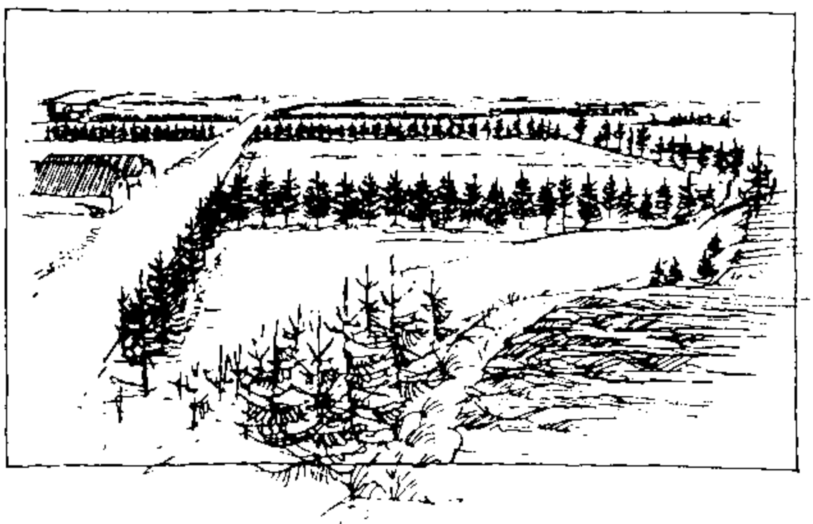


Figure 6. Terrain classes 1, 2 and 3 in the Danish Wind Atlas (drawings by Søren Rasmussen). Further description is given in Table 1.

Table 1. Types of terrain, roughness classes, and roughness lengths.

Roughness class	Terrain	Roughness length	Relative energy
0	– water areas	0–1 mm	10
1	– open country areas with very few bushes, trees, and buildings	1–3 cm	7
2	– farmland with scattered buildings and hedges with separation in excess of 1 km	5–10 cm	5
3	– built-up areas, forests, and farmland with many hedges	30–40 cm	3

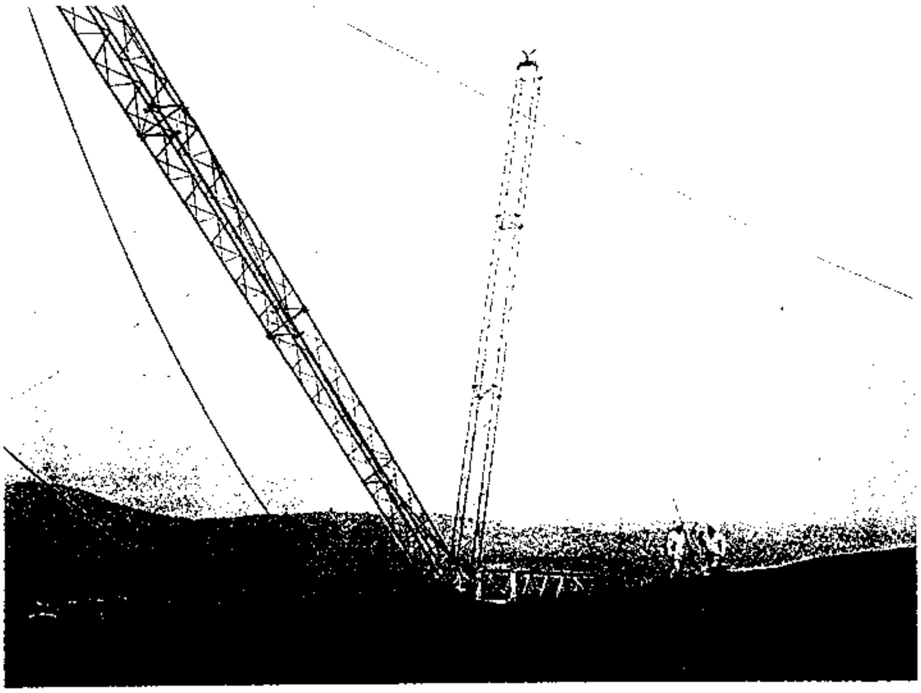


Figure 7. The erection of a 48 m experimental meteorological mast at the Askervein hill on the Outer Hebrides.

Verification

During the construction of the Wind Atlas it was of great importance to verify the applied methodology. This was done by comparing the calculated and observed distribution functions of the wind speed at various places that were distributed evenly over the country. Airport data were found to be of high quality and especially suitable for the purpose as for natural reasons airports are placed on flat plains which can be considered horizontally homogeneous. The verifications, of which fourteen are shown in the Wind Atlas, show that the method is able to reproduce the measured wind distributions to a high degree of accuracy.

The final verification of the method has been the comparison of energy actually produced by turbines, with the energy production estimated by the Wind Atlas method. Such investigations have been performed by several independent parties. None of them have contradicted the prediction in the Wind Atlas claiming that it is possible to estimate the energy production with an accuracy of 5% if the turbine is at a site with surroundings that are not too complicated.

Some of the main physical models used in the construction of the Wind Atlas have been tested through esperiments sponsored by the Wind Power Programme of the Ministry of Energy and the utilities. One experiment, named JYLEX, was designed specifically for testing the model that accounts for the change in the wind field, when it moves from one terrain category to another. In the JYLEX esperiment four masts, instrumented with cup anemometers and other instruments at several levels up to 30 meters, were placed at distances 0, 1, 5 and 25 km inland from the west coast of Jutland. Consecutive data exist from this experiment for a period of more than two years. The mean wind and the mean energy at 24 meters height at the mast at the west coast and at the mast 25 km inland were observed to be 8.5 and 6.1 m/s and 853 and 383 kWh/m²/year, respectively. It was found that the model employed in the Wind Atlas was able to reproduce these differences in the mean energy between the two stations, to an accuracy which is better than 10%.

As is well-known, it is advantageous to place a wind turbine at the top of a hill where the wind is stronger. A well-selected site, may result in more than 100% increase in the yearly energy production compared with other sites in the immediate vicinity. In this connection Risø staff participated in an international meteorological experiment under the auspicies of the International Energy Agency (IEA) that took place in the years 1982-83 on the »Askervein« hill of the outer Hebrides. Figure 7 shows one of the two 48 m masts which were erected, instrumented and run by Risø as part of the experiment. Askervein is 123 m high and 1000 m long. The measured speed-up (acceleration) is more than a factor of two as shown at Fig. 8. This gives a theoretical increase in mean energy production by a factor of eight. Results from the Askervein experiment, as shown in Fig. 8, have proved that the method employed in the Wind Atlas for the speed up effects has a sufficient accuracy.

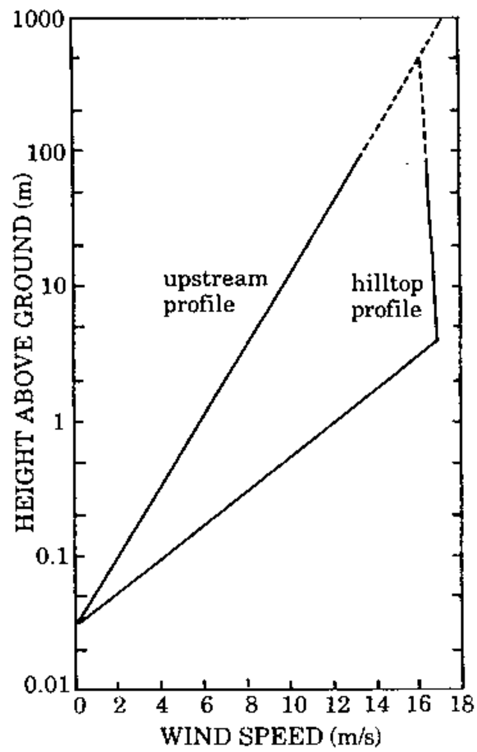
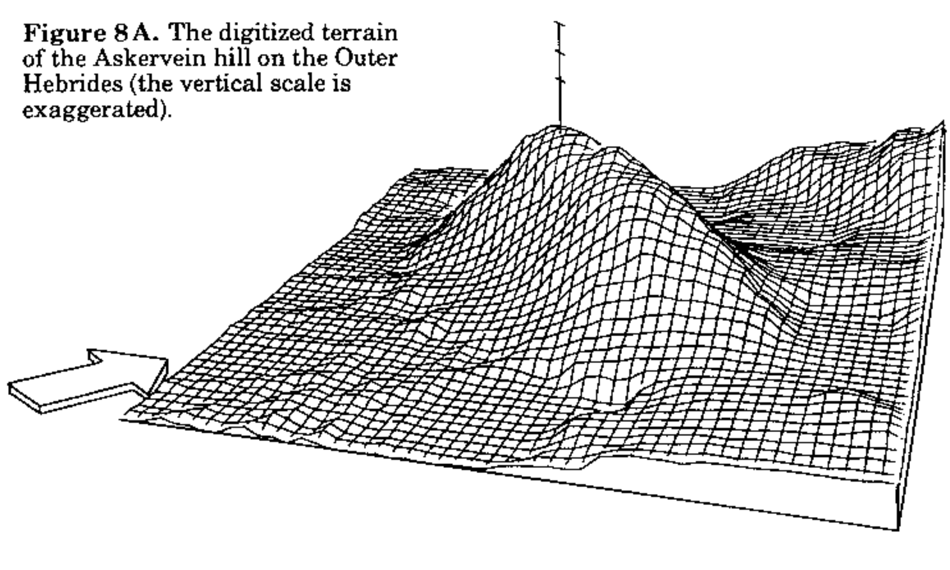


Figure 8. Simultaneously recorded wind profiles upstream and on the top of the Askervein on the Isle of South Uist on the Hebrides, during an international field experiment with participants from Canada, Denmark, F.R. Germany, New Zealand and United Kingdom.

Figure 8 A. The digitized terrain of the Askervein hill on the Outer Hebrides (the vertical scale is exaggerated).



The European Wind Atlas

The wind energy resources vary greatly over Europe, from the oceanic climate of the British Isles over the continental climate of central Germany to the Mediterranean climate of the Greek islands. The variation covers more than a decade on the energy scale. But not only does the mean energy content in the wind vary over large scales - also on a very local scale can large variations be experienced.

Therefore, when it comes to serious considerations of using large electricity producing wind turbine installations in the EC countries it is a necessary requirement to have reliable data and methods for calculating the wind energy potential at the selected locations. The overall effort of the European Community countries to promote the market for electricity production from the wind resources in Europe and to develop associated technologies and systems, prompted the Commission to initiate the Wind Atlas work in 1981 during the first wind energy programme.

The 656-page *European Wind Atlas* is the result of a comprehensive investigation of the climatic wind conditions in the European Community countries. The investigation was conducted by a network of meteorological and other institutions in which Risø National Laboratory, Denmark was responsible for project coordination, theoretical work, numerical modelling, data analysis, and reporting.

The data

Almost two hundred meteorological stations in the European Community countries were selected for calculating regional wind climatologies.

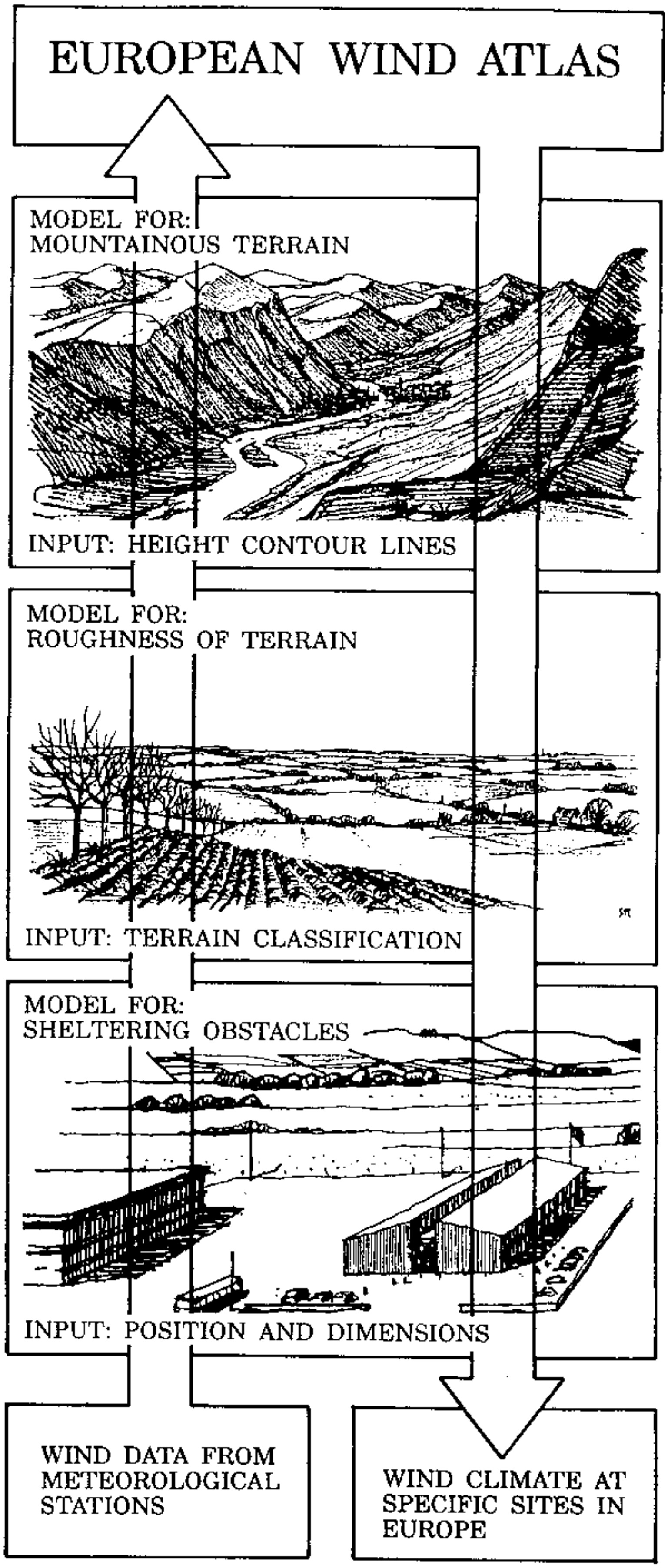
For each station a data-set of meteorological measurements taken every three hours over a period of 10 years was provided. In addition, an accurate description of the station and its topographical setting was supplied.

The analysis

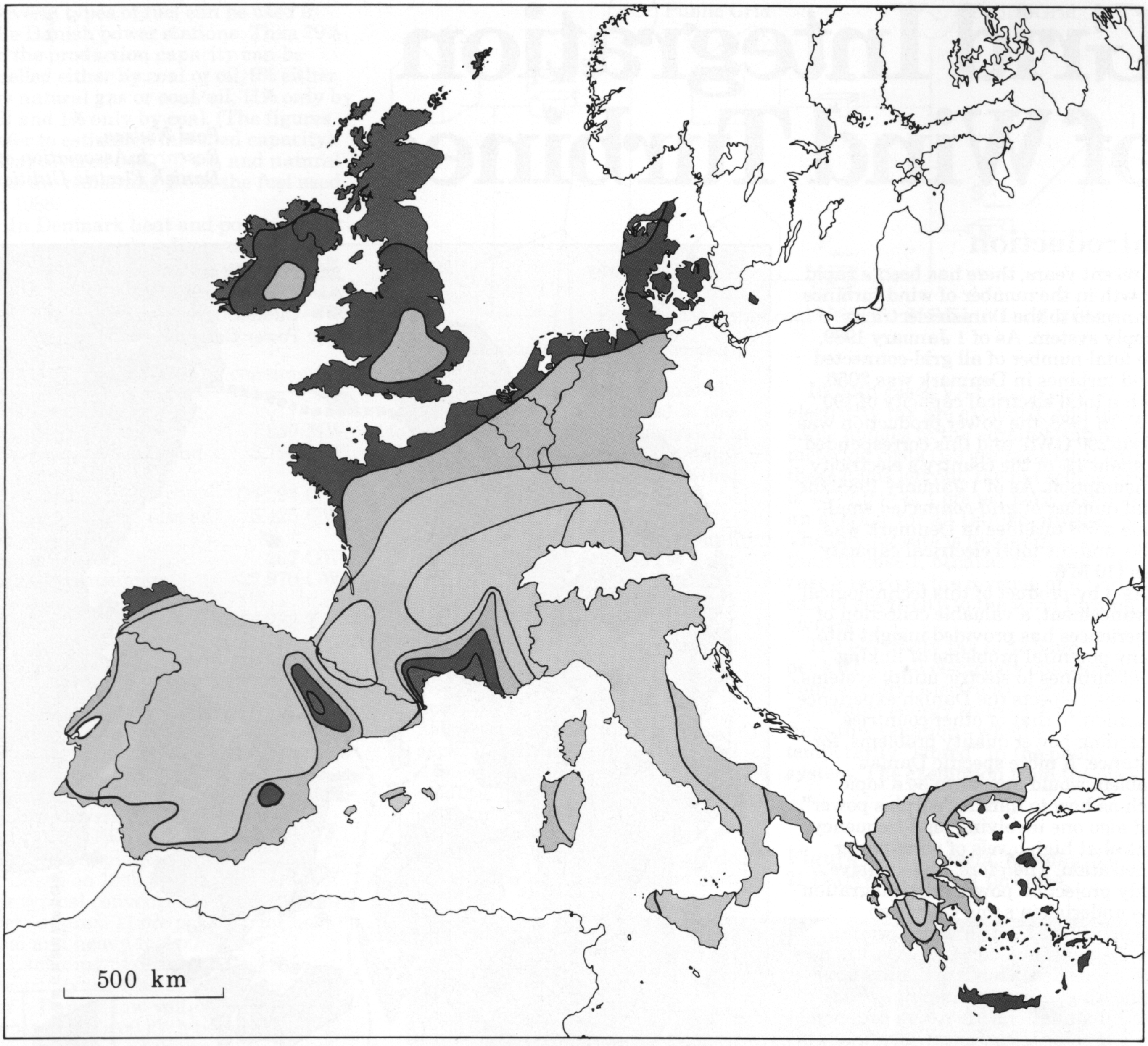
The information from each station was used to calculate a wind climatology considered to be representative of a region out to a distance of approx. 100 km from the station. To do this it was necessary to consider and correct for the influence of local topography on the measured wind data. The analysis was carried out by means of a set of meteorological models developed to perform the appropriate corrections on the wind data. The models take into account the effect of different surface conditions, sheltering effects due to buildings and other nearby obstacles, and the modification of the wind imposed by the specific terrain height variations around the meteorological station in question.

The result

The result of the analysis is an "atlas" of regional wind climate in the form of Weibull parameter tables corresponding to standard azimuth sectors, heights above ground surface, and surface roughness conditions.



Meteorological models were used to calculate the regional wind climatologies from the raw data. In the reverse process - the application of the Wind Atlas - the wind climate at any specific site may be calculated from the regional climatology.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

1. The resources refer to the power present in the wind. A wind turbine can utilize between 20 and 30% of the available resource. The resources are calculated for an air density of 1.23 kg $\mathrm{m^{-3}}$, corresponding to standard sea level pressure and a temperature of 15°C. Air density decreases with height, but up to 1000 m a.s.l. the resulting reduction of the power densities is less than 10%.
2. Urban districts, forest and farm land with many windbreaks (roughness class 3).
3. Open landscapes with few windbreaks (roughness class 1). In general, the most favourable inland sites on level land are found here.
4. The classes pertain to a straight coastline, a uniform wind rose and a land surface with few windbreaks (roughness class 1). Resources will be higher, and closer to open sea values, if winds from the sea occur more frequently, i.e. the wind rose is not uniform and/or the land protrudes into the sea. Conversely, resources will generally be smaller, and closer to land values, if winds from land occur more frequently.
5. More than 10 km offshore (roughness class 0).
6. The classes correspond to 50% overspeeding and were calculated for a site on the summit of a single axisymmetric hill with a height of 400 metres and a base diameter of 4 km. The overspeeding depends on the height, length and specific setting of the hill.

The Atlas

The European Wind Atlas contains descriptions and data summaries for all the meteorological stations as well as the calculated regional wind climatologies. In addition to the basic meteorological data, the Atlas contains a handbook for regional wind resource assessment and local siting of wind turbines. Furthermore, the wind atlas data have been compiled into maps of wind resources for each EC country.

The wind resource map provides means for the estimation of the wind energy resource at a height of 50 metres above ground. The map depicts the geographic distribution of five wind energy classes, each class representing a range of mean wind energy density or equivalent mean wind speed, the range being topography dependent. The expected ranges of mean wind energy and mean wind speed are given in Table 1 for five different topographical conditions: sheltered terrain; flat open farmland; the sea coast; open sea (more than 10 km offshore); well exposed hills and ridges. These conditions are chosen merely to illustrate typical wind energy ranges, and the estimates should be considered only as such.

The Application

The Atlas is the meteorological basis for estimating the wind climate and wind energy resources of any particular site in the EC. The application of the Atlas as a "siting handbook" is explained in detail in the Atlas.

To facilitate resource calculations and specific siting of wind turbines, the Wind Atlas is furnished with a diskette containing all the regional statistics. The diskette files can be used directly with the "Wind Atlas Analysis and Application Program" (WA^{s}P), which was developed especially for the production of the Wind Atlas and for use in practical siting.

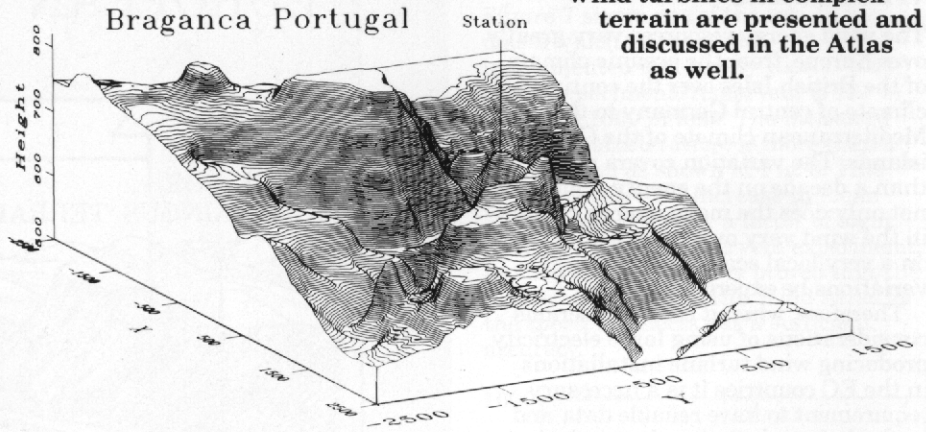
Concluding Remarks

The principles used in the Danish Wind Atlas have enabled Danish producers of wind turbines to document the energy production of their turbines using the same basic wind statistics.

Furthermore, the producers or the wind energy consultancy firms can provide customers with advice for siting wind turbines. Using the Danish Wind Atlas, planning authorities have been able to evaluate various levels of wind energy in the Danish power supply system.

The Danish Wind Atlas provided at the time of its publication and for several years thereafter a very valuable tool for detailed resource assessment and siting in Denmark. The methods provided in the Danish Wind Atlas have been very much improved and extended in the European Wind Atlas. One major deficiency in the Danish Wind Atlas was the lack of adequate calculation methods for siting in hilly and more complex terrain. The orographic model together with a large number of other improvements in the flow modelling is provided in the European Wind Atlas and in the general analysis and siting programme WA^{s}P which is now used in all parts of the world.

The inclusion in the Atlas of stations situated in complex terrain is one major achievement of the European Wind Atlas. Procedures for siting of wind turbines in complex terrain are presented and discussed in the Atlas as well.



UNITED KINGDOM

Manchester

Terraintype 1	02° 16′ 00″ W 53° 21′ 00″ N	UTM 30 E 548817 m N 5911582 m	78 m a.s.l.

Located about 14 km south of the centre of Manchester in the middle of a half-basin bounded by the Pennines bearing from 330° through 360° to 150°. These mountains lie 40 km away, reaches about 600 m and give good shelter. Shelter is also provided by the Welsh Mountains 50 to 60 km away to the SW. Winds are channelled through the gap between the Pennines and the Welsh Mountains giving as a result that the most frequent winds come from the south. To the W there is an open exposure to the Irish Sea, which is approximately 50 km away.
At smaller distances from the station extensive housing estates encroach from W through N to SE. Otherwise the surroundings are cultivated farmland. The anemometer is placed between the runways of Manchester Airport (Ringway) with the airport buildings in the W to NW sector.

Sect	z_{01}	X_1	z_{02}	X_2	z_{03}	X_3	z_{04}	X_4	z_{05}	X_5	z_{06}	Pct	Deg
0	0.01	750	0.10	2000	0.40								
30	0.01	500	0.40										
60	0.01	1500	0.10	3000	0.40								
90	0.01	1000	0.10	3500	0.30								
120	0.01	800	0.20										
150	0.01	600	0.20										
180	0.01	750	0.10										
210	0.01	1500	0.10										
240	0.01	400	0.20										
270	0.01	400	0.30										
300	0.01	150	0.30	750	0.20								
330	0.01	500	0.10	4000	0.40								

Height of anemometer: 10.0 m a.g.l. Period: 71010103–80122400

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	3.2	202	145	152	170	121	79	62	32	15	15	3	2	1	0	3.8	1.56
30	5.0	112	80	126	167	148	135	111	69	30	22	2	0	0	0	4.9	2.12
60	7.1	105	87	118	152	132	123	100	79	38	47	13	5	0	0	5.2	1.88
90	6.6	123	123	132	152	132	118	81	57	31	35	10	7	1	0	4.8	1.67
120	5.5	132	125	146	170	136	100	76	59	30	23	4	0	0	0	4.4	1.76
150	8.1	99	93	134	201	142	115	82	66	25	37	5	1	0	0	4.7	1.82
180	17.5	64	91	131	187	158	124	101	62	35	35	11	2	0	0	5.0	1.93
210	12.4	74	87	105	147	143	122	127	87	47	45	13	2	1	0	5.5	2.06
240	8.6	103	118	119	125	113	109	106	79	49	59	16	4	0	0	5.3	1.83
270	10.3	89	106	104	131	127	114	101	81	46	65	26	7	1	0	5.6	1.81
300	10.4	71	68	96	149	155	148	126	80	47	45	12	3	1	0	5.6	2.16
330	5.1	149	154	157	173	103	110	64	45	23	15	4	3	1	0	4.1	1.59
Total	100.0	96	100	122	160	138	120	100	70	37	40	11	3	0	0	5.1	1.86

UTC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	4.9	4.2	4.2	3.8	3.7	3.0	2.9	3.0	3.5	3.7	4.5	4.9	3.8
3	4.7	4.1	4.1	3.5	3.4	2.9	2.7	2.8	3.3	3.7	4.5	4.9	3.7
6	4.8	4.0	4.1	3.6	3.4	3.2	2.9	2.9	3.4	3.8	4.2	4.8	3.8
9	4.9	4.3	4.7	4.8	4.7	4.5	4.0	4.1	4.3	4.2	4.5	4.9	4.5
12	5.6	5.1	6.0	5.6	5.3	5.0	4.8	4.8	5.2	5.3	5.5	5.3	5.3
15	5.4	5.2	6.0	5.8	5.6	5.2	5.2	4.9	5.4	5.1	5.3	5.3	5.4
18	4.9	4.4	5.0	5.4	5.3	4.9	4.7	4.4	4.2	4.0	4.6	5.1	4.7
21	4.8	4.3	4.4	4.0	4.1	3.5	3.3	3.2	3.6	3.9	4.5	5.0	4.0
Day	5.0	4.5	4.8	4.6	4.4	4.0	3.8	3.8	4.1	4.2	4.7	5.0	4.4

Sample station description. Following a verbal description are the roughness classification and an analysis of the measured data giving the frequency of occurrence of wind speed in 12 direction sectors and hourly averages month by month.

MANCHESTER

Roughness Class 0

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	5.8	7.1	7.7	7.1	6.6	6.9	7.2	7.3	7.9	8.7	9.8	8.5	7.7
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
25	6.3	7.8	8.3	7.8	7.1	7.5	7.8	8.0	8.6	9.5	10.6	9.2	8.4
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
50	6.7	8.2	8.8	8.2	7.6	7.9	8.2	8.4	9.1	10.0	11.2	9.7	8.8
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
100	7.1	8.7	9.3	8.7	8.0	8.4	8.7	8.9	9.6	10.6	11.9	10.3	9.3
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
200	7.4	9.1	9.8	9.1	8.4	8.8	9.2	9.4	10.1	11.1	12.5	10.8	9.8
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
Freq	4.0	4.3	6.3	6.8	5.9	7.1	13.8	14.5	10.0	9.7	10.4	7.2	100.0

Roughness Class 1

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.1	5.4	5.4	4.9	4.6	5.0	5.1	5.3	5.8	6.3	7.2	5.1	5.5
	1.53	2.03	1.88	1.68	1.71	1.81	1.91	2.01	1.82	1.80	2.08	1.61	1.79
25	4.9	6.5	6.5	6.0	5.6	6.0	6.1	6.4	6.9	7.6	8.7	6.2	6.6
	1.59	2.11	1.96	1.75	1.78	1.89	1.99	2.10	1.90	1.87	2.17	1.67	1.86
50	5.6	7.4	7.4	6.8	6.3	6.9	7.0	7.3	7.9	8.6	9.9	7.0	7.5
	1.64	2.18	2.02	1.81	1.84	1.95	2.06	2.17	1.96	1.94	2.24	1.73	1.91
100	6.4	8.4	8.4	7.7	7.2	7.8	7.9	8.3	9.0	9.8	11.1	7.9	8.5
	1.70	2.26	2.09	1.87	1.90	2.01	2.13	2.24	2.02	2.00	2.31	1.78	1.97
200	6.9	9.1	9.1	8.4	7.8	8.4	8.6	9.0	9.7	10.6	12.1	8.6	9.2
	1.70	2.26	2.09	1.87	1.90	2.01	2.13	2.24	2.02	2.00	2.31	1.78	1.97
Freq	3.5	4.8	6.8	6.7	5.7	7.7	16.3	13.2	9.1	10.1	10.3	6.0	100.0

Roughness Class 2

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.5	4.8	4.7	4.3	4.0	4.4	4.4	4.7	5.1	5.5	6.3	4.1	4.8
	1.54	2.07	1.87	1.68	1.76	1.82	1.92	2.05	1.82	1.80	2.12	1.58	1.79
25	4.4	5.9	5.9	5.4	5.0	5.5	5.6	5.9	6.4	6.8	7.9	5.1	6.0
	1.61	2.15	1.94	1.75	1.83	1.90	2.00	2.13	1.90	1.87	2.21	1.64	1.87
50	5.2	6.9	6.8	6.3	5.9	6.4	6.5	6.8	7.4	8.0	9.2	6.0	6.9
	1.66	2.22	2.01	1.81	1.90	1.96	2.07	2.20	1.96	1.94	2.28	1.70	1.92
100	6.0	7.9	7.8	7.2	6.8	7.3	7.4	7.9	8.5	9.2	10.6	6.9	8.0
	1.71	2.30	2.07	1.87	1.96	2.02	2.13	2.27	2.02	2.00	2.36	1.75	1.98
200	6.6	8.7	8.6	7.9	7.4	8.0	8.2	8.6	9.4	10.1	11.6	7.6	8.8
	1.71	2.30	2.07	1.87	1.96	2.02	2.13	2.27	2.02	2.00	2.36	1.75	1.98
Freq	3.3	4.9	7.1	6.6	5.6	8.0	17.1	12.7	8.7	10.2	10.3	5.6	100.0

Roughness Class 3

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.9	3.8	3.7	3.3	3.2	3.4	3.5	3.8	4.1	4.4	4.9	3.0	3.8
	1.59	2.08	1.85	1.67	1.77	1.82	1.94	2.06	1.83	1.83	2.12	1.58	1.80
25	3.9	5.1	4.9	4.5	4.3	4.6	4.7	5.0	5.4	5.9	6.6	4.0	5.0
	1.65	2.17	1.93	1.74	1.84	1.90	2.02	2.15	1.91	1.91	2.21	1.65	1.87
50	4.7	6.1	5.9	5.4	5.2	5.5	5.7	6.1	6.6	7.1	8.0	4.8	6.1
	1.71	2.24	1.99	1.79	1.90	1.96	2.08	2.22	1.97	1.97	2.28	1.70	1.93
100	5.5	7.2	7.0	6.4	6.1	6.6	6.7	7.2	7.8	8.4	9.4	5.7	7.2
	1.76	2.31	2.06	1.86	1.97	2.02	2.15	2.29	2.04	2.04	2.36	1.76	1.99
200	6.2	8.1	7.9	7.2	6.9	7.4	7.6	8.1	8.7	9.4	10.6	6.4	8.1
	1.76	2.31	2.06	1.86	1.97	2.02	2.15	2.29	2.04	2.04	2.36	1.76	1.99
Freq	3.3	5.2	7.1	6.5	5.7	9.0	17.1	12.0	8.7	10.1	10.3	5.0	100.0

z	Class 0		Class 1		Class 2		Class 3	
10	6.8	385	4.9	152	4.2	100	3.3	49
25	7.4	491	5.9	255	5.3	187	4.5	112
50	7.8	583	6.7	364	6.2	285	5.4	191
100	8.3	687	7.5	510	7.1	419	6.4	305
200	8.7	802	8.2	652	7.8	559	7.2	435

The regional wind climatology of the same station contains the Weibull parameters of the wind speed distribution functions for 4 roughness classes, 5 heights and 12 direction sectors. A summary table gives the mean wind speed and the mean energy content of the wind for each of 4 roughness classes and 4 heights.

List of Literature

Wind Atlas for Denmark.
(A rational method of wind energy siting). Risø R-48. January 1981.
By E.L. Petersen, I. Troen, S. Frandsen, and K. Hedegaard.

* European Wind Atlas.
Risø National Laboratory 1989, 656 p.
By I. Troen and E.L. Petersen.

* WA^{s}P - Wind Atlas Analysis and Application Programme. User's Guide (Release 2.0). Risø National Laboratory 1988, 96 p. By I. Troen, N.G. Mortensen, and E.L. Petersen.

* Information about the European Wind Atlas and the WA^{s}P programme is available on request from Risø National Laboratory.

Manchester

Terraintype 1	02° 16′ 00″ W 53° 21′ 00″ N	UTM 30 E 548817 m N 5911582 m	78 m a.s.l.

Located about 14 km south of the centre of Manchester in the middle of a half-basin bounded by the Pennines bearing from 330° through 360° to 150°. These mountains lie 40 km away, reaches about 600 m and give good shelter. Shelter is also provided by the Welsh Mountains 50 to 60 km away to the SW. Winds are channelled through the gap between the Pennines and the Welsh Mountains giving as a result that the most frequent winds come from the south. To the W there is an open exposure to the Irish Sea, which is approximately 50 km away.
At smaller distances from the station extensive housing estates encroach from W through N to SE. Otherwise the surroundings are cultivated farmland. The anemometer is placed between the runways of Manchester Airport (Ringway) with the airport buildings in the W to NW sector.

Sect	z_{01}	X_1	z_{02}	X_2	z_{03}	X_3	z_{04}	X_4	z_{05}	X_5	z_{06}	Pct	Deg
0	0.01	750	0.10	2000	0.40								
30	0.01	500	0.40										
60	0.01	1500	0.10	3000	0.40								
90	0.01	1000	0.10	3500	0.30								
120	0.01	800	0.20										
150	0.01	600	0.20										
180	0.01	750	0.10										
210	0.01	1500	0.10										
240	0.01	400	0.20										
270	0.01	400	0.30										
300	0.01	150	0.30	750	0.20								
330	0.01	500	0.10	4000	0.40								

Height of anemometer: 10.0 m a.g.l. Period: 71010103–80122400

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	A	k
0	3.2	202	145	152	170	121	79	62	32	15	15	3	2	1	0	3.8	1.56
30	5.0	112	80	126	167	148	135	111	69	30	22	2	0	0	0	4.9	2.12
60	7.1	105	87	118	152	132	123	100	79	38	47	13	5	0	0	5.2	1.88
90	6.6	123	123	132	152	132	118	81	57	31	35	10	7	1	0	4.8	1.67
120	5.5	132	125	146	170	136	100	76	59	30	23	4	0	0	0	4.4	1.76
150	8.1	99	93	134	201	142	115	82	66	25	37	5	1	0	0	4.7	1.82
180	17.5	64	91	131	187	158	124	101	62	35	35	11	2	0	0	5.0	1.93
210	12.4	74	87	105	147	143	122	127	87	47	45	13	2	1	0	5.5	2.06
240	8.6	103	118	119	125	113	109	106	79	49	59	16	4	0	0	5.3	1.83
270	10.3	89	106	104	131	127	114	101	81	46	65	26	7	1	0	5.6	1.81
300	10.4	71	68	96	149	155	148	126	80	47	45	12	3	1	0	5.6	2.16
330	5.1	149	154	157	173	103	110	64	45	23	15	4	3	1	0	4.1	1.59
Total	100.0	96	100	122	160	138	120	100	70	37	40	11	3	0	0	5.1	1.86

UTC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	4.9	4.2	4.2	3.8	3.7	3.0	2.9	3.0	3.5	3.7	4.5	4.9	3.8
3	4.7	4.1	4.1	3.5	3.4	2.9	2.7	2.8	3.3	3.7	4.5	4.9	3.7
6	4.8	4.0	4.1	3.6	3.4	3.2	2.9	2.9	3.4	3.8	4.2	4.8	3.8
9	4.9	4.3	4.7	4.8	4.7	4.5	4.0	4.1	4.3	4.2	4.5	4.9	4.5
12	5.6	5.1	6.0	5.6	5.3	5.0	4.8	4.8	5.2	5.3	5.5	5.3	5.3
15	5.4	5.2	6.0	5.8	5.6	5.2	5.2	4.9	5.4	5.1	5.3	5.3	5.4
18	4.9	4.4	5.0	5.4	5.3	4.9	4.7	4.4	4.2	4.0	4.6	5.1	4.7
21	4.8	4.3	4.4	4.0	4.1	3.5	3.3	3.2	3.6	3.9	4.5	5.0	4.0
Day	5.0	4.5	4.8	4.6	4.4	4.0	3.8	3.8	4.1	4.2	4.7	5.0	4.4

Roughness Class 0

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	5.8	7.1	7.7	7.1	6.6	6.9	7.2	7.3	7.9	8.7	9.8	8.5	7.7
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
25	6.3	7.8	8.3	7.8	7.1	7.5	7.8	8.0	8.6	9.5	10.6	9.2	8.4
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
50	6.7	8.2	8.8	8.2	7.6	7.9	8.2	8.4	9.1	10.0	11.2	9.7	8.8
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
100	7.1	8.7	9.3	8.7	8.0	8.4	8.7	8.9	9.6	10.6	11.9	10.3	9.3
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
200	7.4	9.1	9.8	9.1	8.4	8.8	9.2	9.4	10.1	11.1	12.5	10.8	9.8
	1.68	2.05	2.10	1.88	1.86	1.96	2.06	2.13	2.03	1.96	2.16	1.95	1.94
Freq	4.0	4.3	6.3	6.8	5.9	7.1	13.8	14.5	10.0	9.7	10.4	7.2	100.0

Roughness Class 1

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	4.1	5.4	5.4	4.9	4.6	5.0	5.1	5.3	5.8	6.3	7.2	5.1	5.5
	1.53	2.03	1.88	1.68	1.71	1.81	1.91	2.01	1.82	1.80	2.08	1.61	1.79
25	4.9	6.5	6.5	6.0	5.6	6.0	6.1	6.4	6.9	7.6	8.7	6.2	6.6
	1.59	2.11	1.96	1.75	1.78	1.89	1.99	2.10	1.90	1.87	2.17	1.67	1.86
50	5.6	7.4	7.4	6.8	6.3	6.9	7.0	7.3	7.9	8.6	9.9	7.0	7.5
	1.64	2.18	2.02	1.81	1.84	1.95	2.06	2.17	1.96	1.94	2.24	1.73	1.91
100	6.4	8.4	8.4	7.7	7.2	7.8	7.9	8.3	9.0	9.8	11.1	7.9	8.5
	1.70	2.26	2.09	1.87	1.90	2.01	2.13	2.24	2.02	2.00	2.31	1.78	1.97
200	6.9	9.1	9.1	8.4	7.8	8.4	8.6	9.0	9.7	10.6	12.1	8.6	9.2
	1.70	2.26	2.09	1.87	1.90	2.01	2.13	2.24	2.02	2.00	2.31	1.78	1.97
Freq	3.5	4.8	6.8	6.7	5.7	7.7	16.3	13.2	9.1	10.1	10.3	6.0	100.0

Roughness Class 2

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	3.5	4.8	4.7	4.3	4.0	4.4	4.4	4.7	5.1	5.5	6.3	4.1	4.8
	1.54	2.07	1.87	1.68	1.76	1.82	1.92	2.05	1.82	1.80	2.12	1.58	1.79
25	4.4	5.9	5.9	5.4	5.0	5.5	5.6	5.9	6.4	6.8	7.9	5.1	6.0
	1.61	2.15	1.94	1.75	1.83	1.90	2.00	2.13	1.90	1.87	2.21	1.64	1.87
50	5.2	6.9	6.8	6.3	5.9	6.4	6.5	6.8	7.4	8.0	9.2	6.0	6.9
	1.66	2.22	2.01	1.81	1.90	1.96	2.07	2.20	1.96	1.94	2.28	1.70	1.92
100	6.0	7.9	7.8	7.2	6.8	7.3	7.4	7.9	8.5	9.2	10.6	6.9	8.0
	1.71	2.30	2.07	1.87	1.96	2.02	2.13	2.27	2.02	2.00	2.36	1.75	1.98
200	6.6	8.7	8.6	7.9	7.4	8.0	8.2	8.6	9.4	10.1	11.6	7.6	8.8
	1.71	2.30	2.07	1.87	1.96	2.02	2.13	2.27	2.02	2.00	2.36	1.75	1.98
Freq	3.3	4.9	7.1	6.6	5.6	8.0	17.1	12.7	8.7	10.2	10.3	5.6	100.0

Roughness Class 3

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	2.9	3.8	3.7	3.3	3.2	3.4	3.5	3.8	4.1	4.4	4.9	3.0	3.8
	1.59	2.08	1.85	1.67	1.77	1.82	1.94	2.06	1.83	1.83	2.12	1.58	1.80
25	3.9	5.1	4.9	4.5	4.3	4.6	4.7	5.0	5.4	5.9	6.6	4.0	5.0
	1.65	2.17	1.93	1.74	1.84	1.90	2.02	2.15	1.91	1.91	2.21	1.65	1.87
50	4.7	6.1	5.9	5.4	5.2	5.5	5.7	6.1	6.6	7.1	8.0	4.8	6.1
	1.71	2.24	1.99	1.79	1.90	1.96	2.08	2.22	1.97	1.97	2.28	1.70	1.93
100	5.5	7.2	7.0	6.4	6.1	6.6	6.7	7.2	7.8	8.4	9.4	5.7	7.2
	1.76	2.31	2.06	1.86	1.97	2.02	2.15	2.29	2.04	2.04	2.36	1.76	1.99
200	6.2	8.1	7.9	7.2	6.9	7.4	7.6	8.1	8.7	9.4	10.6	6.4	8.1
	1.76	2.31	2.06	1.86	1.97	2.02	2.15	2.29	2.04	2.04	2.36	1.76	1.99
Freq	3.3	5.2	7.1	6.5	5.7	9.0	17.1	12.0	8.7	10.1	10.3	5.0	100.0

z	Class 0		Class 1		Class 2		Class 3	
10	6.8	385	4.9	152	4.2	100	3.3	49
25	7.4	491	5.9	255	5.3	187	4.5	112
50	7.8	583	6.7	364	6.2	285	5.4	191
100	8.3	687	7.5	510	7.1	419	6.4	305
200	8.7	802	8.2	652	7.8	559	7.2	435

Energy Primer: Portola Institute California USA. 1974. ISBN 0 914774 00 X

WIND

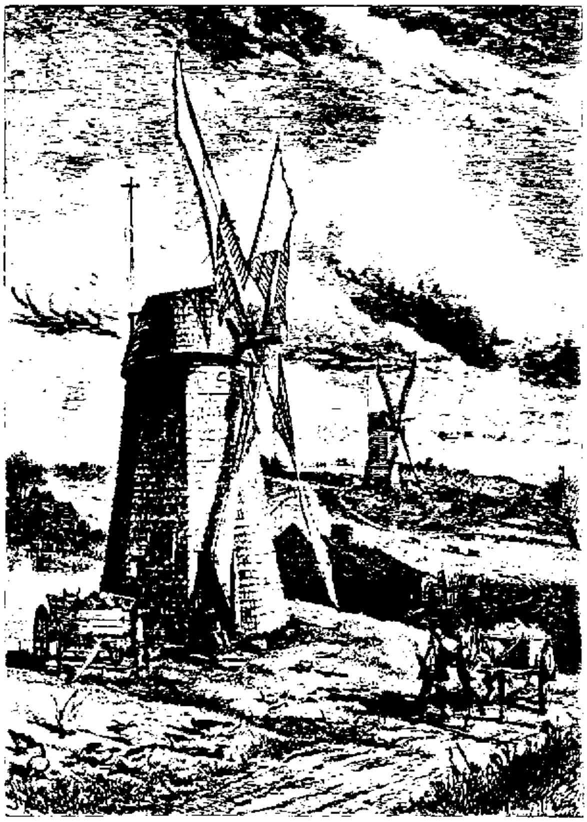
Wind is another form of energy, created by the sun; the heating of our atmosphere during the day and its absence cooling the night sky. It's like breathing—that's it, the earth breathes. Wind is the reaction of our atmosphere to the incoming energy from the sun. Heat causes low pressure areas and the lack of heat results in high pressure areas. This process causes the wind.

It seems ironic that probably the oldest and most constant character of the universe, e.g., massive movements of energy, heating to cooling (entropy), the motion of our atmosphere is suddenly rediscovered as a "new source" of energy. History tells us that next to agriculture, it is very possible that wind may have been one of the first sources harnessed by man.

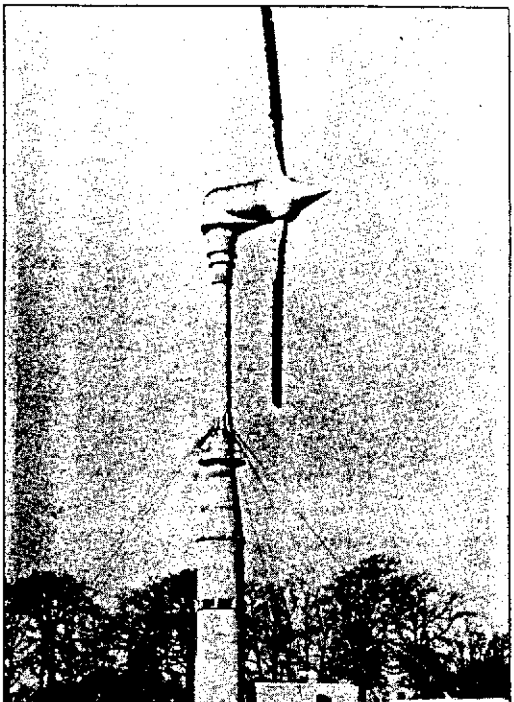
Our main concern regarding wind energy is that it is not as constant and/or predictable as, say, the sun. There are many solutions to this problem, but usually the situation is managed by a *storage system* designed to have the energy available at the time it is needed or desired. Yet, on the other hand, one might look at this concern in a different perspective and not see it as a problem at all, but simply as a challenge to our ability to adapt. If we are truly aware of our capabilities to adapt or adjust, then we also realize our limitations. It should be noted that we have adapted to our lifestyles most effectively considering we inhabit the planet in so many numbers. So that the problem with *wind* is not predictability, but it is *our* ability to respond.

Our dependent, real and intimate relationship with the biosphere can no longer afford to be overlooked. Wind systems are visual indicators of amounts of energy used, and therefore assist us in understanding this *environmental relationship.* The right perspective of this situation is important, for then and only then are we able to design our part of the environment, without selling short our individuality or our abilities.

All things in life change, as does the Sun, the Wind, the Water, and all living things in accordance with them.

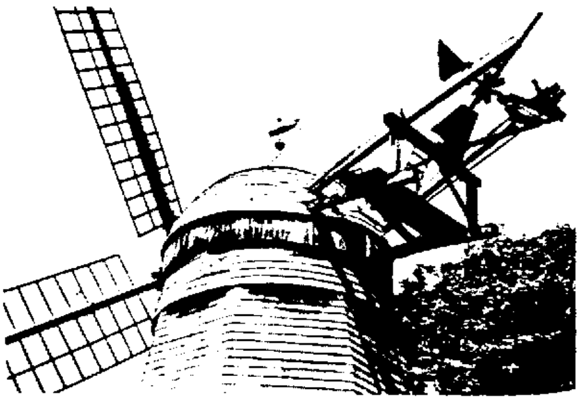


ALL THIS IS POSSIBLE, AND IN THE STARRES AND WINDES. .
—William Shakespeare



ENFIELD - ANDREAU WIND TURBINE

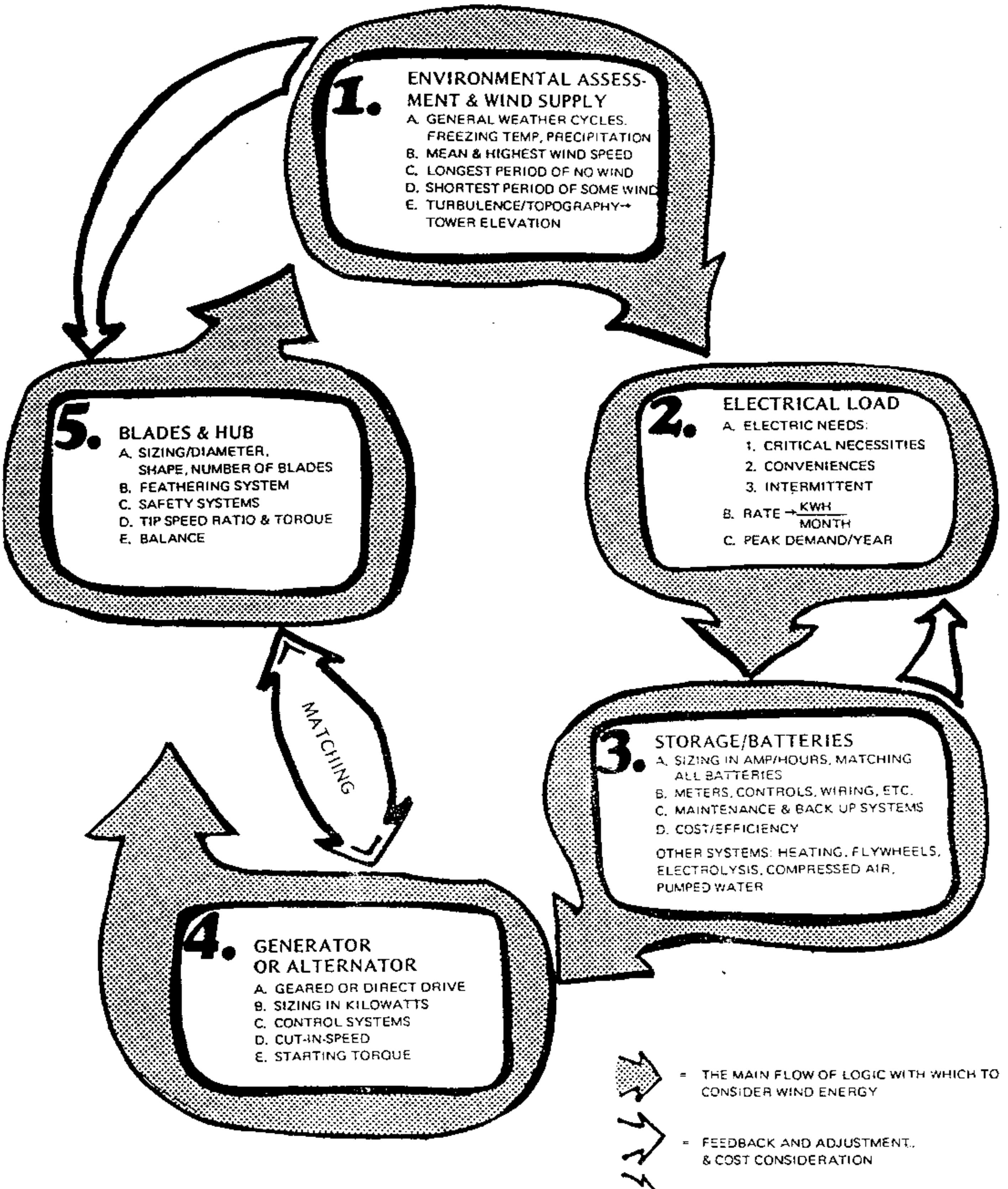
Living things dance with their surroundings,
and so
our ways also
will see.
The evolution of life is the act of creation
and its particularity
its distinction
is its movement,
its visibility.
The way, itself
will define it
in the process
These systems should do as well!



The one nice thing about the correct approach, or the right question to a situation is that the *answers* always reveal themselves as if they were always there.

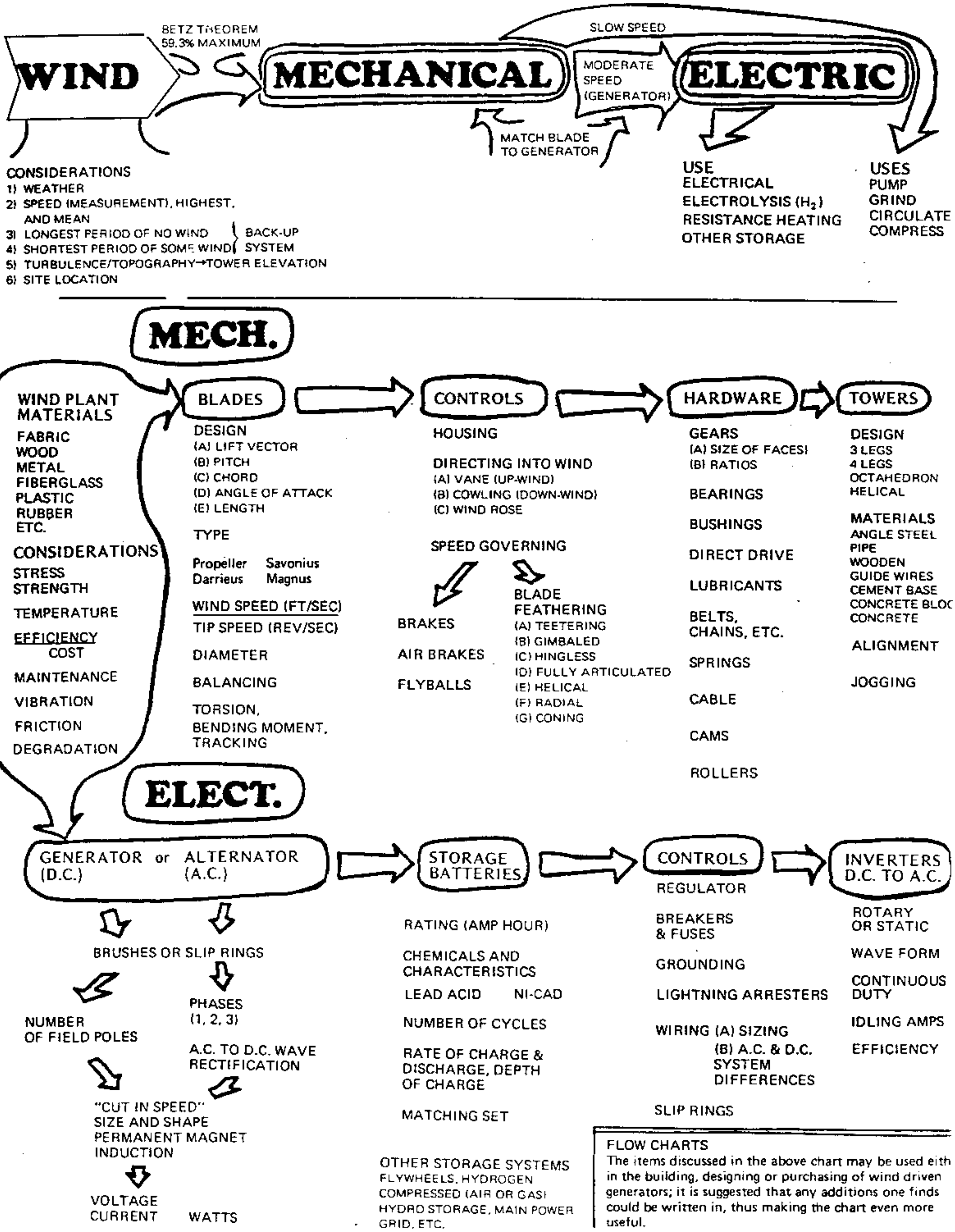
—T.W.

WIND SYNERGY TECHNIQUE

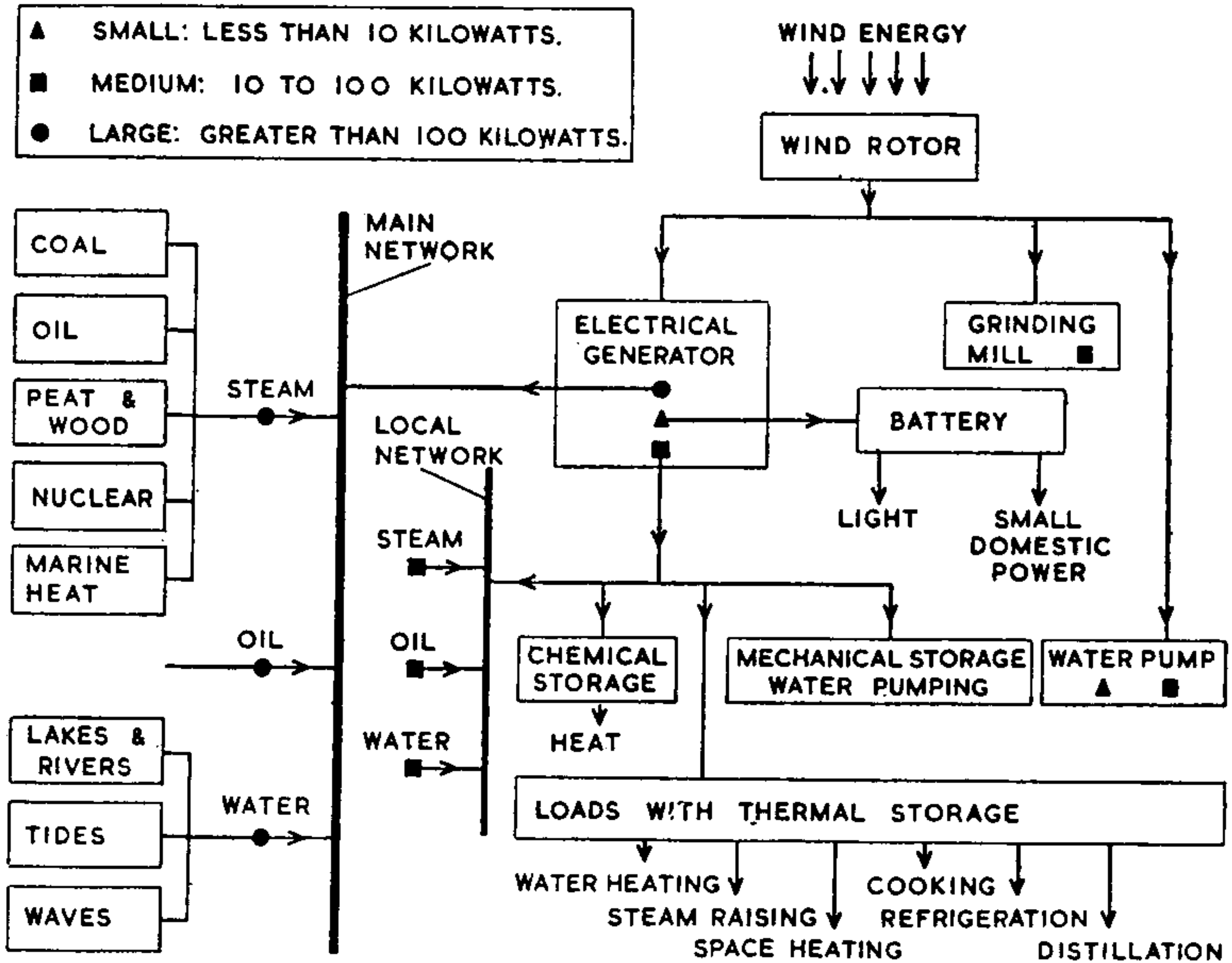


Systematic assessment by which a task is accomplished.

Wind Energy Conversions



FLOW CHARTS
The items discussed in the above chart may be used eith in the building, designing or purchasing of wind driven generators; it is suggested that any additions one finds could be written in, thus making the chart even more useful.



Utilization diagram for wind power

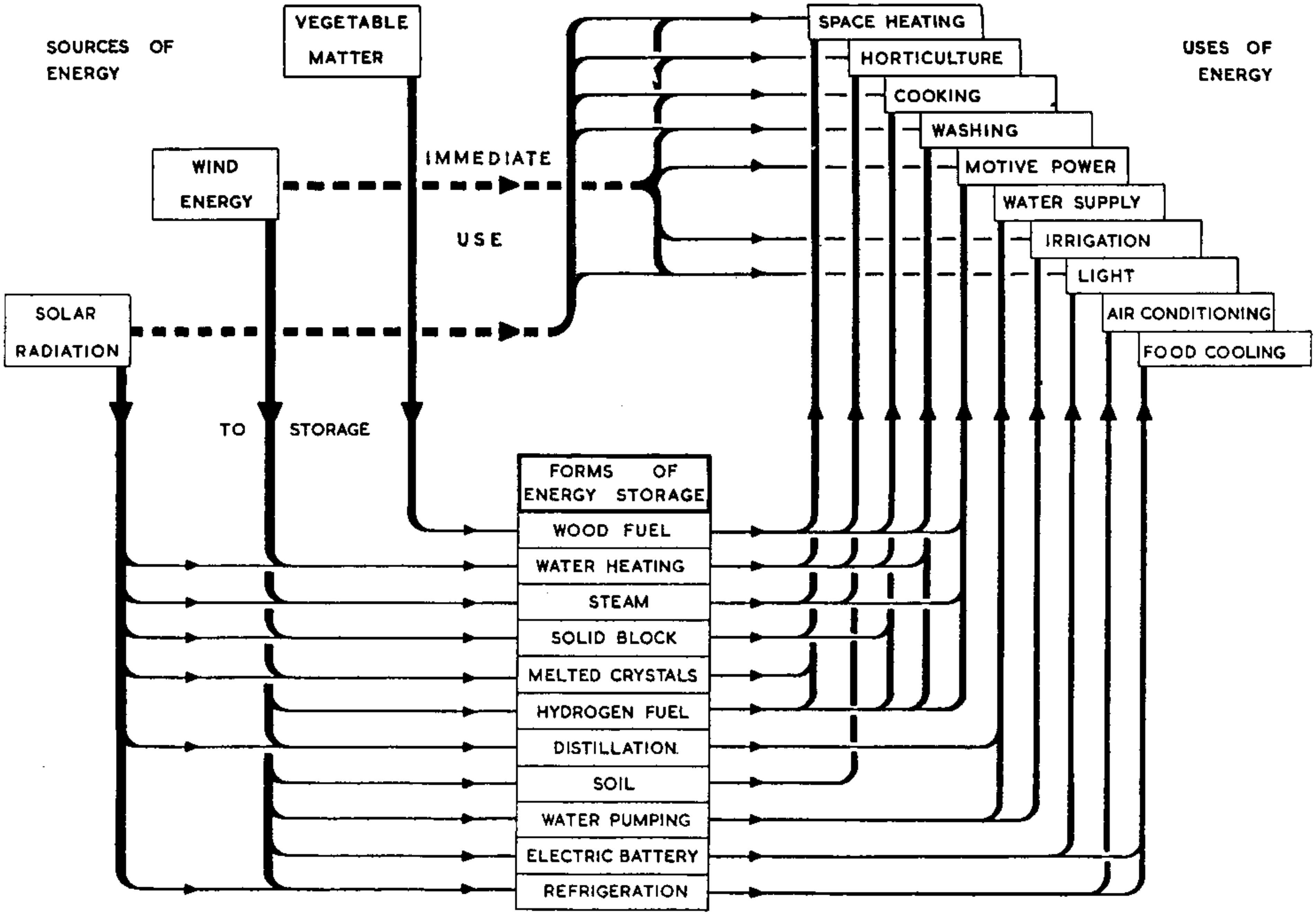
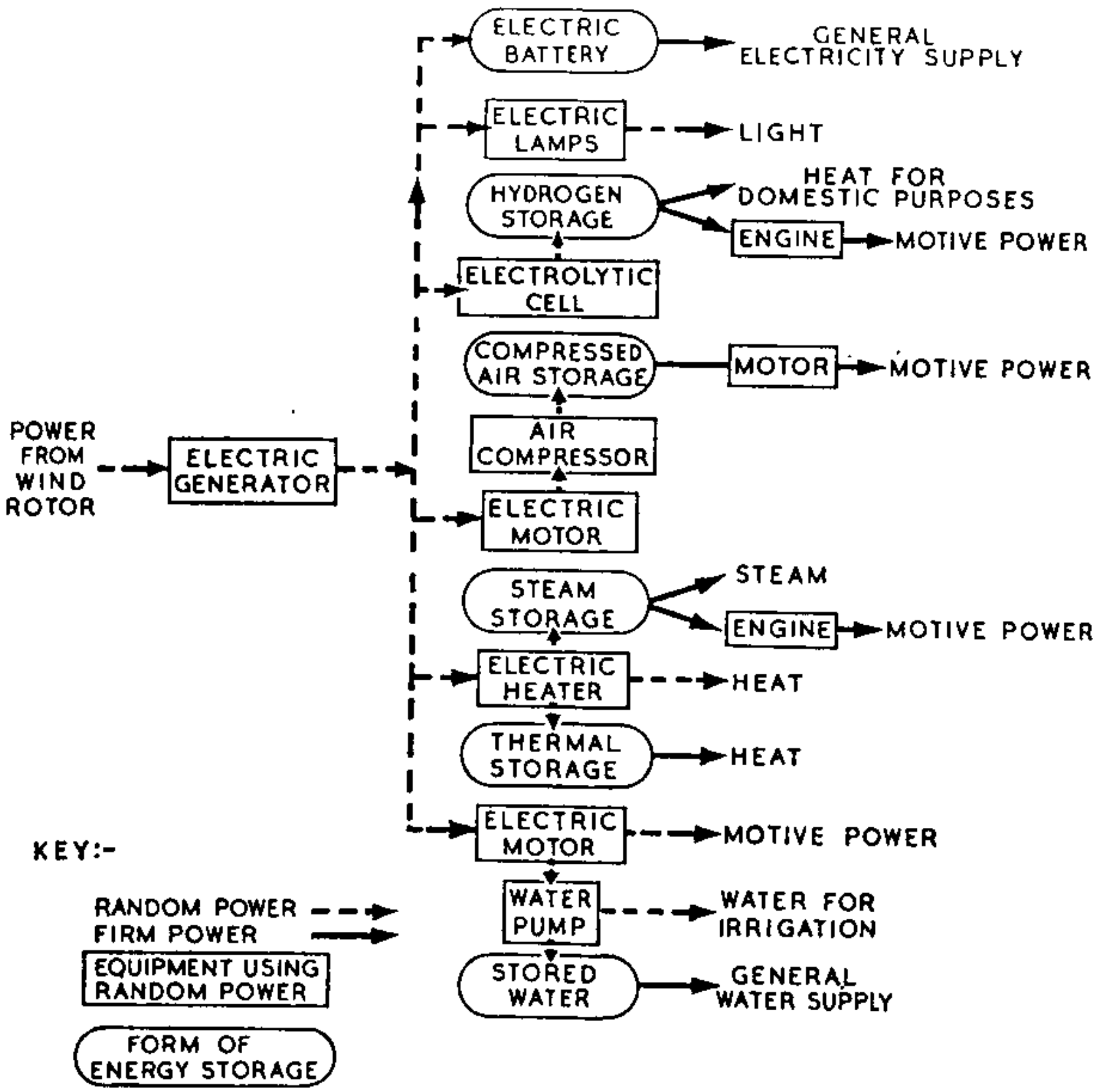


FIG. 101. *Utilization of wind energy in combination with other sources*



Uses of wind power directly and with storage

WIND DRIVEN GENERATORS

BY

James Sencenbaugh
Electrical Engineer

INTRODUCTION

Perhaps the primitive horizontal windmills of 10th century Persia were the first attempt at harnessing wind. This mill, with its sails revolving on a vertical axle mounted in a square tower, was used to grind corn. Diagonally opposed slots in the walls ducted air to the enclosed sail assembly. Tradition tells of the prisoners of Genghis Khan introducing the mills into the East. Horizontal mills became commonplace throughout China, where they were used primarily for irrigation. At the end of the 12th century, mills could be found throughout Northern Europe. By the late 13th century they were in use in Italy, but almost 200 years later the windmill was still unknown in Spain. German crusaders driving through Asia Minor probably instituted the technique in this region. Design from this period on varied greatly and improvements developed independently in many countries.

Unlike windmills which use the wind directly for mechanical energy, a modern wind driven generator extracts energy from the wind and converts it into electricity. A complete wind driven system consists of a: (1) tower to support the wind generator, (2) devices regulating generator voltage, (3) the propeller and hub system, (4) the tail vane, (5) a storage system to store power for use during windless days, and (6) an inverter which converts the stored direct current (D.C.) into regulated alternating current (A.C.) if it is required. An optional backup system, such as a gas or diesel generator, is used to provide power through extremely long calm periods.

With the invention of automobiles and the development of their electrical systems, small D.C. generators of low output and moderate speed input became available on a large scale. Changes in wiring enabled these early generators to be used in the first wind driven designs. At the same time, the rapid increase in aeronautical research led to intensive investigation on airfoil and (propeller) blade design. With this background, the wind driven generator came into its own as the first form of free private electrical power generation. It was first sold as an accessory to battery powered radios. The Zenith radio corporation offered a small 200 watt windplant at a reduced price when bought with one of their battery powered radios. It was during this period that the Wincharger Co. of Sioux City, Iowa was reported to have been turning out 1000 units per day. The wind driven generator field bloomed in the late 1920's and 30's and at its peak over 300 companies were formed throughout the world. A large number of varied designs were available, from a down-wind 1800 watt Win Power to the 3000 watt Jacobs unit. The introduction of the Rural Electrification Agency (REA) in the United States brought a cheaper, more convenient method to have larger amounts of electricity, and wind plants all but disappeared. Jacobs finally closed its doors around 1956 and Wincharger now only makes the original 200 watt 12 volt D.C. model designed in the 1930's.

At present there are only six *major* manufacturers of wind driven generators in the world. Two are in the United States: Dynatechnology (Wincharger) and Bucknell Engineering (bought by Precise Power Corporation). Both build very small 200 watt units on a limited production basis. Dunlite of Australia (which builds plants marketed by Quirk's) manufactures two basic models: a D.C. generator type and a brushless alternator type. Elektro G.M.B.H. of Winterthur, Switzerland offers a complete line of windplants from 50 to 6000 watts. Aerowatt of Paris, France, builds a number of excellent wind plants designed for commercial and marine applications, but their prices are extremely high. Last is Lübing Maschine Fabrik of Barnstorf, West Germany. They primarily build water pumping windplants, but do offer a small 400 watt, 24 volt unit.

The most economical windmill is one which furnishes the kilowatt-hr at the lowest cost. The production of energy by windmills at a favorable cost is made difficult by the fact that the wind is an intermittent source of energy. During a large part of the time it blows too little to produce any useful output and other times it is of such velocities as to cause potential damage to the windplant.

The actual power available from the wind is proportional to the cube of the windspeed. In other words, if the windspeed is doubled, you will get eight times as much power (Cube Law). Another fundamental principle governing windmill design is that it is theoretically impossible in an open-air windplant to recover more than 59.26% (A. Betz) of the kinetic energy contained in the wind. If the prop itself is 75% efficient, and the generator 75% efficient, then 33.34% of the kinetic energy of the wind may be converted into electricity. The other important factor to point out is that the amount of energy captured from the wind by a windplant depends on the amount of wind intercepted; that is, the disk area swept by the blades. A well designed windplant irrespective of the number of blades decelerates the whole horizontal column of air to one-third its free velocity. These facts and the nature of wind currents generally restrict the designer to the most common wind velocities of 3 to 10 meters per second (6.7 to 22.3 mph).

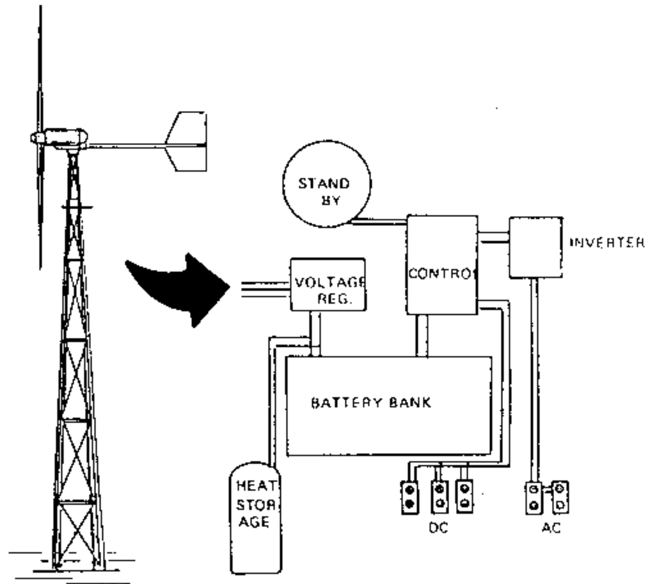


FIG. 1

IN THIS SYSTEM, THE WIND DRIVEN GENERATOR CHARGES A BATTERY BAN from which DC power is taken directly for use or inverted, making AC for appliances like T.V., and radios. Excess power runs a heating storage system.

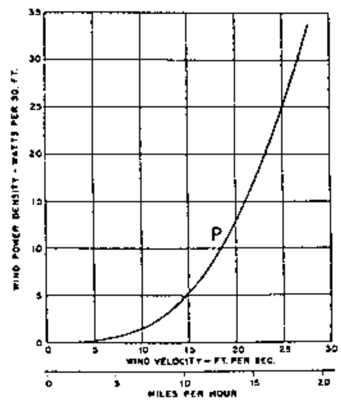


FIG. 2. THEORETICAL POWER DENSITY OF WIND

$$P = (K \cdot A \cdot V^3) \cdot (.5926)$$

Unit of Power P	Unit of Area A	Unit of Velocity V	Value of K
Kilowatts	Square feet	Miles per hour	0·0000053
Kilowatts	Square feet	Knots	0·0000081
Horse power	Square feet	Miles per hour	0·0000071
Watts	Square feet	Feet per second	0·00168
Kilowatts	Square metres	Metres per second	0·00064
Kilowatts	Square metres	Kilometres per hour	0·0000137

WIND FORMULA TABLE 1: Where P= Power in Kilowatts, K= Constant (Air density and other conversion factors), A= Area swept, and V= Wind Velocity.

Table 2 will give an appreciation for the principles involved in windplant design. A 6 foot diameter prop, operating at 70% efficiency in a 20 mph wind, can produce 340 watts. This shows the relationship between windspeed and output. If the wind speed is doubled, you will get eight times as much power. Also note the relationship between propeller diameter and output. Keeping the results for the 6 footer in mind, let us double the prop diameter to 12 feet and note the output at 10 and 20 mph. At 10 mph the 12 footer can produce up to 170 watts and at 20 mph, 1360 watts. Hence the power output from the 12 feet diameter prop is 4 times that of the 6 footer, or *power is proportional to the square of the diameter of the prop.* Double the size of the propeller and the power output will increase by a factor of four.

Propeller Diameter in Feet	Wind Velocity in mph					
	5	10	15	20	25	30
2	0.6	5	16	38	73	130
4	2	19	64	150	300	520
6	5	42	140	340	660	1150
8	10	75	260	610	1180	2020
10	15	120	400	950	1840	3180
12	21	170	540	1360	2660	4600
14	29	230	735	1850	3620	6250
16	40	300	1040	2440	4740	8150
18	51	375	1320	3060	6000	10350
20	60	475	1600	3600	7360	12760
22	73	580	1940	4350	8900	15420
24	86	685	2300	5180	10650	18380

TABLE 2. WINDMILL POWER OUTPUT IN WATTS, assuming $P = (K \cdot A \cdot V^3) \cdot (.5926) \cdot (.70) \cdot (.70)$

ENVIRONMENTAL ASSESSMENT

It is not enough just to know these fundamental principles before deciding to build or buy a windplant. Your choice of site must be assessed to see if a windplant will give you equitable returns, in addition to the positive environmental effects.

Consider the following conditions at the site on a *frequency* and *intensity* basis: rain, freezing temperatures, icing, sleet, hail, sandstorms, and lightning. The life and longevity of a wind plant, as well as its structural design and cost, depend on the completeness of your weather assessment. (Note: Most manufactured wind systems are "tropic-proofed;" be sure to check this if buying a system.)

In order to determine the usable output (Kw-hrs. per month) produced by a particular size wind driven system, the output characteristics of the windplant and the average yearly wind speed at the site must be known. The average yearly winds at a location can be obtained from the National Weather Bureau records center, U.S. Weather Bureau, Federal Building, Asheville, N.C. 28801. They carry statistical data for the U.S. for the last 50 years. Although they might not have information for your exact location, they should have records of a city or area very near. This information is a good start for estimating if the winds in your area are suitable for wind power. Another source of wind information will be your local airport. The next step should be the purchase of an anemometer (wind gauge) to estimate local wind conditions. A small hand held unit is available from Dwyer for \$6.95 (see page 99). There is also a more expensive remote reading anemometer by Taylor of Rochester, N.Y., for about \$75.00 (see page 99). The transmitter assembly can be mounted on a T.V. type mast at the height the wind plant is to be installed.

Another means of assessing local wind velocities is by using the Beaufort scale (Table 3). If readings are taken with regularity and then compared to the local Weather Bureau data, the scale is a very accurate and inexpensive way of measuring wind speed. Readings should be taken every day at the same times for accurate results (typically four times a day). Data should be taken for at least one month, and preferably longer, to determine mean average wind speed. Determining the longest period of no wind and the shortest period of some wind annually are two calculations that will be very helpful in figuring storage systems and back-up system requirements. If the test results show that there is over a 10 mph wind average on an norm of 2 to 3 days per week, you have an adequate site for wind power. The site findings should be compared to official Weather Bureau data for sites nearby to see if they correlate with the 10 year monthly averages fo that area.

Effect Caused by the Wind: On Land	At Sea	Beaufort Number	Description	Speed (m/sec)	(miles/hr)
Still smoke rises vertically	Surface mirror like	0	Calm	0–0.2	0–1
Smoke drifts but vanes remain still	Only ripples form	1	Light air	0.3–1.5	1–3
Wind felt on face, leaves rustle, vane moves	Small, short wavelets, distinct but not breaking	2	Light breeze	1.6–3.3	4 7
Leaves and small twigs move constantly, streamer or pennent extended	Larger wavelets beginning to break, glassy foam, perhaps scattered white horses	3	Gentle breeze	3.4–5.4	8–12
Raises dust and loose paper, moves twigs and thin branches	Small waves still but longer, fairly frequent white horses	4	Moderate breeze	5.5–7.9	13–18
Small trees in leaf begin to sway	Moderate waves, distinctly elongated many white horses, perhaps isolated spray	5	Fresh breeze	8.0–10.7	19–24
Large branches move, telegraph wires whistle, umbrellas hard to control	Large waves begin with extensive white foam crests breaking, spray probable	6	Strong wind	10.8–13.8	25–31
Whole trees move; offers some resistance to walkers	Sea heaps up, lines of white foam begin to be blown downwind	7	Stiff wind or moderate gale	13.9–17.1	32–38
Breaks twigs off trees; impedes progress	Moderately high waves with crests of considerable length; foam blown in well-marked streaks; spray blown from crests	8	Stormy wind or fresh gale	17.2–20.7	39–46
Blows off roof tiles and chimney pots	High waves, rolling sea, dense streaks of foam, spray may already reduce visibility	9	Storm or strong gale	20.8–24.4	47–54
Trees uprooted, much structural damage	Heavy rolling sea, white with great foam patches and dense streaks, very high waves with overhanging crests; much spray reduces visibility	10	Heavy storm or whole gale	24.5–28.4	55–63
Widespread damage (very rare inland)	Extraordinarily high waves, spray impedes visibility	11	Hurricane-like storm	28.5–32.6	64–72
	Air full of foam and spray, sea entirely white	12	Hurricane	32.7–36.9	73–82

TABLE 3. THE BEAUFORT SCALE

The relative wind velocity prevailing in any location determines wha size of wind generator is best suited for that region. Table 4 shows a sample region having annual average velocities of 10 mph or greater. Note that the 10 mph average wind is made up of many low winds and a few high winds. A 6 mph wind is generally considered to be the lowest wind for any practical use. In terms of energy available, 12 to 25 mph is the range of higher winds providing good power conversion. The relationship between the wind and power available to a wind generator can be exemplified by the detailed study that was made of wind records at Dayton, Ohio. Data was taken from 1936 to 1943, covering a 7 year period. In each month two groups of winds exist. First, there are the frequent or *prevalent winds* ranging from 5 to 13 mph. Second there are the *energy winds* which blow less frequently, ranging from 13 to 23 mph. A quick glance at Table 4 will give a clue to the energy winds. The prevalent winds blow 2–1/2 times more frequently than the more vigorous energy winds; for example, 5 days prevalent as opposed to 2 days of the energy winds. But because the energy varies with the cube of the velocity, the energy winds produce 3/4 of the total power. A windmill utilizing the prevalent winds must be twice the diameter of a windmill running *only* on the energy winds, if each is to produce the same amount of electricity per month.

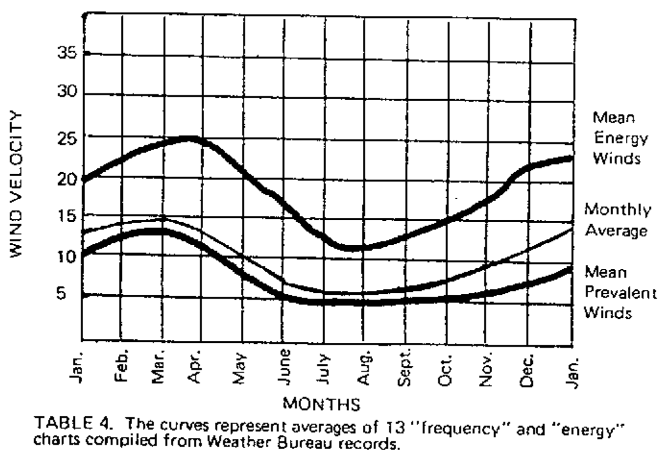


TABLE 4. The curves represent averages of 13 "frequency" and "energy" charts compiled from Weather Bureau records.

Tower design and installation are as important as site selection. A support must be built that is strong enough to handle loads from the deac weight of the generator assembly itself, as well as the thrust loads developed from the propeller at the highest anticipated windspeed. Most commercial towers are designed for a wind loading of at least 140 mph, and then a generous safety factor is added. Manufacturers discourage the installation of these larger units on home roofs because the loads on a 12 or 14 foot diameter prop are so powerful in winds over 45 mph that they could cause serious structural damage to the rafters, or even send the plant crashing down through the roof. A six or eight foot diameter prop on a wood frame structure can cause noise to be transmitted throughout the structure, even though the plant is balanced and running smoothly. This noise, which resembles a low howl or groan, can bother even the most sound sleeper.

The best location for a wind plant is as high as economically possible to reach undisturbed air. Placing a windplant a minimum of 30 to 40 feet above the ground (not on a roof!) will greatly increase the amount of power available to the swept area. Ideally the plant should be placed 15 to 20 feet above all obstacles within a 500 foot radius because surrounding objects have a very disturbing effect on the air and cause whirling eddy currents that greatly effect plant performance.

TURBULENCE/TOPOGRAPHY → TOWER ELEVATION

A hill or ridge of high ground lying in the path of the wind will have a considerable influence on the wind. Remember, also, that the winds blow *parallel* to the ground, not perpendicular to gravity. Obtaining a topographical map from the U.S.G.S. will enable you to estimate any turbulence due to topography. Tall trees behind a wind plant, as well as trees in front, interfere with a wind plant's operation. Most commercial wind plants are designed so that they can be installed 500 to 600 feet away from the point where power is required, so there is leeway for avoiding obstacles.

LOAD

The next assessment which needs to be made is how much power your appliances will actually require. The more accurately you figure these needs, the lower your storage costs become. The storage system expense is a direct result of the load. Figure *all* electrical needs:

1. Critical needs (e.g. refrigerator)
2. Convenience needs (e.g. electric blanket)
3. Intermittent needs (e.g. power saw)

Construct a chart, as shown below, listing the devices in use, hours per day each is in use, and the number of watt-hours each device requires.

Appliances	Watt Rating	Hours/Day in Use	Watt-Hr./Day
4 light bulbs	100 each	6	2400
1 stereo	80	4	320
1 percolator	480	1	480
1 sewing machine motor	30	1	30
List of Appliances (see page 83)		total	3230

Nominal Output Rating of Generator in Watts	Average Monthly Wind Speed in mph 6	8	10	12	14	16
50	1.4	3	5	7	9	10
100	3	5	8	11	13	15
250	6	12	18	24	29	32
500	12	24	35	46	55	62
1,000	22	45	65	86	104	120
2,000	40	80	120	160	200	235
4,000	75	150	230	310	390	460
6,000	115	230	350	470	590	710
8,000	150	300	450	600	750	900
10,000	185	370	550	730	910	1090
12,000	215	430	650	870	1090	1310

TABLE 5. AVERAGE MONTHLY OUTPUT IN KILOWATT-HOURS

1. From the table find the average wind speed vs. generator rating to determine Kw-hr./month output. Let's assume the wind-generator is operating in an area with 10 mph average winds and that the generator rating is 4 Kw: from the table we find the expected monthly output to be about 200 Kw-hr./month (the table gives the figure 230, but we'll work with a more conservative figure). To find out how many Kw-hr. per day of electricity we could use (i.e. the *use rate*) with a 200 Kw-hr./month supply from the wind, divide the power available for the whole month (kw-hr./month) by the days in the month (30):

$$\frac{200 \text{ Kw-Hr./month}}{30 \text{ days}} = 6670 \text{ watt-hr./day}$$

This is an excellent planning figure to design around when you are trying to estimate the number of watts consumed by devices, appliances, etc. to be used each day. In this example, with a windplant of the given size and average winds of 10 mph, you have 6670 watt-hrs. per day available to you

2. The next step is to find the capacity in kw-hr. of the battery system in use. Assume a battery capacity of 270 amp/hrs. at 115 volts. Watts in the system is found by multiplying amps by volts. Therefore, 115 volts x 270 amp/hrs. = 31,050 watt-hours or 31,050 Kw-hrs.

3. Find the number of days you could expect to operate, assuming no wind, with 6670 watts/day load, from a 31,050 watt-hour storage system.

$$\frac{31{,}050 \text{ watts}}{6670 \text{ watts}} = 4.66 \text{ days}$$

Roughly, you could operate for at least four days directly from the batteries, with no input from the wind generator or the stand-by unit.

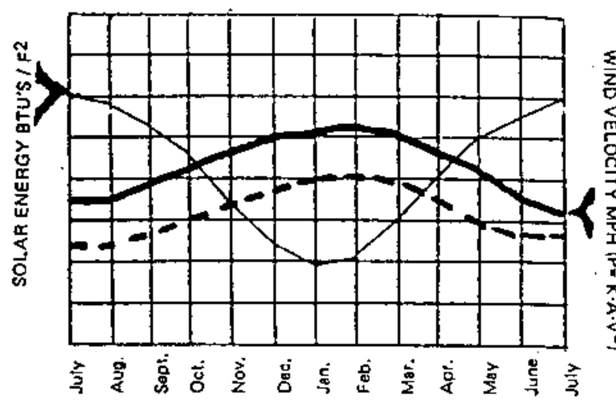


TABLE 6. COORDINATED WIND ELECTRIC DEMAND

Peak electrical demand could be coordinated with the peak energy period. This situation does not exist everywhere, but where it does it should be utilized.

Power company output is typically 60 cycles per second alternating current (A.C.). A battery storage system is direct current(D.C.). All resistance and heating devices (e.g., light bulbs, toasters) and universal motors (having brushes) can run on A.C. or D.C. The following require A.C. only; they will not operate on D.C:

1. Fluorescent lights (unless rewired).
2. Devices with transformers (e.g., televisions, radios, tape decks).
3. Appliances with standard induction motors.

If D. C. power is inadvertently supplied to an A.C. appliance, there is a high probability that the appliance will be destroyed.

BATTERY AND STORAGE SECTION

The most difficult and important calculation to make is the sizing of your storage system. Although there are many sophisticated and perhaps exotic methods of energy storage presently in development which could be used in this application, the most reliable at present is the lead acid storage battery. This battery still represents the cheapest practical method of electrical energy storage available for the individual user of wind power. Because the wind itself is an intermittent source of energy, a battery storage system must be capable of storing power through long, windless periods with reasonable efficiency at moderate cost.

Batteries used in wind plants are designed for repeated cycling over a period of many years. Their construction allows them to go repeatedly from a fully discharged to a fully charged state without damage. Some designs can withstand approximately 2000 complete cycles. These batteries are commonly known as stationary or houselighting batteries and are available in sizes from 10 amp/hr. to 8000 amp/hr. The normal voltage of the system is determined by the number of cells in series (each cell is approximately 2 volts), but the amount of storage capacity is determined by the plate thickness and area.

These batteries have thicker plates than the standard automobile battery and employ separators made of glass fiber material. The structural integrity

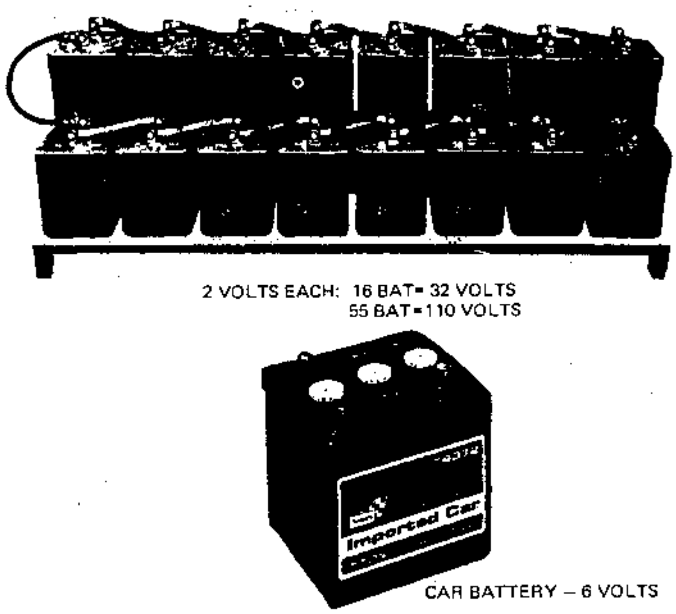


FIG. 3 SIZE AND VOLTAGE DIFFERENCES BETWEEN CAR BATTERY AND LIGHTING PLANT BATTERIES

of these cells is much greater, and large amounts of reserve space between the bottom of the plates and the case is common. This allows a large amount of area for material to collect without any damage from internal shock or shorting. Golfcart batteries have similar characteristics. Gould P B220, a 6 volt-220 amp cell, and Trojan P J217, a 6 volt-217 amp cell, can be used with reasonable success (see page 99).

A battery on charge is not a fixed or static potential, and is subject to change in its voltage and current output characteristics with changes in light, temperature elevation, etc. Simple testing methods compensate and adjust for these changes.

One important thing to remember is that when a battery is charging and discharging, there is a change not only in its amperage but also in its voltage level. Figure 4 shows that the battery voltage rises slowly until it reaches the 80-85 percent capacity-returned point, rises sharply between about 2.3 and 2.5 volts per cell (the gassing point where H_2 is created), and then flattens out at about 2.6 volts when the battery is fully charged. This sharp rise in voltage, during which only a small part of the charge is returned, is a characteristic of a lead acid cell and does create some design and operational problems. To return the last 15 percent of the charge in a reasonable time the charge voltage must increase by about 20%, or 0.5 volts. The high charge voltage required to complete the charge process may be unattainable because of the operating voltage of appliances. The current charge rate (amps) should be reduced at the gassing point 2.6 volts/cell to below the 20 hours rate. $\left(\frac{270\ \text{amp/hr}}{20\ \text{hr}} = 13.5\ \text{amps}\right)$. This should be done by the electronic control and regulating system in your windplant.

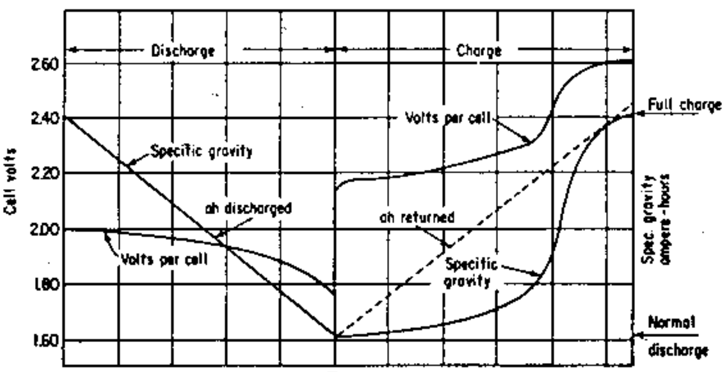


FIG. 4. TYPICAL VOLTAGE AND GRAVITY CHARACTERISTICS DURING A CONSTANT RATE DISCHARGE AND RECHARGE.

BATTERY CAPACITY

The nominal rated capacity of most lead acid batteries is taken at 8, 10 or 20 hour discharge rates down to a cell voltage of 1.85 volts per cell. At higher discharge rates the capacity is reduced, while at lower discharge rates the available capacity is increased. Figure No. 5 illustrates the change in capacity with the rate of discharge. At the 12 hour rate, for example, a nominal 500 amp hour capacity battery has an available capacity of 550 amp hour, or 110%, down to a discharge voltage of 1.85 volts per cell. The capacity taken out of the battery is approximately 1040 amp hr. and about 83% of the total available capacity. This limitation on the extent of discharge is to ensure that the battery is not worked excessively and to provide a reserve capacity, which will greatly extend the life of the battery.

One of the key factors in guaranteeing the life of the battery system is the regularity of maintenance. It is vital that the electrolyte level in all batteries is maintained. This is done by adding distilled water to each battery when needed. All batteries must have tight connections to minimize (1) corrosion, (2) unequal voltage per cell, and (3) reduced capacity. The battery set must be an originally matched set. Do not mix batteries of different ages. Batteries should be located a few inches off the floor and away from the wall to permit good air circulation. For more exact information on batteries write the battery companies in your area.

A new battery does not become fully active until used the equivalent of about 30 complete cycles, because the plates are somewhat hard and do not absorb and deliver the full current. On a battery of 400 amp/hr. capacity this break-in period requires a few months with an average load.

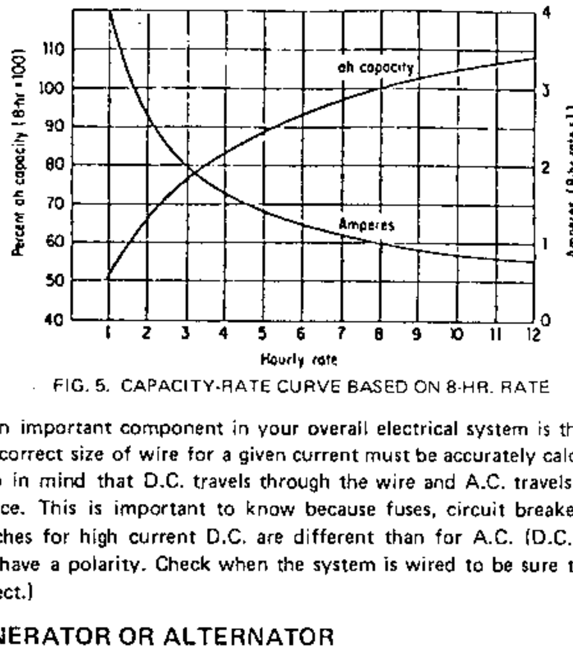


FIG. 5. CAPACITY-RATE CURVE BASED ON 8-HR. RATE

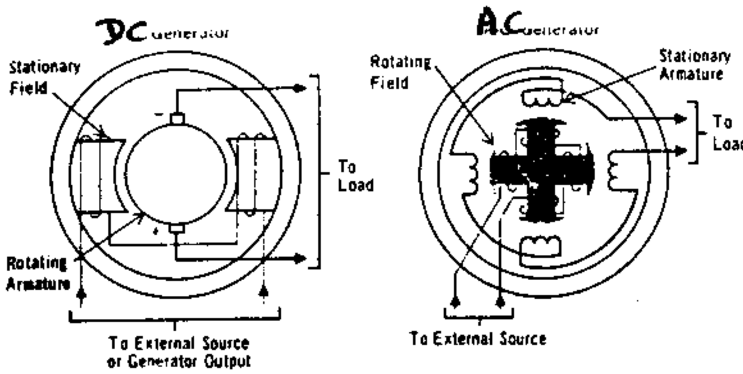
An important component in your overall electrical system is the wire. The correct size of wire for a given current must be accurately calculated. Keep in mind that D.C. travels through the wire and A.C. travels on the surface. This is important to know because fuses, circuit breakers, and switches for high current D.C. are different than for A.C. (D.C. outlets will have a polarity. Check when the system is wired to be sure they are correct.)

GENERATOR OR ALTERNATOR

The combined data of electrical needs and the size of the storage system necessary (which is based on the average wind speed) will determine the generator size necessary for your system. The last critical matching problem will be that of the blades to the generator.

Since propeller speed seldom exceeds 300-400 rpm, especially in the larger diameters, this calls for a low-speed generator designed to match the torque and horsepower output parameters of the prop in use. Dunlite compromises a bit by using an alternator which develops maximum output at 750 rpm, corresponding to a prop speed of only 150 rpm. Hence a 5:1 step-up gear is used. Elektro on the other hand utilizes all direct drive with the exception of the larger 6000 watt unit, which is geared. All major manufacturers are now using a multi-poled alternator which produces alternating current. An alternator is used for two reasons: (1) it operates at a lower cost than a comparable wattage D.C. generator, and (2) perhaps the most favorable factor, the high current is taken directly from the stator coils (see Fig. 6) and not through brushes as in a D.C. generator. Eventually the brushes wear down and need replacement.

One of the major cost factors in a modern wind system is the low speed continuous duty alternator or generator. Conventional alternators generally are designed for high rotational speeds (1800 to 3600 rpm), being driven by a gasoline engine, and therefore cannot be used for wind driven systems. Wind driven generators require a low cut-in speed. By using direct drive or a very low gearing ratio such as in the Dunlite unit, losses are kept to a



The d-c generator has a rotating armature and a stationary field. Voltage for its field can be obtained either from an external source or from the generator's own output

The a-c generator has a stationary armature and a rotating field. Voltage for its field must come from an external source, called an exciter

FIG. 6. AN AC GENERATOR AND A DC GENERATOR

minimum and overall machine efficiency remains relatively high. The design of direct drive generators is materials efficient and the low rotational speed keeps wear to a minimum.

Special electronic regulators are designed as part of generating systems to control the amount of current delivered to the batteries at a safe charging rate. Once the batteries are fully charged, the alternator will put out only a trickle charge, as is the case for the Dunlite unit. In the Elektro design, the entire windplant shuts down when the voltage regulator registers the battery cell voltage is above a predetermined level. This prevents any chance of overcharging the battery.

BLADES AND HUB

The efficiency of your entire wind system depends on what type of prop (blade profile) you use. All modern wind driven systems use two or three long slender blades with an airfoil section designed to produce maximum lift with minimal drag in the rpm range for which it operates. These efficient blades operate at a high tip speed ratio, which is the ratio of propeller tip speed (U) to wind velocity (V). The outstanding characteristic of the propeller-windmill is that at a given wind speed it rotates 5 to 10 times faster than a conventional multi-bladed windmill of the same size. The propeller type excels in lightness of construction, reduction of gearing difficulty, and is the only type of windmill through which direct generator drive can be accomplished. A higher tip speed ratio means higher rpm for a given wind speed, and higher rpm generally means more power output.

It is critical that the balance of the blade and hub system and its tracking are precisely adjusted. Static balancing insures equal mass distribution at all points in the rotation system. The procedure is fairly simple for two blade systems but becomes increasingly complex as more blades are added. Three dimensional configurations, such as Savonius rotors, are even more difficult. The figures below may be of some help.

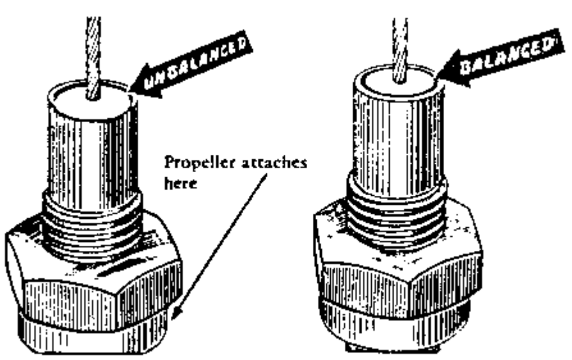
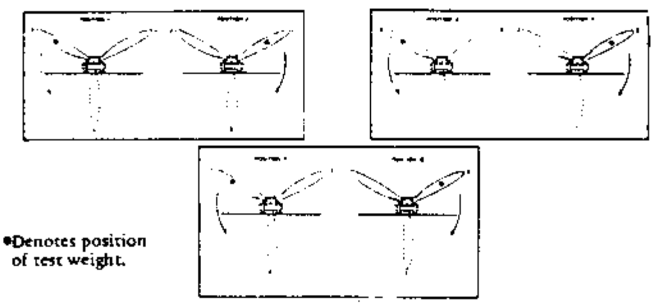


FIG. 7. A METHOD DEVELOPED BY THE ARMY FOR BLADE BALANCING

Dynamic balance is very difficult to achieve. The main concern is to prevent vibrations. Therefore all blades must be identical in their lift or reaction components. Tracking means that the blades follow each other in exactly the same plane of rotation. The blade tips should track within 1/8", if possible, and should be no closer than one foot to the tower. The better the tracking the less the vibration.

Fig.8 shows the relative tip speed and power curves for the various propeller types and VERTICAL AXIS rotors (SAVONIUS). The Figure shows the advantages of the propeller type windplant (curves 3,4,5,6,8 & 11) over the Savonius type plant (curves 1,7,9 &10). Also see "Additional Notes and Thoughts" (page 84) for more information on the Savonius Rotor.

One has the choice of whether to use two or three blades. It is generally a decision based on economics and the relative output of the generator to be used. Although a two-bladed prop will run at a slightly higher aerodynamic efficiency than a similarly designed 3-bladed prop, it is seldom used in commercial plants with generator ratings above 2000 watts output. This is because the three-bladed prop provides the extra starting torque necessary to overcome difficulties found in lower winds, fluxing and eddying. They run slightly smoother when orienting to changes in wind direction. In comparison, it was found early in wind-generator design that the two-bladed system is "choppy" when the tail vane shifts during wind direction changes. When the blades are straight up and down they have no centrifugal resistance to the tail movements. When the blades are parallel to the ground the resistance is maximum. However, it is interesting to note that the Elektro two-bladed wind plants do not exhibit this trait since the variable pitch weight arms are placed at 90 degrees to the blade element and, in terms of balance, the assembly "looks" like a 4-bladed prop during rotation. Hence wind direction changes are very smooth.



•Denotes position of test weight.

KNIFE EDGE BALANCING METHOD REQUIRES A PAIR OF PERFECTLY ALIGNED AND LEVELED EDGES OF HARD STEEL, A SPINDLE AND A HOIST

Once maximum power is developed at the rated windspeed of the generator (typically in the 16 to 25 mph range), excess power developed by the prop is potentially destructive and must be controlled. There are as many methods of overspeed control as there have been manufacturers of windmills, and each system has its own merits and disadvantages. The airbrake or airspoiler was used by several manufacturers during the 1920's and 30's on small diameter machines and is still used on the 200 watt unit built by Dynatechnology. Two small sheet metal vanes, resembling barrel slats, were placed at 90 degrees to each prop about the center axis of the hub. Springs held the vanes in normal position until centrifugal force pulled the vanes outward, diverting air away from the prop and thus decreasing rpm. This system was successful for small diameter units. Airbrakes are undesirable for larger scale operations since they throw heavy loads onto the entire structure.

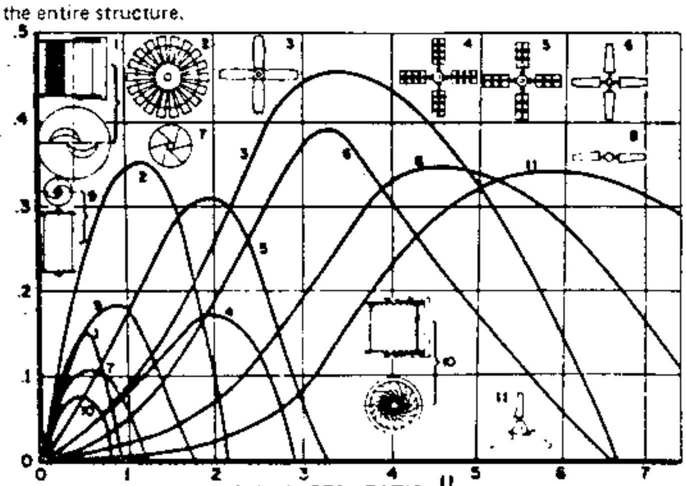


FIG. 8.

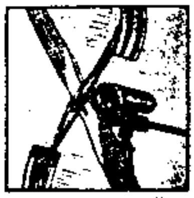


FIG. 9 "NORMAL" "GOVERNING"

Quirk's, built in Australia, used a system in its early years which was similar in operation to the prairie windmills. The generator and prop assembly was mounted off axis from the supporting tower. The thrust developed by the prop would push the generator assembly around the tower axis, against a tail hung by gravity, at a design windspeed. Thus, the prop would turn partially sideways from the oncoming wind, slowing the prop down. A popular method among the home-built units in the 1920's was the use of a pilot vane set parallel to the prop. The arm of the vane was equal in distance to the radius of the propeller, and the area exposed to oncoming air would help to push the prop and generator assembly out of the wind. The disadvantage of these types of swinging systems is that they induce gyroscopic vibration and eliminate the power supply at the very time when the best winds are available. However, well designed systems are able to operate directly into the airstream and then be activated at a predetermined windspeed. More sophisticated designs utilize a feathering principle (which regulates the propeller rpm by changing the angle of attack (pitch)) at high wind speeds. Pitch regulation is *attractive* since it holds the energy absorption nearly constant at all wind velocities, and allows continuous power output in high winds without inducing stress. Both Elektro and Quirk's utilize centrifugal force to act upon a set of spring-loaded weights to change pitch. Noting the Elektro diagram (Fig.10) it can be seen that the weights work on a direct line of centrifugal force and hence the actual density of the weight element itself is about 1 lb. For the two-bladed units, the assembly is designed to begin changing pitch (feathering) at about 400 rpm propeller speed. At this speed there is about 25 lbs. of centrifugal force on the weight arm itself. Quirk's utilizes a component of centrifugal force to act upon its weights, which are placed out from the prop shaft itself.

FIG. 10. CONTROL-PROPELLER HUB OF HEAT-TREATED NON-CORROSIVE LIGHT METAL WITH REGULATING MEMBERS, ADJUSTING MOVEMENT ON TAPEROLLER AND NEEDLE BEARINGS, EASY TO LUBRICATE, PROTECTED FROM WEATHER, NO RISK OF ICE-BUILDING. (ELEKTRO)

This positioning, and the lower prop speed of 150 rpm, results in the necessity of a 4 lb. weight at the end of each arm. Both systems are very successful in the control of any overloading, and can maintain safe rpm into winds of hurricane force. However, even though these units are stressed for 80 mph winds, the manufacturer still recommends that the propeller be stopped manually and/or rotated sideways to the wind. Most models have a brake control at the bottom of the tower for this purpose. Special windplants by these companies are available to operate unattended in winds up to 140 mph. Quirk's uses the conventional windplant, fitted with smaller diameter propellers (generally 10 ft. diameter). The latter, being shorter in arm length and with added internalstiffeners, allows the unit to operate head-on into high winds. Elektro prefers to shut down the plant completely, and has an optional high speed control package which can be added to the standard plants.

Hopefully the multitude of systems to come will be designed around some basic criteria like "Safety, Reliability, and Cost," in that order. These are important considerations particularly for those wishing to build their own design. A real understanding of the force and magnitude of the wind serves to reinforce the need for these criteria. Many a wind system has been literally swept away.

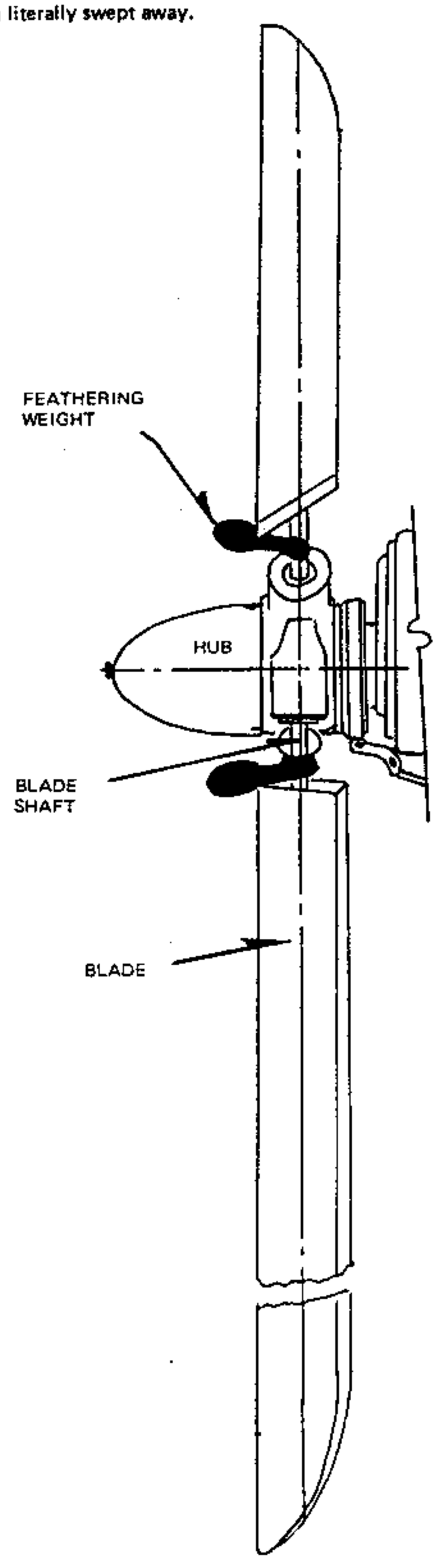


FIG. 11 QUIRK'S FEATHERING SYSTEM

One marvelous feeling that comes to you from taking these responsibilities, that is realizing the ability-to-respond, is the gathering of the sense of freedom. The individual benefits of these renewable energy systems represents only one part of the picture. Along with emoting their sense of ecological satisfaction, they provide a positive direction towards self-determination. A rare thing these days.

All (things) are possible. And in the stars and winds . . .

COMPOSITE OF KILOWATTHOUR RATINGS FOR VARIOUS APPLIANCES
(PRE—ENERGY CRISIS ESTIMATES)

Name	Watts	Hrs/Mo.	KWHRS/Mo.
Air conditioner, central			620*
Air conditioner, window	1566	74	116*
Battery charger			1*
Blanket	190	80	15
Blanket	50-200		15
Blender	350	3	1
Bottle sterilizer	500		15
Bottle warmer	500	6	3
Broiler	1436	6	8.5
Clock	1-10		1-4*
Clothes drier	4600	20	92*†
Clothes drier, electric heat	4856	18	86*†
Clothes drier, gas heat	325	18	6*†
Clothes washer			8.5*
Clothes washer, automatic	250	12	3*
Clothes washer, conventional	200	12	2*†
Clothes washer, automatic	512	17.3	9*
Clothes washer, ringer	275	15	4*†
Clippers	40-60		½
Coffee maker	800	15	12
Coffee maker, twice a day			8
Coffee percolator	300-600		3-10
Coffee pot	894	10	9
Cooling, attic fan	1/6-3/4HP		60-90*†
Cooling, refrigeration	3/4-1½ ton		200-500*
Corn popper	460-650		1
Curling iron	10-20		½
Dehumidifier	300-500		50*
Dishwasher	1200	30	36*
Dishwasher	1200	25	30*
Disposal	375	2	1*
Disposal	445	6	3*
Drill, electric, ¼"	250	2	5
Electric baseboard heat	10,000	160	1600
Electrocuter, insect	5-250		1*
Electronic oven	3000-7000		100*
Fan, attic	370	65	24*†
Fan, kitchen	250	30	8*†
Fan, 8"-16"	35-210		4-10*†
Food blender	200-300		½
Food warming tray	350	20	7
Footwarmer	50-100		1
Floor polisher	200-400		1
Freezer, food, 5-30 cu.ft.	300-800		30-125*
Freezer, ice cream	50-300		½
Freezer	350	90	32*
Freezer, 15 cu.ft.	440	330	145*
Freezer, 14 cu.ft.			140*
Freezer, frost free	440	180	57*
Fryer, cooker	1000-1500		5
Fryer, deep fat	1500	4	6
Frying pan	1196	12	15
Furnace,electric control	10-30		10*
Furnace, oil burner	100-300		25-40*
Furnace, blower	500-700		25-100*†
Furnace, stoker	250-600		3-60*†
Furnace, fan			32*†
Garbage disposal equipment	1/4-1/3 HP		½*
Griddle	450-1000		5
Grill	650-1300		5
Hair drier	200-1200		½-6*
Hair drier	400	5	2*
Heat lamp	125-250		2
Heater, aux.	1320	30	40
Heater, portable	660-2000		15-30
Heating pad	25-150		1
Heating pad	65	10	1
Heat lamp	250	10	3
Hi Fi Stereo			9*
Hot plate	500-1650		7-30
House heating	8000-15,000		1000-2500
Humidifier	500		5-15*
Iron	1100	12	13
Iron			12
Iron, 16 hrs/month			13
Ironer	1500	12	18
Knife sharpener	125		¼*
Lawnmower	1000	8	8*†
Lighting	5-300		10-40
Lights, 6 room house in winter			60
Light bulb, 75	75	120	9
Light bulb, 40	40	120	4.8
Mixer	125	6	1
Mixer, food	50-200		1
Movie projector	300-1000		
Oil burner	500	100	50*
Oil burner			50*
Oil burner, 1/8 HP	250	64	16*
Pasteurizer, ½ gal.	1500		10-40
Polisher	350	6	2
Post light, dusk to dawn			35
Power tools			3
Projector	500	4	2*
Pump, water	450	44	20*†
Pump, well			20*†
Radio			8
Radio, console	100-300		5-15*
Radio, table	40-100		5-10*
Range	8500-1600		100-150
Range, 4 person family			100
Record player	75-100		1-5
Record player, transistor	60	50	3*
Record player, tube	150	50	7.5*
Recorder, tape	100	10	1*
Refrigerator	200-300		25-30*
Refrigerator, conventional			83*
Refrigerator-freezer	200	150	30*
Refrigerator-freezer 14 cu.ft.	326	290	95*
Refrigerator-freezer, frost free	360	500	180*
Roaster	1320	30	40
Rotisserie	1400	30	42*
Sauce pan	300-1400		2-10
Sewing machine	30-100		½-2
Sewing machine	100	10	1
Shaver	12		1/10
Skillet	1000-1350		5-20
Skil Saw	1000	6	6
Sunlamp	400	10	4
Sunlamp	279	5.4	1.5
Television	200-315		15-30*
TV,BW	200	120	24*
TV, BW	237	110	25*
TV, color	350	120	42*
TV, color			100*
Toaster	1150	4	5
Typewriter	30	15	.5*
Vacuum cleaner	600	10	6
Vacuum cleaner, 1 hr/wk			4
Vaporizer	200-500		2-5
Waffle iron	550-1300		1-2
Washing machine, 12 hrs/mo			9*
Washer, automatic	300-700		3-8*
Washer, conventional	100-400		2-4*
Water heater	4474	89	400
Water heater	1200-7000		200-300
Water pump (shallow)	½HP		5-20*†
Water pump (deep)	1/3-1 HP		10-60*†

AT THE BARN

Name	Capacity HP or watts	Est. KWHR
Barn cleaner	2-5 HP	120/yr.*
Clipping	fractional	1/10 per hr.
Corn, ear crushing	1-5 HP	5 per ton*
Corn, ear shelling	¼-2	1 per ton*†
Electric fence	7-10 watts	7 per mo.*†
Ensilage blowing	3-5	½ per ton
Feed grinding	1—7½	½-1½ per 100 lbs.*†
Feed mixing	½-1	1 per ton*†
Grain cleaning	¼-½	1 per too bu*†
Grain drying	1-7½	5-7 per ton*†
Grain elevating	¼-5	4 per 1000 bu*†
Hay curing	3-7½	60 per ton*
Hay hoisting	½-1	1/3 per ton*†
Milking, portable	¼-½	1½ per cow/mo.*†
Milking, pipeline	½-3	2½ per cow/mo.*†
Sheep shearing	fractional	1½ per 100 sheep
Silo unloader	2-5 HP	4-8 per ton*
Silage conveyer	1-3 HP	1-4 per ton*
Stock tank heater	200-1500 watts	varies widely
Yard lights	100-500 watts	10 per mo.
Ventilation	1/6-1/3 HP	2-6 per day*† per 20 cows
IN THE MILKHOUSE		
Milk cooling	½-5 HP	1 per 100 lbs. milk*
Space heater	1000-3000	800 per year
Ventilating fan	fractional	10-25 per mo.*†
Water heater	1000-5000	1 per 4 gal
FOR POULTRY		
Automatic feeder	¼-½ HP	10-30 KWHR/mo*†
Brooder	200-1000 watts	½-1½ per chick per season
Burglar alarm	10-60 watts	2 per mo.*
Debeaker	200-500 watts	1 per 3 hrs.
Egg cleaning or washing	fractional HP	1 per 2000 eggs*†
Egg cooling	1/6-1HP	1¼ per case*
Night lighting	40-60 watts	10 per mo. per 100 birds
Ventilating fan	50-300 watts	1—1½ per day*† per 1000 birds
Water warming	50-700 watts	varies widely
FOR HOGS		
Brooding	100-300 watts	35 per brooding period/litter
Ventilating fan	50-300 watts	¼—1½ per day*†
Water warming	50-1000 watts	30 per brooding period/litter
FARM SHOP		
Air compressor	¼—½ HP	1 per 3 hr.*
Arc welding	37½ amp	100 per year.*
Battery charging	600-750 watts	2 per battery charge*
Concrete mixing	¼-2 HP	1 per cu. yd.*†
Drill press	1/6—1 HP	½ per hr.*†
Fan, 10"	35-55 watts	1 per 20 hr.*†
Grinding, emergy wheel	1/4—1/3 HP	1 per 3 hr.*†
Heater, portable	1000-3000 watts	10 per mo.
Heater, engine	100-300 watts	1 per 5 hr.
Lighting	50-250 watts	4 per mo.
Lathe, metal	¼—1 HP	1 per 3 hr.
Lathe, wood	¼—1 HP	1 per 3 hr.
Sawing, circular 8"—10"	1/3—1/2 HP	1/2 per hr.
Sawing, jig	1/4—1/3 HP	1 per 3 hr.
Soldering, iron	60-500 watts	1 per 5 hr.
MISCELLANEOUS		
Farm chore motors	½—5	1 per HP per hr.
Insect trap	25-40 watt	1/3 per night
Irrigating	1 HP up	1 per HP per hr.
Snow melting, sidewalk and steps, heating—cable imbedded in concrete	25 watts per sq. ft.	2.5 per 100 sq. ft. per hr.
Soil heating, hotbed	400 watts	1 per day per season
Wood sawing	1—5 HP	2 per cord

Symbol Explanation
*AC power required
†Normally AC, but convertible to DC

Notes: Lighting in this table is assumed to be incandescent—if flourescent, the wattage bulbs consume the same power but deliver 3 times as much light—flourescent bulbs also require AC, but can be converted to DC.

These figures can be cut by 50% with conservation of electricity.

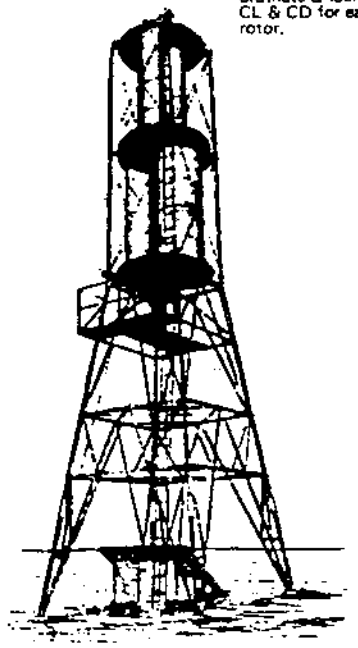
1) Sources for this table represent a conglomerate of several separate tables taken from:

a) Northern States Power Co., Mpls, Mn
b) University of Minnesota, Agricultural Extension Service
c) Seattle City Light, Seattle, Washington
d) Energy Conservation Techniques, National Bureau of Standards
e) Garden Way Labs
f) Henry Clews
g) Real Gas and Electric

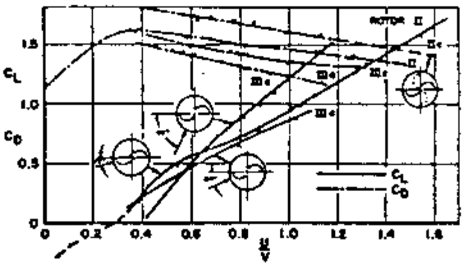
SAVONIUS ROTOR

A detailed look at the graph "TORQUE COEFFICIENTS OF 11 WINDMILLS" and Fig. 8 show the relationship of SAVONIUS type mills to the propeller type. The other graphs show a comparison of regular and modified SAVONIUS rotors. The changes in efficiency (coefficient of lift CL over coefficient of drag CD) by modifying the blade shape, are shown in graph No. 1.

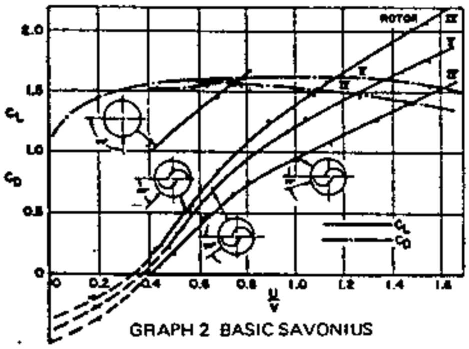
This information plus the inherent problems with Bearings and Balancing, put the SAVONIUS rotor in a better perspective from a design and life-of-the-system stand point. The life of the system is not usually viewed as an economic problem, but we find in the long run it is an important parameter. It becomes obvious that dependable, long term economic electrical power from the wind is best provided by the propeller type designs. The best application of the SAVONIUS rotor is for pumping and grinding (slow speed, medium torque uses).



VERTICAL-AXIS DOUBLE SAVONIUS WINDMILL-TYPE F-13 OF THE SOVIET WIND ENERGY INSTITUTE

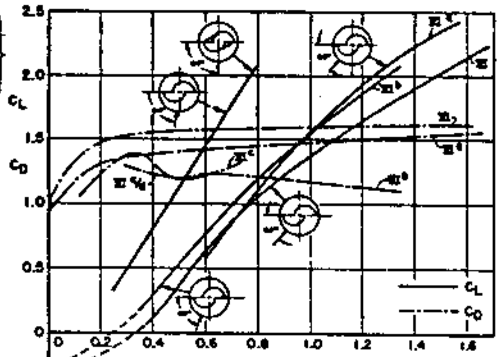


GRAPH 1 MODIFIED SAVONIUS



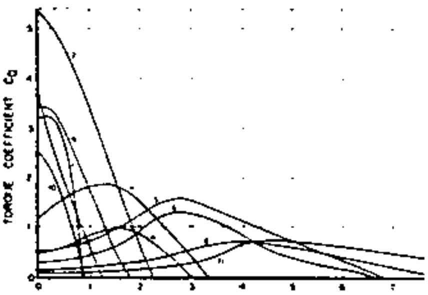
GRAPH 2 BASIC SAVONIUS

Roman Numerals Co-ordinate & identify CL & CD for each rotor.



GRAPH 3 U/V Tip Speed Ratio

AERODYNAMIC PERFORMANCE OF A COLLECTION OF BASIC AND MODIFIED SAVONIUS ROTORS THROUGH POWER EXTRACTION (BRAKED). U/V RANGE UP TO U/V MAX.



TORQUE COEFFICIENT OF 11 WINDMILLS (See page 81, Fig. 8)

RULES OF THUMB

1. Air is 800 times less dense than water.
2. Use a two battery system where possible, lead antimony or lead calcium and pure lead (only loses 15% maximum of charge).
3. You should be able to get by with an inverter rated between one quarter and one half the wattage rating of your wind generator.
4. Never let the rate of discharge of a battery in amperes exceed 15% of the amp-hour rating.
5. A general rule is that batteries should never be discharged below 20% of rated charge.
6. When using bearings use tapered roller bearings or thrust bearings for turn table.
7. Motoring of the generator sometimes helps icing problems/shut down in sleet.
8. Question, what is the largest helicopter blade length?
9. Look for compound winding in the generator.
10. A blade is always spilling power.
11. The quality of a battery is the function of the softness (paste to lead ratio) of the plates.
12. Armature equals amperage, field equals voltage.
13. The base of a tower should be in the ground a minimum of 5 feet.
14. The tower cap should be 15 feet higher than the tallest object within 500 feet.
15. Never use bearings or gears in a feathering mechanism.
16. Grease is cheaper than steel.
17. Trees grow.
18. Plumb your tower, perfectly and square.
19. An overdesigned tower is better than an underdesigned tower.
20. Wind blows parallel to the ground—<u>not</u> perpendicular to gravity.
21. Vibrations kill bearings.
22. Back up systems should equal wind generation output.

ADDITIONAL NOTES AND THOUGHTS

Wherever there is a high standard of living, there is also a low standard and the cost of these high standards is paid for by future generations.

Ideally one who knows freedom understands the responsibility and gravitates toward self-sufficiency, self-perpetuation and realizes self-determination.

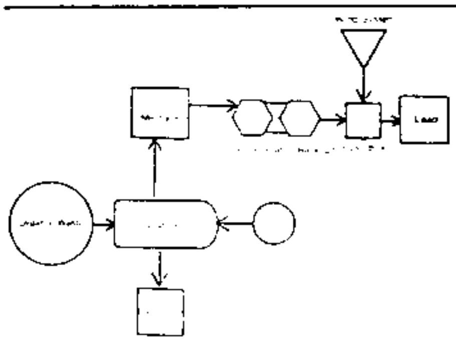
What is life cycle costing?

Compressors should compress gases, not "air."

Junk cars will always be a resource.

Information→ Knowledge → Power → Money. The more you know, the less you pay.

—T.W.



POSSIBLE USE FOR METHANE GAS SINCE THE AMOUNT OF GAS IS USUALLY SMALL AND

PERIODS OF NO WIND MAY ALSO Be SHORT

"THE DEW IMPEARLED WINDS OF DAWN"
—TENNYSON

A partial list of wind generator companies in the U.S.A. 1910-1970
—T.W.

Air Electric	Air Charger
Win Charger	Delco
Paris-Dunn	Western Electric
Jacobs	Nelson
Wind Power	Allied
Rural Lite	Miller
Air King	Aerodyne

"Wind, water and solar power are running to waste."
— 1903 DAILY CHRONICLE, 1/14

AEOLUS – THE GOD OF WIND
BOREAS – THE NORTH WIND
NOTUS – THE SOUTH WIND
EURUS – THE EAST WIND
ZEPHYR = WEST WIND

ELECTRICAL THOUGHTS ON WIND DRIVEN GENERATORS

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Editor ASE Newsletter

The basic principle of a generator is that electric power is produced when a conductor moves through a magnetic field (Fig. 6). By increasing the magnetic field strength of a generator, the power output is increased proportionally. Voltage output can be stepped up by increasing the number of armature windings or by increasing the speed of the generator. For example, by doubling the number of turns in an armature, the generator will put out twice the voltage at the same speed as before, since the number of wire conductors crossing the magnetic field per unit time has been doubled. The current output is limited by the size of the wire used. See page 81.

Generators of vastly different physical size can have the same power rating. This is why the speed at which the generator puts out its rated power should be specified.

There are great differences in quality and cost between a generator rated at 3000 watts at 200 rpm and one rated at 3000 watts at 2000 rpm.

The blades (propeller) of a wind plant generally do not turn faster than about 200 rpm. (The speed of the blade tips is between 4 and 8 times the speed of wind.) Most electric motors and generators are built for speeds of from 100 to 4000 rpm, with 1800 and 3600 rpm being standard speeds for A.C. motors. A good share of wind designs in the past have used gears for matching the low speed of the blade to a relatively high speed generator. Besides the wear the gears are subject to, high speed generators can break down faster than direct slow speed generators.

In direct drive systems the gearing (so to speak) is electrical. The generator is designed to give its maximum output at the same speed as the blade system gives its maximum output. This results in a long-lived, reliable system, but uses more copper and steel.

The direct drive system can be used with either a D.C. generator or with an alternator. Old Jacobs' wind generators were a sturdy, direct drive design. Unfortunately, most were the 32 volt design which is not compatible with modern 100 volt equipment. (I am presently re-building one for 110 volt operation...) See page 105.

The generator, along with the storage system is the most important part of the wind plant. From the day it is put up, the generator will be turning more or less continuously for years.

Most often, people have used car alternators in their homebuilt windplants. But car alternators are not well suited for wind generators as they are high speed devices and are very inefficient. (A D.C. car generator takes much less horsepower from the car's engine than an alternator.) When alternators were first used widely in cars, the industry promoted the myth that they charge better at low engine speeds, and that alternators had some inherent characteristic which made this possible. Actually the industry converted to alternators because of economics. They found that alternators were a higher speed device which needed less construction materials and had a shorter life. A D.C. generator could not function at the speeds at which alternators turn. The "trick" of the car alternator is that the pulley ratio is higher than with generators, allowing the alternator to be operated at top engine speeds . . . (10,000 ALT. rpm).

To show the difficulties of making a direct drive unit out of a car alternator, consider the following example. Assume the alternator will generate 1000 watts at 3000 rpm and that it is wound with 12 turns per coil of number 16 wire. To rewind the alternator for the speed range of the blades, cut the speed by a factor of 16 to 187 rpm. This would mean using 128 turns of number 28 wire per winding and the power output would be 62 watts. Obviously the only way to use a high speed alternator is with a gear or belt design. The disadvantage of this set-up is that its lifetime will not be very long.

Many people ask whether a wind system would be compatible with their present appliances, motors and tools. First it should be pointed out that when you change to a wind system, you will be changing the way you live Many of the solar house designs to date have tried to duplicate exactly the characteristics of fossil fuel houses so the "public would accept the design." The result in the past was that these designs were often overly complicated and expensive

The same applies to wind systems. There are two options—to use the D.C. voltage from the batteries directly or to convert the D.C. to A.C. with a rotary or electronic inverter. The D.C. system is simpler and cheaper in that no inverter is needed. Any heating element device such as light bulbs and irons will work equally well on A.C. or D.C. Most power tools can run on A.C. or D.C.—that is, tools using universal motors (they have brushes) and using A.C./D.C. switches. Electronic devices such as stereos can be run off of small A.C. inverters. The main problem is to find a refrigerator or freezer which will run on D.C. Refrigerators made in the last 15 or 20 years have sealed units. Before that, they had belt drive compressors allowing the use of any type motor. Commercial units still can be obtained with belt drive compressors. Also the recreational vehicle industry is now producing refrigerators which will run on A.C., D.C., or gas. They are expensive, but a used market should be developing soon. D.C. motors are not easily available, but car generators can be rewound for 110 or 32 volt operation and used where a 1/4 or 1/3 hp motor is needed. *If* you can't purchase one locally see page 100.

NOTES:

Winnie Redrocker has some information on high speed alternator use in ASE No. 15.

Martin Jopp of Princeton, Minnesota, has 55 years experience with motors and generators. He used a set of car batteries for his windplant for two years while waiting to find a set of used lighting plant batteries for storage. (See "Some Notes on Windmills in ASE No. 12, October 1973.)

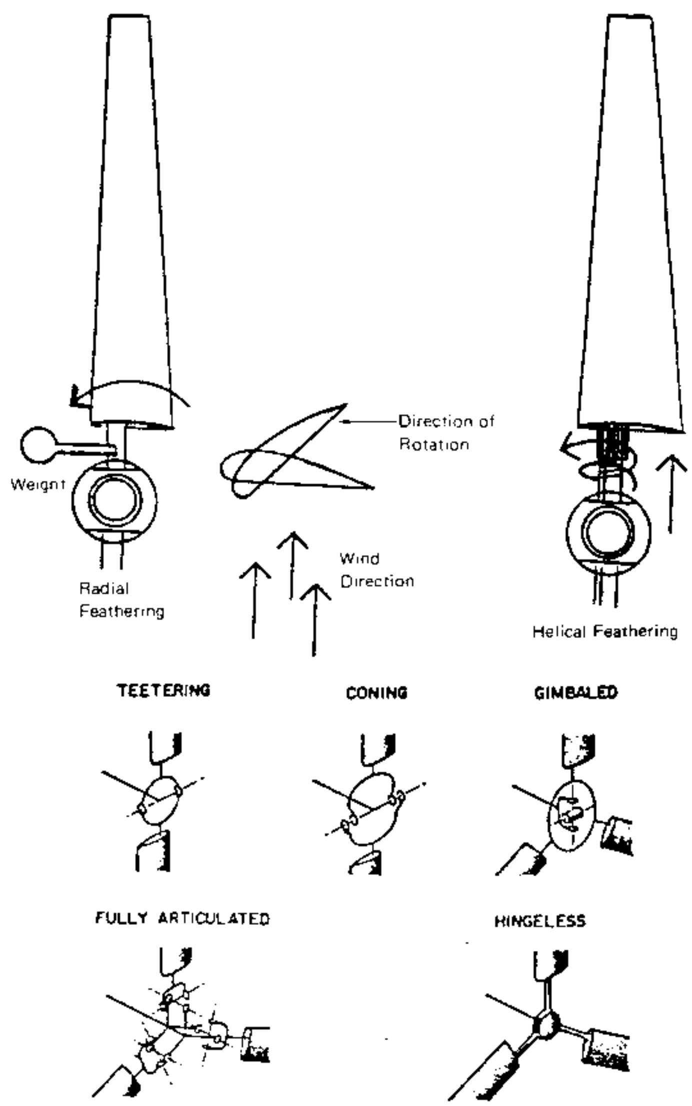


Fig. 12 Typical rotor hub configurations and feathering systems

Radical Technology: G.Boyle, P.Harper. UK. 1976. ISBN 0 394 73093 3

NATURAL, ENDLESS, FREE

The wind is a naturally-distributed, virtually untapped and non-polluting source of energy. As such, it offers many possibilities for the decentralization of power production, since the harnessing of wind can be easily controlled and maintained by the people who make use of its energy.

Everyone knows that wind was once used to push ships around the world—incidentally, some of the ocean crossing times of the old clippers were competitive with the crossing times achieved by modern freighters—and most people are familiar with the Dutch use of windmills to drain land reclaimed from the sea. But few know of the many other devices for harnessing the wind, developed over the centuries since the first windmills—evolved from sailing boats and animal mills—appeared in China and Persia around 2,000 BC.

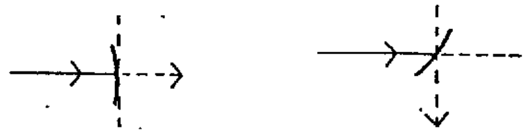
A lot of work on wind has also been done in this century, but unfortunately a large proportion of it has consisted of research into large-scale machines, which are both expensive and very vulnerable in high winds. It is this preoccupation with *large* power stations which has stopped wind power from being fully exploited—quite apart from the essential foolishness of trying to centralize and charge for distributing a form of energy which Nature distributes for nothing. But there is another and more hopeful side to the wind power story.

WINDMILL TYPES

One categorization of windmills divides them into *vertical axis* or *horizontal axis* machines. Vertical axis machines ("panemones") can accept winds coming from any direction, so do not require any orientation system to turn them into the wind, but usually have high drag characteristics. Horizontal axis machines usually have to be turned into the wind (hence requiring special mechanisms for orientation), but tend to have better performance.

Wind machines can also be classified according to the mode of displacement of the blades or sails. There are two main types (see Fig 1): I. Windmills in which the blades move in the same direction as the wind; II. Windmills in which the blades move perpendicularly to the direction of the wind.

Fig 1. Windmill types.



I. Windmills in which the blades move in the direction of the wind.

II. Windmills whose blades move perpendicularly to the direction of the wind.

Fig 2. Screen wind machines.

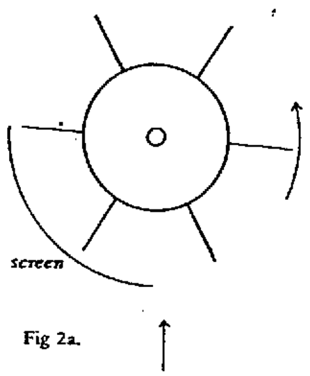
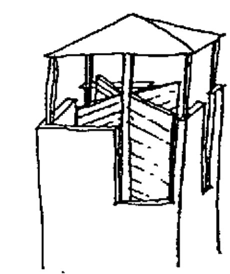
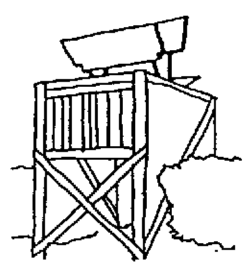


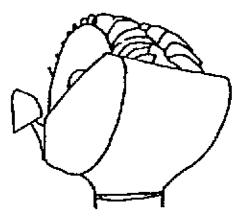
Fig 2a.



2b. Persian vertical axis screen windmill.



2c. Horizontal axis jumbo windmill.



2d. Russian Stastik wind machine.

◆ *I. Windmills in which the blades move in the direction of the wind* These machines are characterized by a tip-speed ratio (see glossary of terms) of less than 1, ie the blades rotate at a speed lower than the wind speed. The blade speed in practice is rarely greater than a third of the wind speed which means that these are 'slow' machines.

The axis of the rotor in such machines is perpendicular to the wind direction and is usually vertical. Generally only one blade or sail is actively 'driving', while one or more of the blades is rotating against the wind—which retards the overall speed of the mill. The different methods employed to overcome this problem of retardation are what distinguish the different wind machines in this category.

a) Windmills with simple drag With these machines, the blade moving against the wind changes its position so that it offers minimal resistance to the wind, or is screened off on the windward side.

1. Screen wind machine (see Fig 2). A suitably-placed screen dispenses with the problem of retardation of the blades turning against the wind. The screen can either be fixed or moveable, the former obviously being only suitable when the wind direction is fairly constant. With a moveable screen, the machine can accept winds coming from any direction, although it can be a complicated process to move the screen. Screen machines can have a vertical axis (these are sometimes called 'merry-go-round' windmills; see Fig 2b), or a horizontal axis (these are sometimes known as 'jumbo' windmills; see Fig 2c). The Russian Stastik windmill (Fig 2d), in which the whole machine was kept oriented into the wind was a horizontal-axis version.

2. 'Clapper' type wind machine (see Fig 3a). The blades or sails are hinged, and swing about a vertical axis. A stop situated near each blade holds it back

when it is in the drive arc of its cycle, yet leaves it free to feather in the wind for the rest of its cycle. This arrangement has the disadvantage of involving considerable machine maintenance because of the continual shocks received by the sails or blades when they bump up against the stops; it is this bumping action which gives the 'clapper' type its name. The clapper windmill is believed to have been one of the first windmills; there are some still in existence in China (Fig 3b).

3. Wind machine with cyclic variation in blade angle (see Fig 4). By means of an epicyclic mechanism or a system of belts or chains, the blades of such machines change their angle in relation to the wind, and turn round their vertical axes through half a revolution for each complete revolution of the rotor. The effect is similar to the clapper type without the shocks, but the complicated mechanism involved means that this machine loses one of the main advantages of the simple panemones, namely that of cheapness and simplicity of construction.

b) Windmills with drag difference With these machines the shape of the blade is streamlined so that the drag is less in that part of its cycle that opposes the wind. An important advantage of these machines is that they do not need a mechanism for orientation.

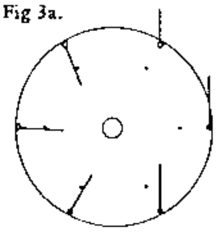
1. Cup-type wind machine (see Fig 5a). The "cup anemometer", used in meteorological stations for measuring wind speed, is the best example of this type of machine. The shape and number of cups may vary—as can be judged from Fig 5b. Such machines are not particularly useful for *harnessing* wind energy.

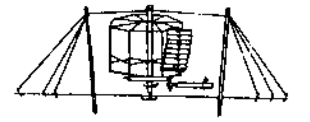
2. Transverse flow wind machine (see Fig 6a). These machines are analogous to the Banki water turbine, and are a transitional type between Type I and Type II machines, as the wind strikes the blade surface not perpendicularly, but at a small angle. The ingoing wind produces only a small part of the driving torque, the main power coming from the outgoing wind. Drag against the wind results in a loss in efficiency, and furthermore, with increasing speed of rotation, the braking torque increases more rapidly than the gross driving torque. There is however an advantage in this apparent inefficiency: no special devices are needed to limit the speed in high winds. This type of rotor also exhibits the 'Magnus effect'—a perpendicular force created by the airfoil-like properties of a cylinder spinning in the windstream. Its efficiency can be increased by the use of guide vanes, when high rotation speeds can be attained (see Fig 6b). This type of wind machine has not received the attention it appears to warrant.

3. Savonius Rotor (see Fig 7). This machine derives from the cup windmill, and bears a resemblance to the transverse flow machine. It consists of a vertical cylinder sliced in half along its vertical axis, the two halves so formed being pulled apart about 20% of the original diameter (there are some variations in this distance and in the shape of the curvature of the blades, from a fairly streamlined almost airfoil shape to a simple semi-circle). This

Fig 3. Clapper type wind machine with stops.

Fig 3a.





3b. Chinese clapper type windmill incorporating sail rig of Chinese junks. (From *Science and Civilisation in China* Vol. on Mechanical Engineering).

Fig 4. Wind machine with cyclic variation in blade angle.

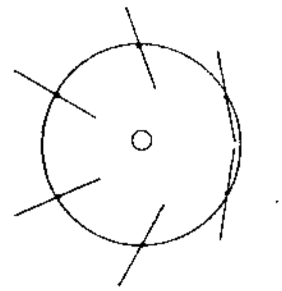
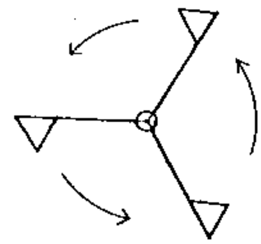
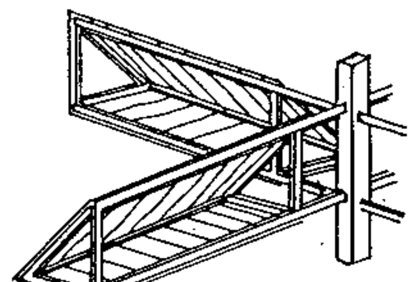


Fig 5. Cup type wind machine.

Fig 5a.

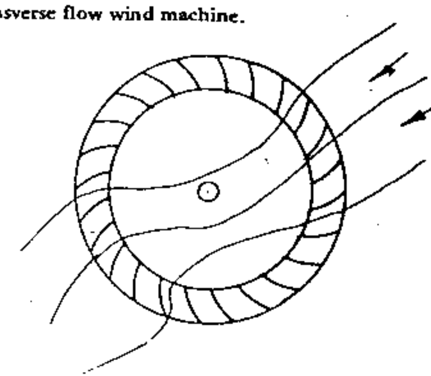


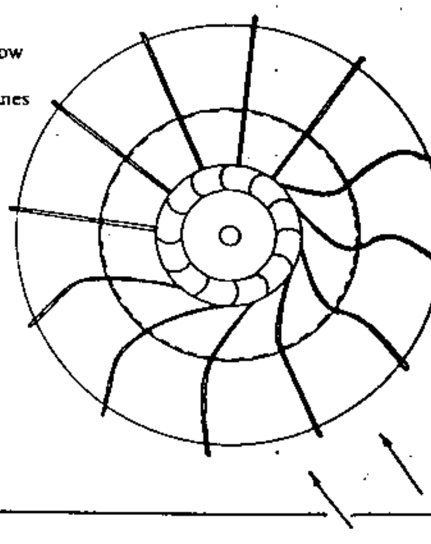


5b Verantius' "Streamlined anemometer sail windmill" (From *Science and Civilisation in China* Vol. on Mechanical Engineering).

Fig 6. Transverse flow wind machine.

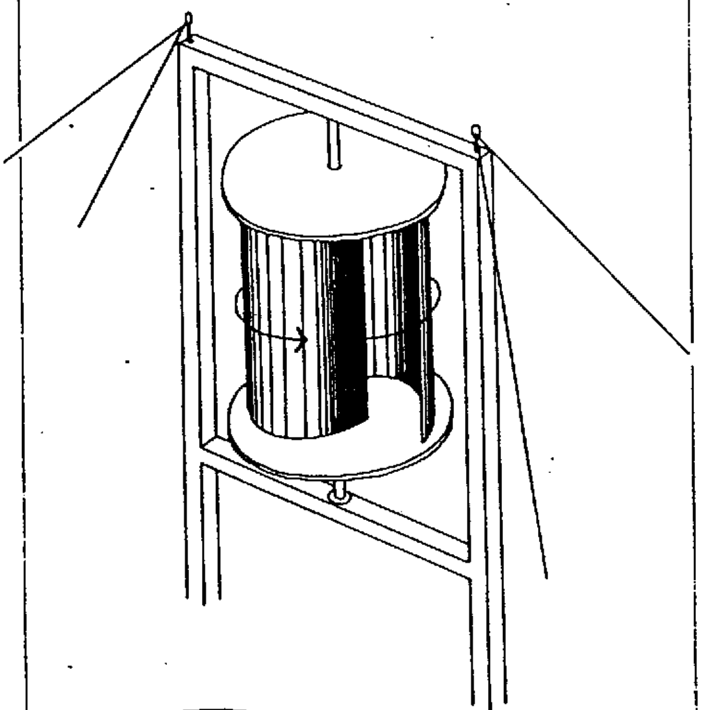
Fig 6a.





6b Transverse flow machine with flexible guide vanes which eliminate drag, and allow high rotation speeds.

type of machine operates in light winds and is ideally suited to pumping or mechanical drive applications, but because of its low tip-speed ratio (0.5 to 1.5), and therefore its slow rotation, it is not really suitable for electricity generation. Savonius rotors have been in use for some time as ventilators on vans and as ocean current measuring devices. The Brace Research Institute at McGill University in Montreal, Canada, catalysed a recent resurgence of the Savonius with its "recycled oil drum" design for Third World waterpumping applications. The oil drum Savonius, although it is rather heavy and has the poor drag characteristics typical of these machines, can provide a cheap source of power.



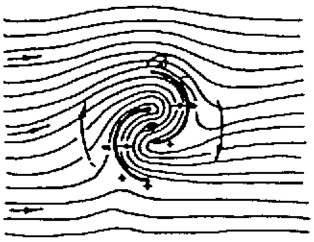


Fig 7. Savonius rotor.

Air streaming and pressure differences around a Savonius rotor (From *Mechanical Engineering*, May 1931 p.334).

◆ ***II. Windmills with rotor blades moving perpendicularly to the wind*** For these machines the tip-speed ratio may often be greater than 1—ie the blade tips rotate at a speed higher than the wind speed. They are, generally therefore 'fast' machines, and can be divided into the following categories: Machines having their axis perpendicular to windflow; Machines with axis parallel to the windflow, and kept oriented into the wind.

a) Machines with axis perpendicular to windflow

1. Vertical axis wind turbine (panemone) with cyclic variation in blade angle (see Fig 8). The blades are of airfoil sections. In these machines the blade is propulsive only in the arcs AB and CD (see diagram). The wind traverses the blades twice, and the variation in blade angle is obtained by a suitable rotation of the blades. Darrieus, a French wind power engineer, patented a version of this machine in 1931.

Fig 8. Vertical axis wind turbine with cyclic variation in blade angle and airfoil blades. (A variation of the Darrieus breed of wind machines).

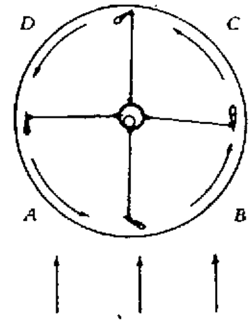
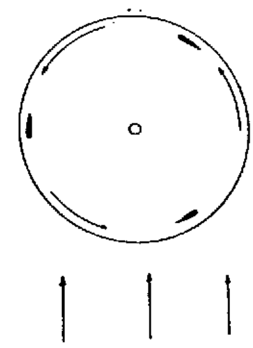


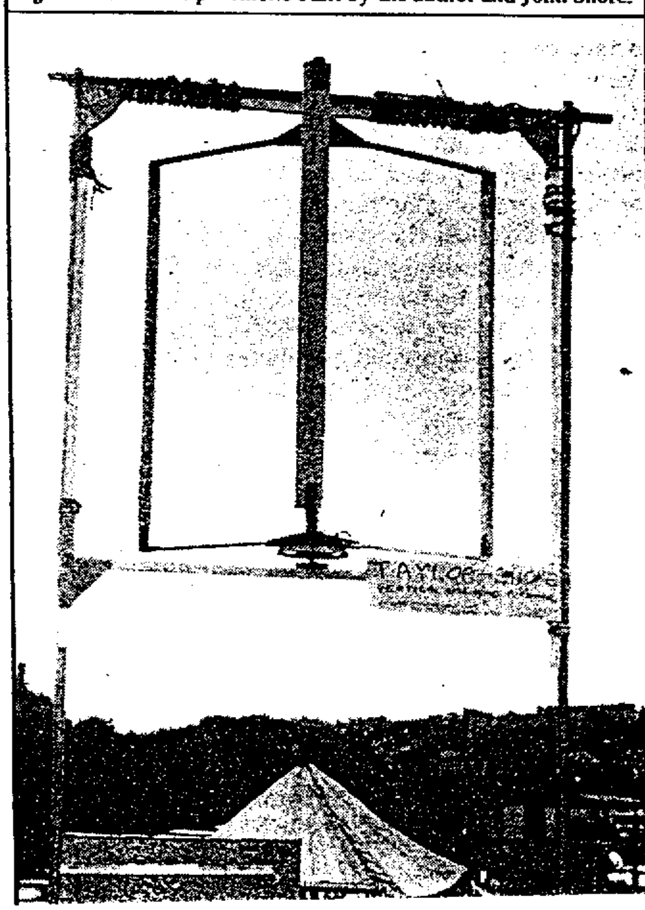
Fig 9a. Vertical axis wind turbine with fixed airfoil blades. (Another of Darrieus' wind machines).



2. Fixed-blade panemone (see Fig 9a and b). These machines only work when the tip-speed is much greater than the wind speed. It is necessary to start the machine in order to initiate self-sustaining operation, (for example by using a Savonius rotor to provide an initial torque). Such a machine, also covered in Darrieus' patent, is much simpler than the variable blade type, easy to construct, and appears to have many advantages and possibilities.

3. Vertical axis catenary wind machine (see Fig 9c). This is another variation of the No.II.2. type, and also covered by Darrieus' patent. The airfoil blades are bent into the form of a catenary (hoop shape) to avoid stresses and bracing. This type of machine has tip-speed ratios ranging from 4 to 7—almost as fast as a propeller type machine—but like No.II.2. it requires a starting device. A Savonius rotor at the centre can be used. Interest in this

Fig 9b. Fixed-blade panemone built by the author and John Shore.



NASA

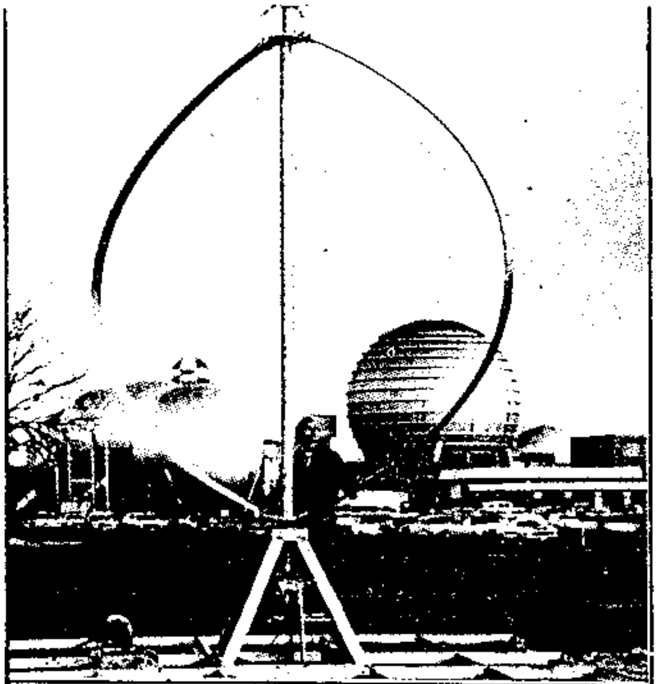
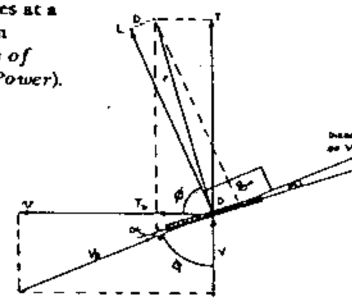


Fig 10. NASA vertical-axis catenary prototype.

Fig 10. Wind velocities at a blade element. (From Golding's *Generation of Electricity by Wind Power*).

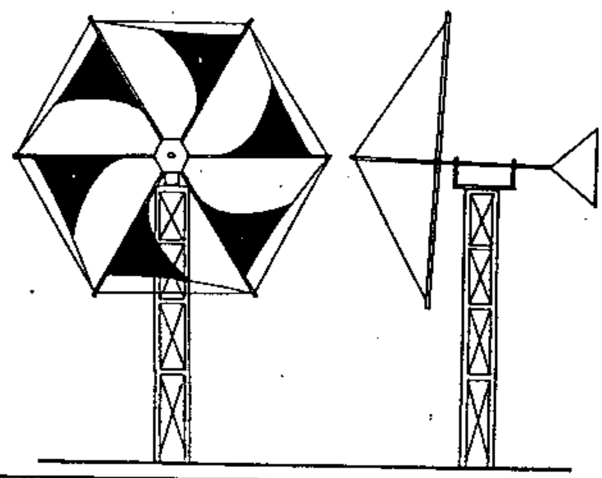


An active surface (flat or airfoil section) is placed so that it makes a large angle ($\phi + \alpha$) with the direction of the wind. V is the velocity of the wind when it approaches the surface. The forces thus result in the surface moving with velocity v perpendicularly to V. The relative wind velocity V_R is V- v. This V_R makes an angle α (angle of attack) with the surface. A force F acts on the surface and this has two components -- lift force L perpendicular to the V_R and a drag force D parallel to V_R.

$$\text{Lift (L)} = C_L \cdot \tfrac{1}{2}\rho A V_R^2 \qquad \text{Drag (D)} = C_D \cdot \tfrac{1}{2}\rho A V_R^2$$

Where A = area of surface ρ = air density C_L = Lift component of the particular aerofoil used C_D = Drag component

Fig 11. Mediterranean type sail windmill.



machine has recently been revitalized by work done at the National Research Council of Canada by two engineers, Raj Rangi and Peter South. They have carried out wind tunnel tests which show that a 5m. diameter turbine can produce 1 kW of electricity in a 20 km/h wind with blades turning at 170 rpm. They estimate that it would weigh 70 kg and cost around £20. This machine is one of the types being considered by NASA as part of its 100 kW windmill research programme, to help make the US independent in energy (!). This turbine has many advantages over conventional windmills, the main one being that it can receive winds from any direction without having to be oriented into the wind. This appears to make it suitable for use in urban situations where the wind direction is constantly changing and where a propeller type machine would spend a lot of its time chasing the wind rather than producing energy.

b) Machines with axis parallel to and oriented into the wind Wind machines of this category are: the Mediterranean-type sail windmill, English and Dutch windmills, propeller driven windmills, and multiblade fan-type windmills. These can further be sub-divided into high and low 'solidity' machines.

High Solidity Machines	Low Solidity Machines
● have a large area of blade proportionate to the total area swept by the wind	● have a small ratio of blade to swept area
● have a low tip-speed ratio	● have airfoil-section thin blades
● can start at low wind speeds	● have a high tip-speed ratio
● are less efficient converters of wind energy than propellor-type low solidity machines	● cannot normally utilize low wind speeds
● tend to be unsuitable for electricity unless high gearing is used	● convert energy more efficiently than high solidity types
	● are suitable for electricity generation

Because of their low rotation speed, their ability to utilize low wind speeds down to about 2.5 m/s (6 mph), and their ability to start under load, high solidity machines are generally used for mechanical purposes--such as pumping and corn grinding.

Low solidity machines, which are more suitable for electricity generation, generally start to turn at wind speeds in excess of about 5 m/s (11 mph) though some machines with variable pitch blades will "cut in" at just over half this speed. They have a high tip-speed, often in excess of five times the wind speed.

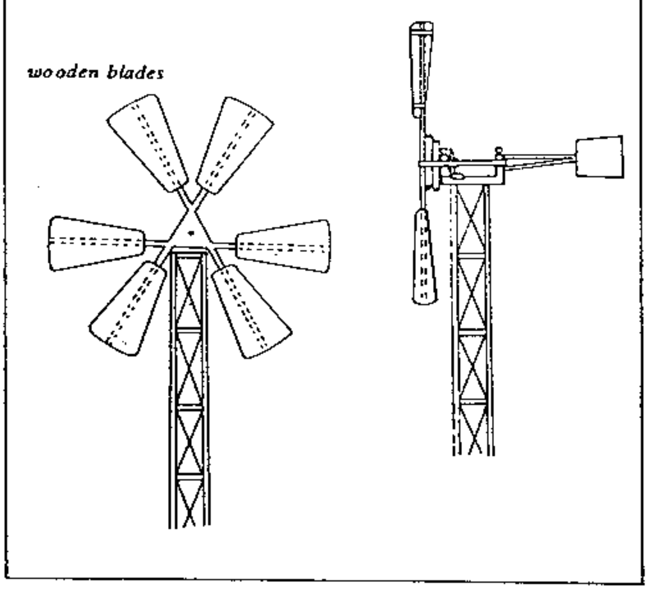
In all machines with their axes oriented into the wind, the active surfaces of the blade are placed at a very small angle to the wind instead of being perpendicular to it, and the driving force, instead of being displaced in the direction of the relative velocity, makes an angle with it (see Fig 10).

The airfoil profile is placed so that it makes a large angle ($\phi + \alpha$) with the direction of the wind when it approaches the surface. The forces brought into play result in the surface moving, with velocity v in a direction perpendicular to the wind.

High solidity machines

a) Mediterranean-type sail windmills (see Fig 11). They consist traditionally of wooden blade arms triangulated with ropes and (usually triangular)

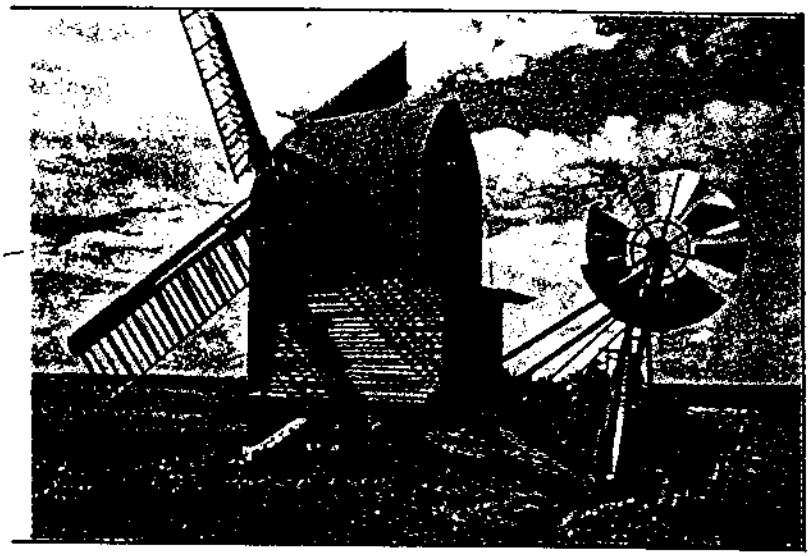
Fig 12. "Battle-Axe" windmill.



canvas sails. Of simple construction, these mills will work in slow winds, but have relatively low rotation speeds. Many are still in use around the Mediterranean notably on the Plain of Lassithi in Crete. The Brace Research Institute and Windworks, a research group based in Wisconsin, are cooperating to develop a machine of this type for use in the Third World to provide mechanical energy for pumping, irrigation and similar applications. Such mills rarely exceed a tip-speed ratio of 2, above which the curvature of the sails assumes an unfavourable profile and gives low torque.

b) 'Battle Axe' windmill (see Fig 12). This is similar to the previous type of machine, except that the sails tend to be wooden and can harness only low wind speeds. It is suitable for mechanical energy needs and is fairly simple to construct. VITA (Volunteers for International Technical Assistance of Maryland) have produced a set of plans for a version of this machine.

c) Traditional English (or Dutch) windmills (see Fig 13). There are many different types of the traditional windmills. They rotate slowly, though their large size gives a lot of power, utilizing up to 16% of the wind energy. Traditional uses include milling of grains and pumping, but these types are not really suitable for electricity production because of the large gearing ratios needed. The sails are of wood, covered with either canvas or with 'venetian blind' roller shutters. Traditional windmills can be useful if restored, but are expensive to build and complicated to operate.



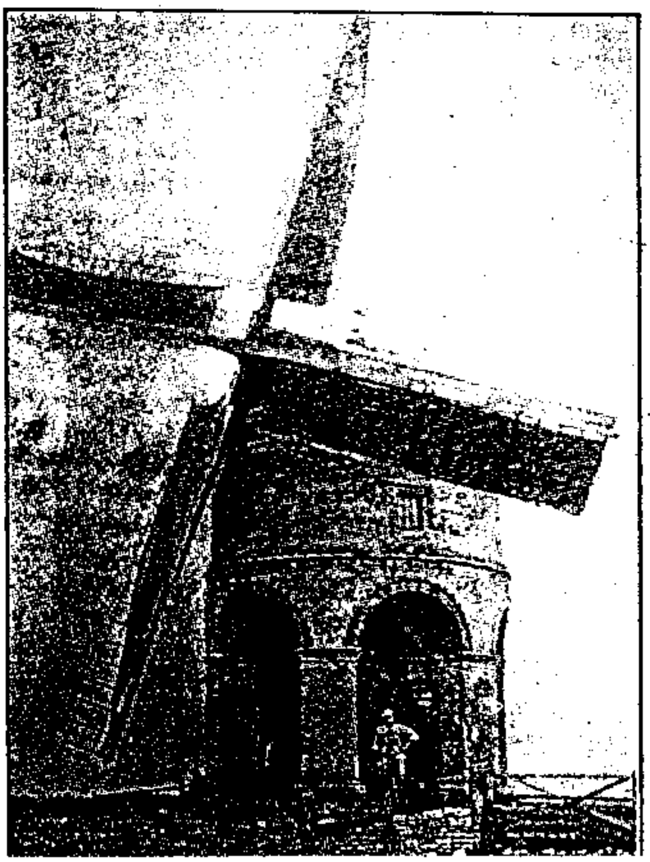
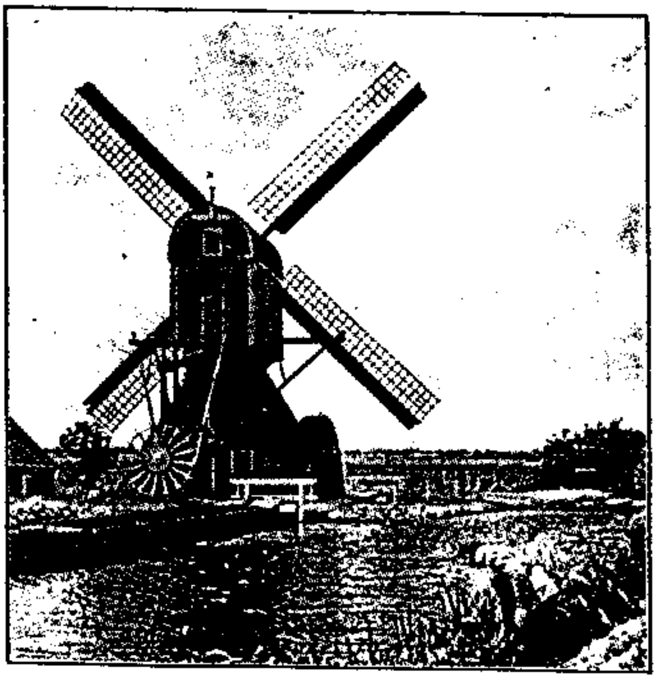


Fig 13. Traditional Windmills. ***(Upper left)*** **Great Chishill post-mill, Cambridgeshire, oriented by a fantail.** ***(Lower left)*** **Chesterton tower-mill: 19th century photograph of a unique structure, possibly designed by Inigo Jones: oriented by a winch inside the cap.** ***(Below)*** **Dutch 'Waterwipmolen': a drainage post-mill oriented by a capstan wheel.** ***(Top right)*** **'Tjasker', smallest and simplest type of Dutch drainage mill lifting water by means of an Archimedian screw.** ***(Lower right)*** **A 'paltrok', a uniquely Dutch type, designed for sawing wood. The entire structure rotated on rollers on a brick base.** ***(Far right)*** **The most characteristic Dutch type, a thatched smock-mill oriented from the outside by a capstan wheel and spars attached to the cap.**



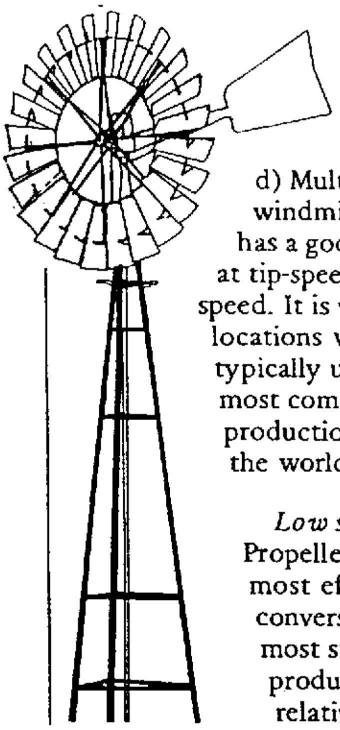


Fig 14. Multiblade, American or fan windmill. Mainly used for pumping.

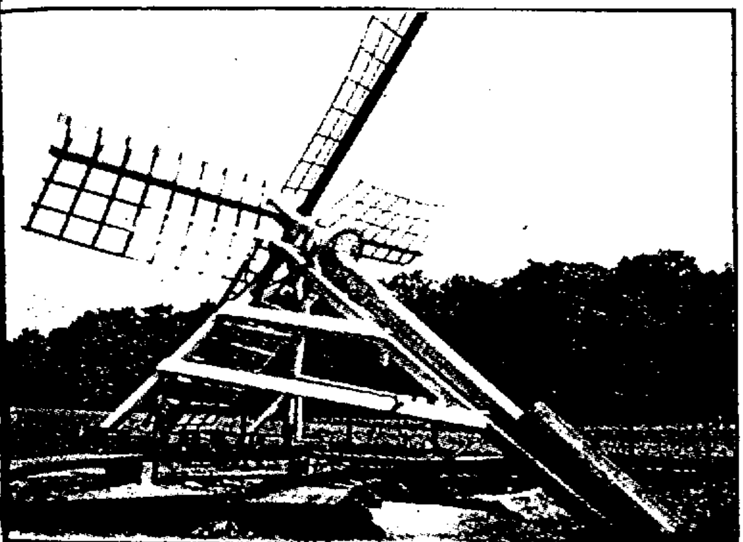
d) Multiblade 'American' or fan-type windmill (see Fig 14). This machine has a good starting torque, and rotates at tip-speeds about equal to the wind speed. It is very suitable for use in locations with low wind speeds, and is typically used for pumping. This is the most common type of wind machine in production, in various forms, around the world.

Low solidity machines

Propeller-driven wind machines are the most efficient in terms of energy conversion at the present and are the most suitable for electricity production. They perform best at relatively high wind speeds, and can seldom make use of light winds. They have received the most attention in modern times because of their relatively high efficiency and because of the enormous amount of work done on airscrew propellers for aviation. They are, however, also the most complex, in view of the relative precision of the shape and curvature of the propeller blades, although once the shape has been designed, they are not too difficult to construct. If you do not feel that you can design the blades yourself there are various sets of plans (see Bibliography) available for small scale applications.

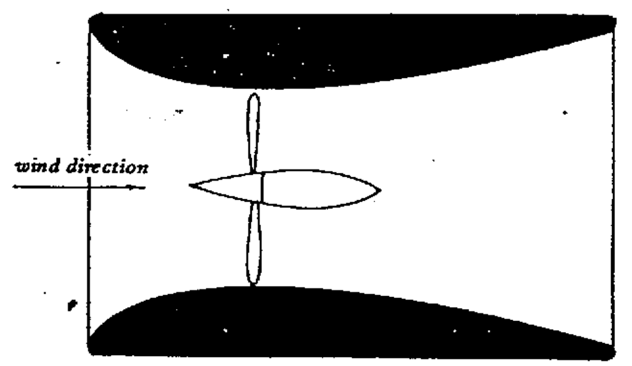
Some variations on the propeller-type and various methods of increasing its efficiency are now described.

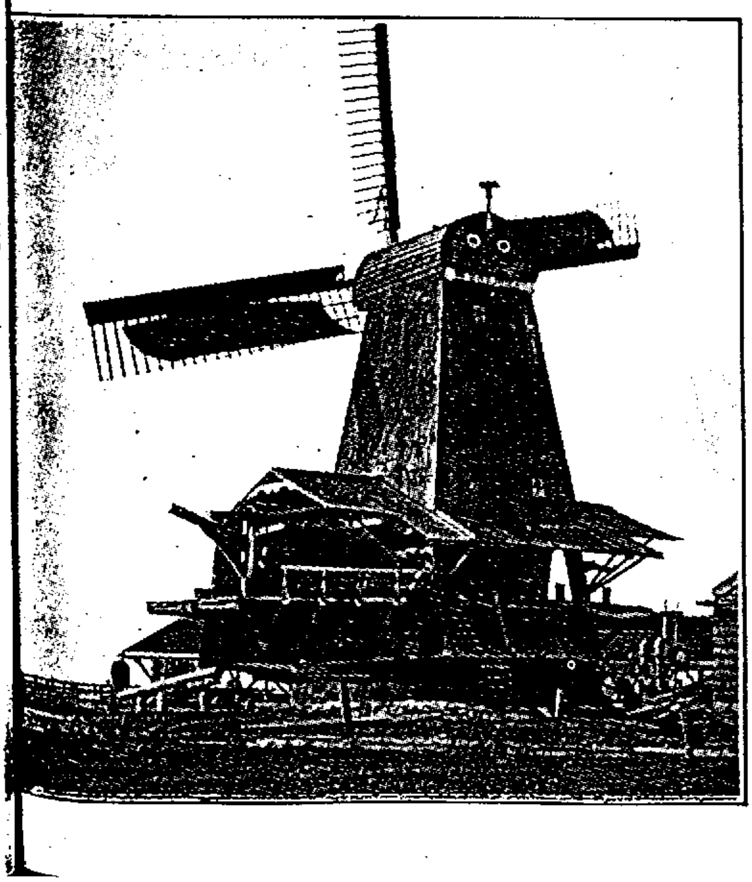
a) Venturi tube (see Fig 15). An idea that has often been suggested is that of positioning the propeller (or indeed any other type of turbine) in the throat of a venturi tube. The tube increases the speed of the airflow, hence the rotation speed of the



DANSKE MOLLER VENNER
DANSKE MOLLER VENNER

Fig 15. Venturi tube or shrouded propeller wind turbine.





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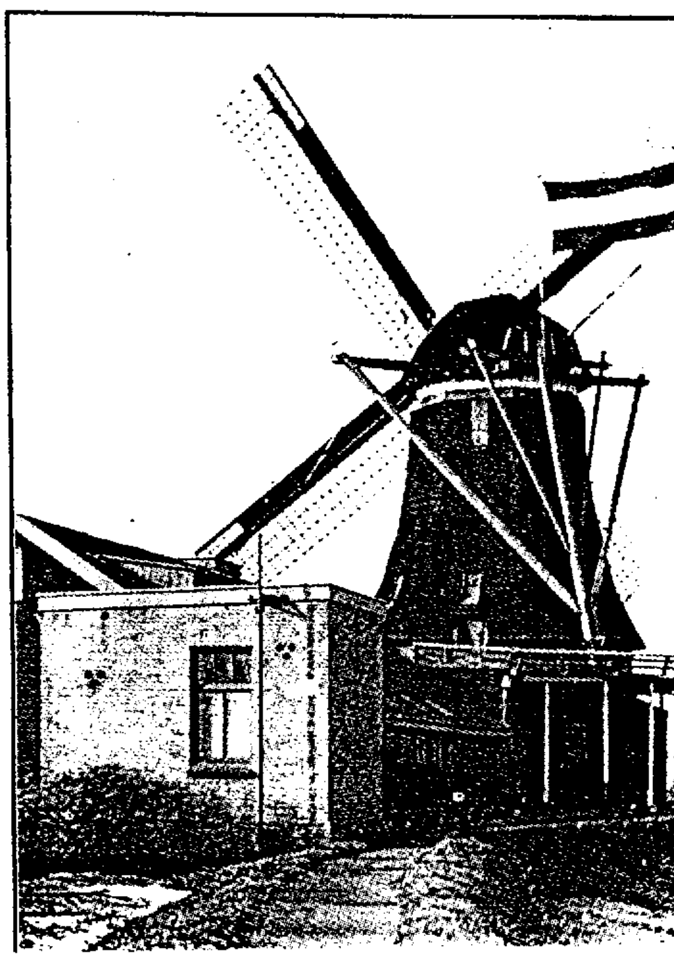


rotor, the power and the aerodynamic efficiency. But this technique is generally considered uneconomic because the whole venturi-rotor assembly must be kept oriented into the wind, and it is usually easier to increase the rotor diameter instead to get the equivalent increase in power. Nonetheless, a fair amount of work on the subject has been done by the Electrical Research Association (see the ERA's publication no.C/T119, *A Preliminary Report on the Design and Performance of Ducted Windmills*, by G.M. Lilley and W.J. Rainbird) and by Windworks (see *Domebook Two*, p.121, 1971).

b) Depression-type wind turbine (see Fig 16). This consists of a hollow-bladed propeller with holes in the tips, which acts as a suction pump to draw air through an air turbine directly coupled to a generator. This is one method of increasing the effective rotation speed without gearing, but it has a low overall efficiency. When the rotor is turned by the wind, air is driven centrifugally out of the ends of the blades. The depression created draws air through the tubular tower, at the base of which is the turbine which drives the generator. A 100kw Enfield Andreau wind unit which operated on this principle was installed in the 1950s on a test site at St Albans, Hertfordshire.

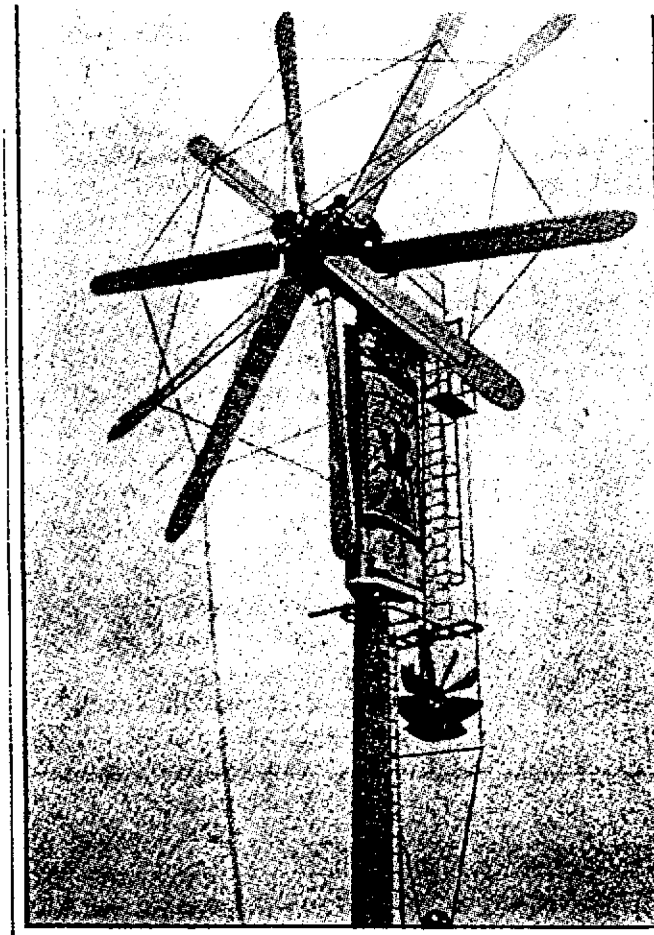


Fig 17b. German NOAH wind generator.

Fig 16. Depression type wind turbine.

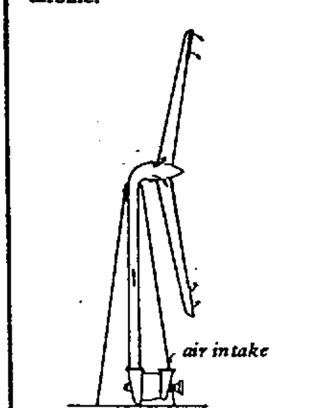


Fig 17a. Counter rotating wind turbine.

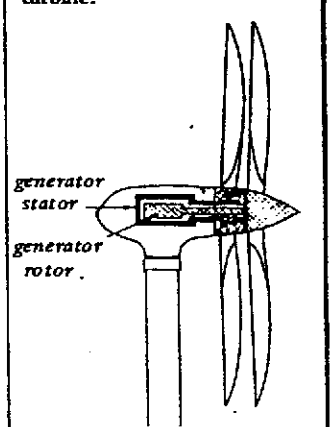
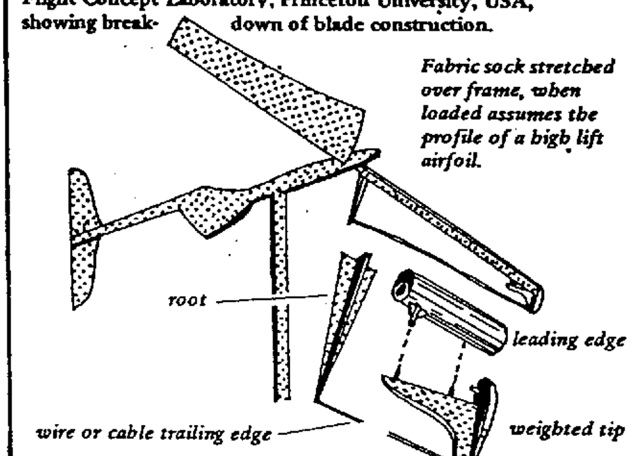


Fig 18. Sailwing windmill designed by Thomas Sweeney of the Flight Concept Laboratory, Princeton University, USA, showing break-down of blade construction.

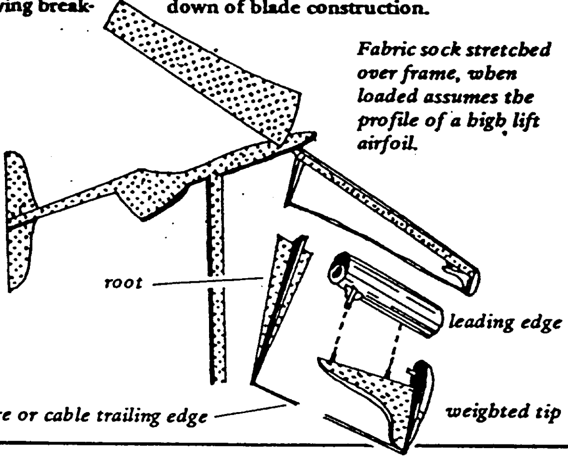


c) Counter-rotating wind turbine (see Fig 17a). This type of machine has two propellers turning in opposite directions, placed one in front of the other. One of the propellers is connected to the rotor, and the other to the stator in a generator. The two opposing speeds of the propellers give an equivalent generator speed of up to double that of one propeller. But one drawback is the complex nature of the transmission mechanism. A version of this type, erected on the German island of Sylt, is the NOAH windmill (see Fig 17b).

d) Sailwing wind turbines (see Fig 18). This idea was evolved by Thomas Sweeney of the Flight Concepts Laboratory at Princeton University, USA, who developed the sailwing concept for the wings of gliders and lightweight aircraft. It consists of a propeller-type windmill (although the idea could also be applied to a Darrieus-type machine) in which the leading edge of each blade is an aluminium tube, and the trailing edge is a tensioned cable. Over these is stretched a fabric sock which when loaded forms itself into a high-lift airfoil. This technique results in an extremely lightweight and efficient propeller. The first machine that Sweeney built had two 4 metre blades, each weighing only 6.5 kg. In a 32 km/h wind it produced seven kilowatts. The Grumman Aircraft Corporation in the US is to manufacture sailwing wind generators under licence, but plans for self-build models will be available shortly from William Flanagan, Flanagan's Plans, Box 5062, Long Island City, New York 11105, USA.

A low-technology version of this machine has been developed by Marcus Sherman of the New Alchemy Institute, using bamboo, string and canvas for the propeller. One of Sherman's mills has been used in India for water pumping, and another to drive a car alternator via a car differential.

Fig 18. Sailwing windmill designed by Thomas Sweeney of the Flight Concept Laboratory, Princeton University, USA, showing break-down of blade construction.



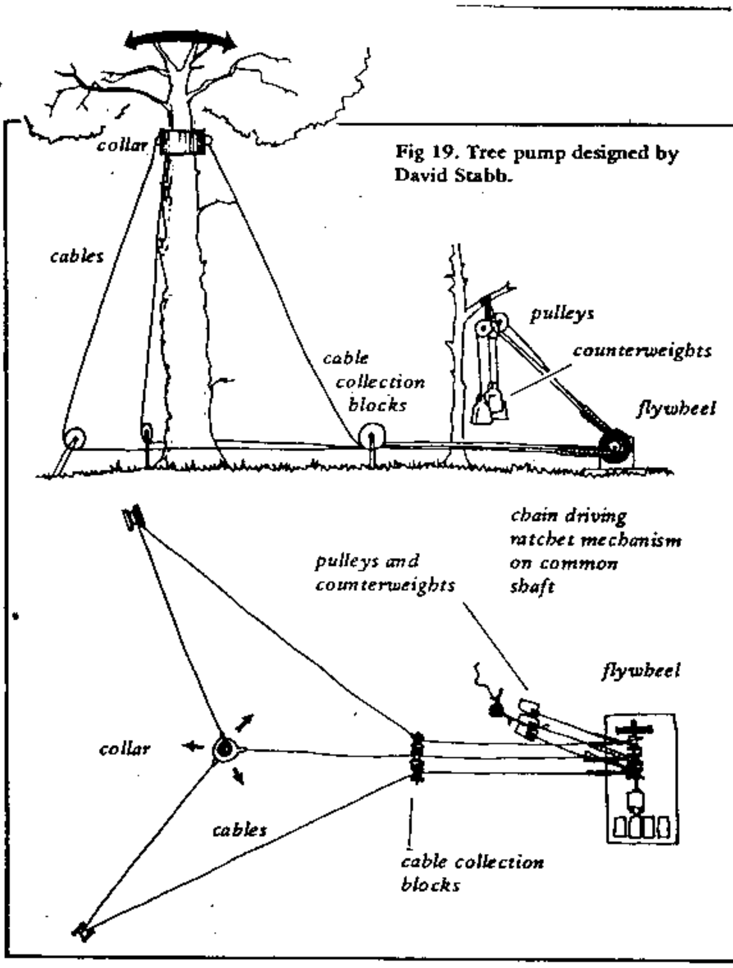


Fig 19. Tree pump designed by David Stabb.

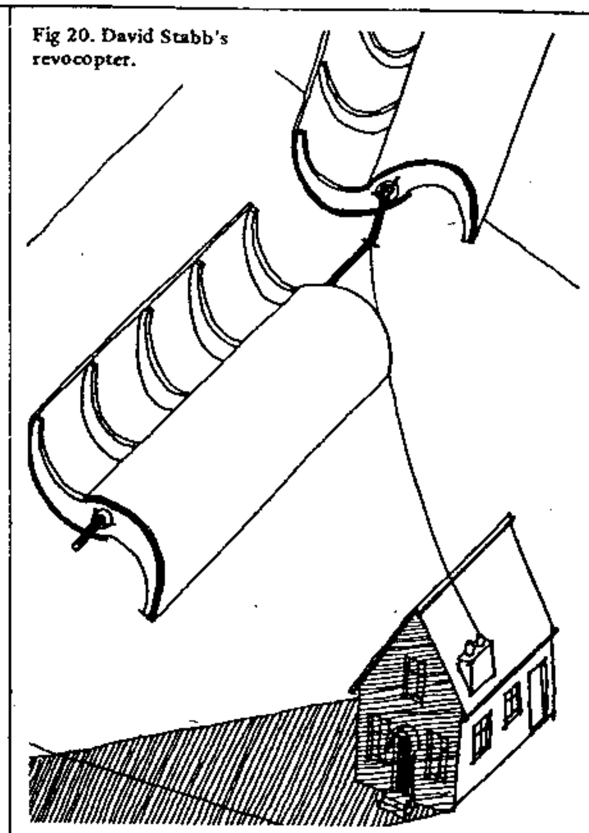


Fig 20. David Stabb's revocopter.

There are also several other wind energy conversion devices which do not fit into any of the previously-mentioned categories. Two that warrant a mention are tree pumps, and kites. Current interest in both of these is mainly due to David Stabb's research.

◆ *Tree Pumps* (see Fig 19). These are mechanical devices that harness wind energy via the intermittent movements of large branches and trees, which are triangulated by means of cables and pulleys to a chain-driven ratchet mechanism which rotates a shaft to supply mechanical power. This is quite an ingenious system, but it remains to be seen whether the idea will prove its worth. Also, extreme care should be taken to avoid damaging the tree, and advice from someone who knows about trees should be sought.

◆ *Kites* A kite has been developed that can climb and stall at a pre-set angle to the wind. It operates by means of a set of 'spoilers' on the nose, which open and drive the nose sharply downwards. During this downward motion a small counterweight rapidly winds in some of the tethering cable. During the lift motion that follows, the tethering cable is drawn out and rotates a ground-mounted ratchet mechanism. A major problem in the use of kites is the fact that they need to be launched whenever energy is required and that they require wind to stay up. This obviously limits any possibility of automatic operation. This limitation conceivably could be overcome by using an airfoil-shaped balloon filled with hydrogen or helium to keep the kite/balloon in the air during calm spells.

David Stabb has also been exploring various unorthodox types of kite, including a giant 'revo-copter' (a sort of flying Savonius rotor,see Fig 20) which would drive an endless tethering cable which in turn would drive a ground-mounted mechanism. Like the tree pump, the kite has yet to prove itself as an energy converter for static power supply. But it has at least one distinct advantage over conventional wind power plants, namely its ability to climb to relatively high altitudes, where wind velocities are much greater than they are near the ground.

HARNESSING THE WIND

Before installing a wind machine it is obviously important to know whether there will be enough wind to utilize. You will need to know:

a) The amount of energy expected annually;

b) The distribution in time—over the day, month, year or longer.

c) The probable duration of very high wind speeds, or of calm spells, during a given period.

The estimated energy available from the wind, globally, according to Golding, is approximately 13 million million kilowatt hours a year. The annual available energy per square metre of swept surface may vary between 100kWh for calm areas and 500kWh for very windy areas.

The annual average wind speed available at any site will depend on the following factors:

a) Its geographical position.

b) Its more detailed location, such as its altitude and its distance from the sea.

c) Its exposure—in particular, the distance away from any higher ground likely to give screening, especially in the direction of the prevailing wind.

d) The nature of the surrounding ground, even though it may not necessarily be high; for instance very broken ground, with rocks, woods or groups of trees, can seriously retard winds near the surface

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of the ground (Fig 21a).

e) The shape of land in the immediate vicinity. Because of the increased wind speed at higher altitudes, hilltops are very suitable locations for wind machines. A steep, though smooth, hill may accelerate the wind flow over the summit by 20% or more, by causing compression of the layers of air in much the same way as an airfoil or venturi tube (see Fig 21c). If the hill is not smooth, or the summit is too sharp, turbulence can be created (see Fig 18).

The most suitable areas for harnessing wind power are coastal areas, ridge lines of hills, and flat plains such as exist in Holland.

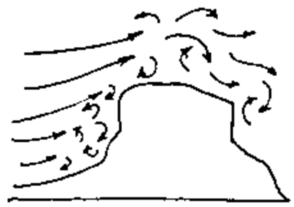


Fig 21a. Air flow over steep and rough terrain.

Fig 21b. Air flow around isolated small obstacles.

Fig 21c. Acceleration of wind over hills.

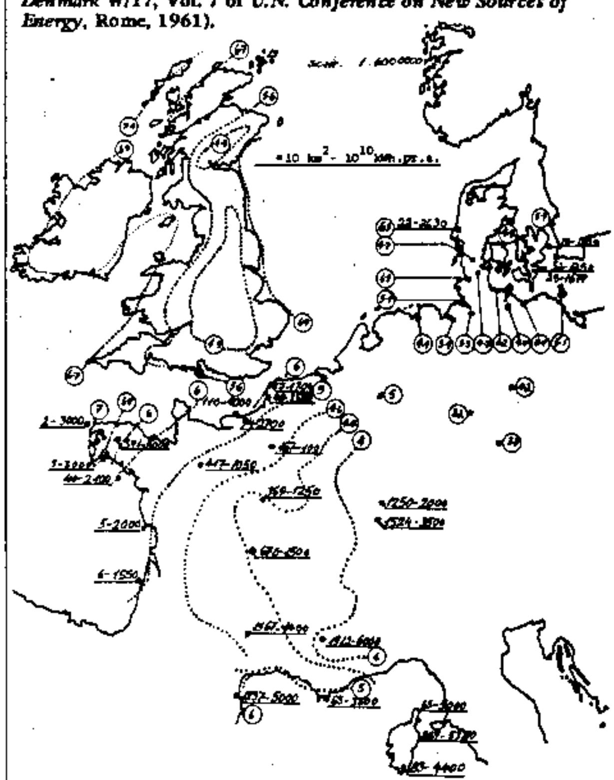
(From K.H. Soliman *'Study of Wind Behaviour and Investigation of Suitable Sites for Wind-driven Plants'*, W/4 Vol. 7 of *U.N. New Sources of Energy*, Rome, 1961)

WIND DATA AND MEASUREMENT

Before you can decide on a particular type of wind machine, besides knowing how much energy is required for the particular task you want the windmill to perform for you, you need to know how much power is available from the wind on your site. You need to know the prevailing wind directions, the mean average wind speed and the most frequent wind speeds. It is possible to get a rough idea for the general area from windroses on Ordnance Survey maps (Fig 22) or from wind contour maps (Fig 23). But practically the only detailed data available in Britain is from a few meteorological stations and for a few sites that were surveyed by the ERA. So the only alternative to taking measurements for at least a year with an anemometer (see Fig 24), is to take a chance, and hope that the nearest available meteorological data does not differ too much from that for your site—or evolve a design by trial and error, trying out various models of different types to see how they perform over a period of time.

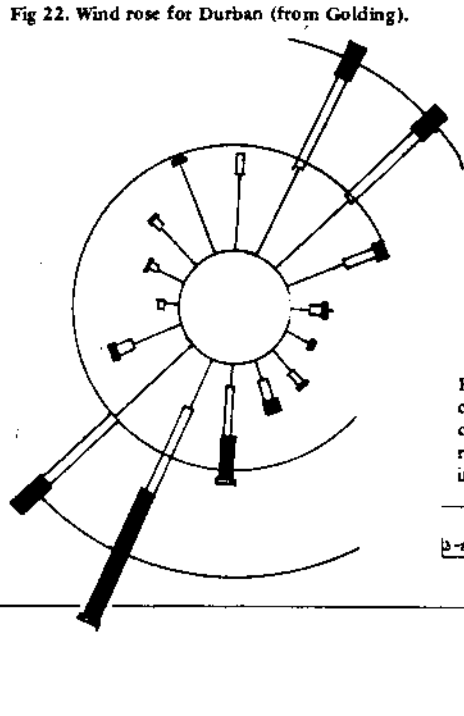
Some enterprising person should set up and co-ordinate a wind (and maybe also solar radiation) measurement programme to be carried out by schools, along the same lines as the recent, very useful, schools pollution monitoring programme.

Fig.23. Wind Contour Map of Western Europe with Wind Speeds & Energies (from J. Juul *The Design of Wind Power Plants in Denmark* W/17, Vol. 7 of *U.N. Conference on New Sources of Energy*, Rome, 1961).



The figures in circles indicate mean annual wind speeds. In the double figures, the first indicates the height of measurement, the 2nd the energy in kwh/m^2, measured in the vertical plane. The top of the map shows the scale together with the swept area required to produce 100,000 million kwh.

Fig 22. Wind rose for Durban (from Golding).



Percentage of calms within circle. Arcs represent 5% intervals

Fig.24. David A. Sankey's do-it-yourself anemometer & wind vane (*Scientific American*, June 1972).

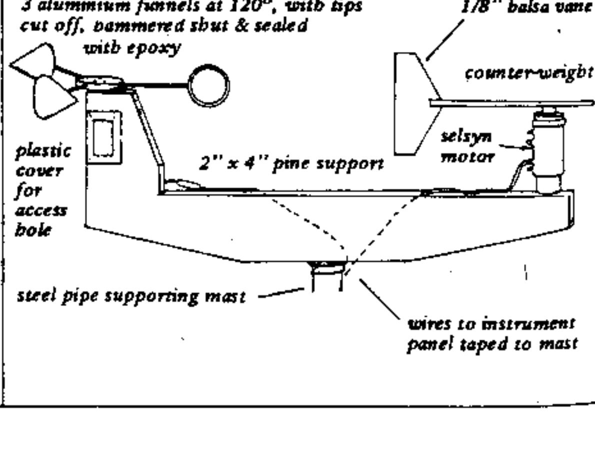


Table 1. Beaufort Scale of Wind Forces
(from Golding *Generation of Electricity by Wind Power*)

Beaufort number (B)	*Description of wind*	*Land observations*	*Equivalent mean velocity (knots)*	*Limit of mean speed at 33' above flat ground in open situations* — *knots*	*mph*	*m/s*	*Mean wind force in lb/ft² at standard density ($P = 0.015B^3$)*
0	Calm	Smoke rises vertically	0	under 1	under 1	under 0.3	0
1	Light air	Light drift of smoke	2	1 – 3	1 – 3	0.3 – 1.5	0.01
2	Light breeze	Wind felt in face, leaves rustle	5	4 – 6	4 – 7	1.6 – 3.3	0.08
3	Gentle breeze	Leaves in motion, light flag extended	9	7 – 10	8 – 12	3.4 – 5.4	0.28
4	Moderate breeze	Small branches move; litter, dust, leaves lifted	13	11 – 16	13 – 18	5.5 – 7.9	0.67
5	Fresh breeze	Small trees sway	19	17 – 21	19 – 24	8.0 – 10.7	1.31
6	Strong breeze	Large branches in motion; telegraph wires whistle	24	22 – 27	25 – 31	10.8 – 13.8	2.3
7	Moderate gale	Whole trees in motion, difficult to walk against wind	30	28 – 33	32 – 38	13.9 – 17.1	3.6
8	Fresh gale	Twigs break off trees	37	34 – 40	39 – 46	17.2 – 20.7	5.4
9	Strong gale	Chimney pots and slates blown off roofs	44	41 – 47	47 – 54	20.8 – 24.4	7.7
10	Whole gale	Trees uprooted, severe structural damage	52	48 – 55	55 – 63	24.5 – 28.4	10.5
11	Storm		60	56 – 63	64 – 72	28.5 – 32.6	14.0
12	Hurricane		68	64 – 71	73 – 82	32.7 – 36.9	18
13			76	72 – 80	83 – 92	37.0 – 41.4	23
14			85	81 – 89	93 – 103	41.5 – 46.1	29
15			94	90 – 99	104 – 114	46.2 – 50.9	35
16			104	100 – 108	115 – 125	51.0 – 56.0	43
17			114	109 – 118	125 – 136	56.1 – 61.2	52

Table 2. Theoretical maximum power extractible from the wind ($P = 0.593kAV^3$)

Wind speed		*Maximum power (kW) from various diameters of windmill*				
(mph)	*(m/s)*	*dia. 6ft 1.8m*	*dia. 10ft 3m*	*dia. 12.5ft 3.8m*	*dia. 25ft 7.6m*	*dia. 50ft 15.2m*
10	4.4	0.078	0.121	0.38	1.5	6.0
20	8.9	0.637	0.984	3.08	12.3	49.2
30	13.4	2.223	3.454	10.4	41.6	166.4
40	17.8	4.960	7.638	24.6	98.4	393.6
50	22.3	10.160	15.710	48.2	192.8	771.2
60	26.8	17.220	26.550	83.2	332.8	1,331.2

For more detailed technical data see Golding's *Generation of Electricity by Wind Power.* See also the ERA publications, especially: *The Aerodynamics of Windmills Used For the Generation of Electricity* (No.IB/T4); *Windmills for Electricity Supply in Remote Areas* (No. C/T120); and *The Potentialities of Wind Power for Electricity Generation (with Special Reference to Small Scale Operations)* (No. W/T16). "Designing Windmill Blades" by Alan Altman in *Alternative Sources of Energy* (No.14), is also useful.

CALCULATION OF POWER

Power is equal to energy per unit time, and the energy available in wind is its kinetic energy. The kinetic energy of any particle is equal to one half of its mass times the square of its velocity, or $\frac{1}{2}MV^2$. Since the volume of air passing in unit time through an area A with velocity V is AV, the mass M of that air is equal to its volume multiplied by its density ρ or, $M = \rho AV$. Substituting this value of the mass in the expression for kinetic energy above, we obtain the formula:

Power = kinetic energy per unit time = $\frac{1}{2}\rho AV.V^2 = \frac{1}{2}\rho AV^3$.

Assuming that the swept area of the mill A is equal to $\pi D^2/4$; where D is the mill diameter, then the power = $\frac{1}{2}\rho\pi D^2/4\ V^3$

Or, in general terms, Power (P) = $k\ A\ V^3$ where k is a constant (equal to $\frac{1}{2}\rho$).

In imperial units, the value of constant k is 53×10^{-7}, when the area of the turbine A is in sq ft, the diameter D is in feet, the velocity V is in mph, and P is in kilowatts. In metric units, k is 64×10^{-7}, when the area A is in square metres, diameter D is in metres, velocity V is in metres per second, and P is in kilowatts.

Putnam gives a general formula which, when converted to metric units, becomes:

$P = 472.\ 10^{-6}.\ D^2.\ V^3$

Encyclopedia Britianica gives a slightly different formula, which, in metric units is:

$P = 484.\ 10^{-6}.\ D^2.\ V^3$

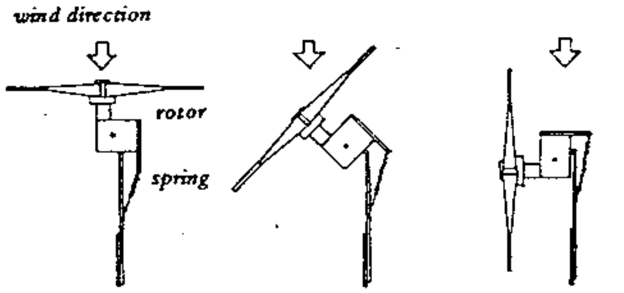
But the maximum amount of power that can in theory be extracted from an ideal windmill has been shown by Betz to be 0.593 times the theoretical power P in the wind, as given above. Hence, in theory, the maximum power extractible, P (max) = $0.593.\ 484.\ 10^{-6}.\ D^2.\ V^3$

But in practice this multiplying factor has been shown to be no greater than 0.4 or maybe less, ie the actual power P (act) $\leq 0.4.\ 484.\ 10^{-6}.\ D^2.\ V^3$

FURLING

The table relating wind speed and power from wind devices shows that there is, for example, more than a hundred times as much power available from a 50 mph wind as there is from a 10 mph wind. The tremendous energies of high winds can easily destroy a machine built to handle lower wind speeds unless special provisions are made for protection. Various devices for "furling" or bringing machines to a safe condition in high winds are illustrated in Fig 25.

Fig 25a. Godwin's automatic governing device for their Hercules wind pumps.

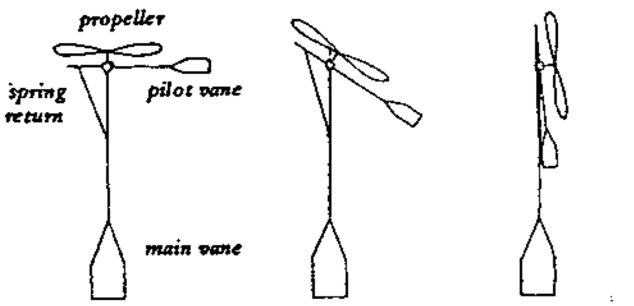


Windmill working position in low and medium winds.

Windmill working position in high winds. Windmill turns slightly out of wind and regulates speed.

Windmill in 'off' position with brake on, activated by violent winds or hand.

Fig 25b. Overspeed device used on many windmills including Kenwood's (1908), Jim Sencenbaugh's and Camm's amongst others.



Windmill in normal operating position.

Working position in high winds. Pressure on pilot vane pulls round propeller.

Windmill in 'off' position.

ESTIMATION OF OUTPUT

To estimate a windmill's output you need to know its characteristics and the frequency of winds at various speeds. For each wind speed there is a corresponding amount of power per unit area, calculable from the formulae given earlier. Knowing the frequency of each wind speed you can calculate the theoretical amount of energy capable of being generated by a wind of that speed. The machine's efficiency will vary at different wind speeds and the total energy available for each wind speed must be altered accordingly. There is also a speed above which the machine must be furled to avoid damage, and this energy is therefore wasted. Below a certain wind speed the machine will not turn at all, so there is an energy loss at each end of the speed spectrum—though variable-pitch machines can sidestep this limitation to some extent.

The annual output of energy supplied depends on the actual wind behaviour, in detail, at the site and upon the design of the machine. These factors cannot be taken fully into account in energy estimations made from wind survey data giving only hourly wind speeds. But one procedure that can be followed, and that is not likely to lead to any misconceptions provided you realize its limitations, is recommended by Golding and is as follows:

i) Relate the results of the wind speed measurements made during a relatively short period—one or two years—to the long-term wind regime at the site so that a velocity-duration curve can be drawn.

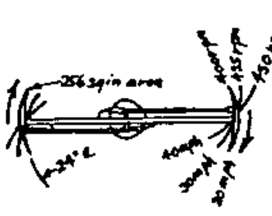
ii) Cube the ordinates of this curve to give the power duration curve for the site (since power is proportional to wind speed cubed).

iii) Estimate the specific output, T_s (expressed in kilowatt hours per annum per kilowatt of installed capacity) corresponding to a given 'rated' wind speed V_p. The rated wind speed is that at which the wind-driven generator gives its full rated power.

WINDMILL USES

◆ ***Pumping and mechanical applications*** For pumping, any type of wind machine is suitable. The specific type chosen depends upon whether the

Fig 25c. Patented air-brake governor used on Dyna Technology's Wincharger machines. Centrifugally operated flaps automatically open and spread the wind away from propeller, when the wind speed exceeds 25 mph. Governor also acts as a flywheel.



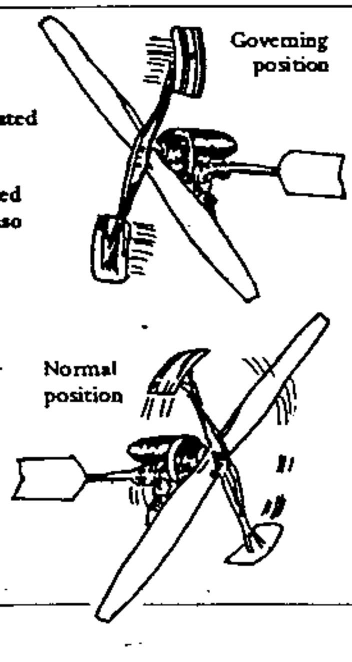
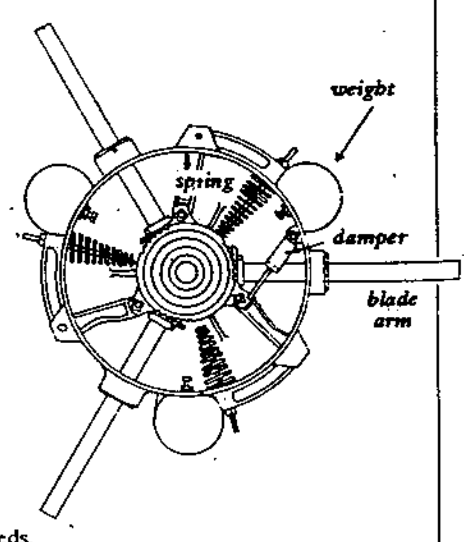


Fig 25d. Patented centrifugally operated variable pitch mechanism used on Jacobs machines. Consists of a set of centrifugally operated weight carrying members. As the wind/prop speed increases the weight is thrown outwards which in turn throws out the lever arm, which rotates the hub gear which engages into the blade arm gear and so adjusting the angle of the blade to spill excess energy at high wind speeds. This device can also be used to enhance starting at low wind speeds.



most frequent wind speeds are low or high, and the skills, material and money available.

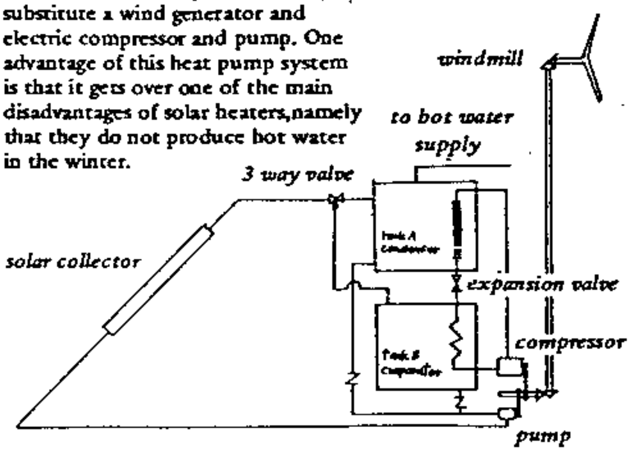
If simplicity of construction is required and the wind regime is mainly one of steady, low wind speeds, then go for a Savonius rotor, Greek-type sail mill, or one of the battle axe or multiblade types. If the wind direction is constantly changing with low wind speeds, then a vertical axis machine that can make use of winds from any direction, such as (again) a Savonius, a simple panemone (II.a.2), or a transverse flow machine (I.b.2) may be more suitable.

If more money is available and steady, relatively high speed winds are experienced then propeller-driven machines will be more suitable. If the wind speed is high, yet the direction of windflow is constantly changing, then the Darrieus vertical-axis turbine, or possibly transverse-flow machine, may be the most satisfactory. For mechanical purposes—such as driving machine tools, milling, compressing air and so on, the same basic criteria as for water pumping apply.

◆ *Electricity generation* Because of the high rotation speed of most normally available generators, and to avoid very high gear ratios, the preferred types of wind machines are limited at the present time to the propeller and Darrieus types—and possibly transverse-flow machines. But these machines do not normally cut-in at low wind speeds, so light winds are effectively wasted. This situation is unlikely to change until some clever electrical engineer comes up with a slow-speed generator which is not of prohibitive size and weight (preferably self-built). This could allow slow winds to be harnessed for electricity production by slow but high-torque machines like the multiblade, Savonius, or Greek-type sail mill.

◆ *Vapour compression* Another use to which a wind machine can be put is to drive the compressor of a heat pump (see Fig 26). This overcomes one of the disadvantages of the heat pump, namely that of dependence on the National Grid for electricity to drive the compressor: the efficiency of power generation on the National Grid is so low that it is probably more efficient to use the fuel which

Fig 26. Windmill used in conjunction with a heat pump cycle having as its heat source solar heated water.
Because of the compressor's particular characteristics it may be necessary to substitute a wind generator and electric compressor and pump. One advantage of this heat pump system is that it gets over one of the main disadvantages of solar heaters,namely that they do not produce hot water in the winter.

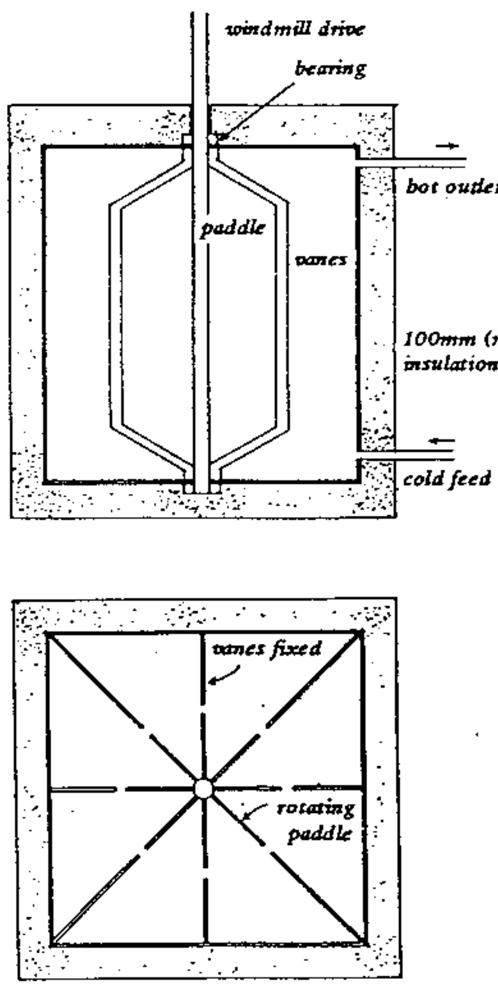


produced the electricity directly for heating on the premises.

One problem with using wind machines to drive heat pumps is that compressors usually have to be driven at a constant speed, whereas a windmill's rotation is irregular—but this problem is probably surmountable.

◆ *Heating water by hydraulic braking* A more direct way of turning wind energy into heat is by creating turbulence in a fluid—a wind-driven version of Joule's classic mechanical equivalent of heat experiment. A simple way to do this would be to couple the wind machine to a paddle rotating in a well-insulated tank of water with inward-projecting vanes to generate turbulence and frictional heat (Fig 27). This will have a braking effect on the wind machine which at low wind speeds would be a disadvantage (and anyway the small quantities of heat developed would not be worth collecting); but at high speeds, such hydraulic devices could simultaneously regulate the machine and make good use of the considerable amounts of energy. The range of wind speeds over which the machine can usefully operate could be extended. Some forms of hydraulic brake have a cube power braking characteristic which matches the cube relation of wind speed and wind energy very well, and these would seem to be particularly appropriate for use in areas where high wind speeds are common. The idea is being explored by David Stabb, Simon Longland and others.

Fig 27. Hydraulic brake.



ORIENTATION SYSTEMS

Horizontal-axis machines need to be kept facing into the wind. Some of the possible orientation systems are as follows:

a) A tail vane mounted downwind from the rotor, which keeps the rotor facing into the wind by an action similar to a rudder on a boat (see for example Figs 11, 12 and 14). Most small wind power plants are oriented by this mechanism.

b) If the blades are angled to point slightly downwind of the mast or tower, the wind pressure on them makes the machine self-orientating. This principle is used in two of the wind generators designed by Windworks, and on the wind generators and wind pumps produced by Lubing (see Fig 28).

c) Fantails. These are mounted on a plane perpendicular to the main rotor, and are in effect small windmills, usually of the multiblade type. They are rotated by any cross wind and drive a reduction gear which orientates the main rotor into the wind. This was one of the main orientation systems of the traditional tower mill (Fig 29), and is still used on some large modern wind generators.

d) Rotating mast. Instead of just pointing the machinery at the top of the mast into the wind, the whole mast can be rotated. The Brace Research Institute's 32 ft diameter airscrew windmill is oriented in this way (see Fig 33). But it does not turn automatically, and has to be moved by means of a hand crank driving a truck crown wheel and pinion at the base. This method is obviously not as suitable as the automatic control offered by systems a, b and c.

There are several other ideas for orientating windmills—'yawing' motors, electrically or hydraulically driven; rotatable tripods with two of the legs carried on bogeys which run around a circular track, while the third rotates in the centre of the circle; or even floating the rotating part on water. But most of these suggestions are rather complicated and are really only suitable for large scale machines—which are of dubious value in any case.

BLADES AND SAILS

The blades of windmill propeller rotors are usually shaped in the form of one or other of the conventional airfoils, some of which are:

NACA 0015 Used in the ERA's 100kw wind generator, erected in the Orkneys in the 1950s.

NACA 2418 Used in the US War Production Board wind turbine project.

NACA 4415 Used in the Brace Research Institute's 10m diameter airscrew wind turbine.

Clark Y Used in Jim Sencenbaugh's 'O_2 Delight' self-build wind generator design. (See 'Designing Windmill Blades' by Alan Altman, *Alternative Sources of Energy* no.14.)

Wortman FX 60–126 Used in Hans Meyer's 10 ft diameter, self-build wind generator design (see *Popular Science*, November 1972, p.103).

Wortman FX 72–MS150B Used in Hans Meyer's 12 ft diameter self-build wind generator design.

Fig 28.

Juul (Gedser Mill) Airfoil (similar to Clark Y) Used on Gedser mill in Denmark in 1958 (the profile is given in Vol.7 of the *Proceedings of the UN Conference on New Sources of Energy*, 1961, p.233.)

Data about NACA and Clark Y airfoils can be obtained from *Theory of Wing Sections* by Ira Abbott and Albert von Doenhoff (Dover, New York, 1959) and data about the Wortman airfoils from *Stuttgarter Profilkatalog I* by D. Althaus (Institut fur Aerodynamik und Gasdynamik der Universitat Stuttgart, 1972). Details of the Lejay Manufacturing Co.'s designs for 6 to 10 ft windmill propellers are given in Fig 24.

The blades themselves may be solid; fabricated (skin covering a skeletal framework); or of the sailwing type described previously. They may vary in number from two to twelve or more but the optimum number of blades is three. They may either be tapered or of the same chord-width throughout their length, and may be of plane form or twisted. Their pitch may be variable or fixed, and they may be rigidly mounted or allowed to 'cone' or 'drag' in the wind, to relieve the stresses set up by rapidly changing wind speeds.

◆ *Blade construction* The material used for blades must be strong and yet light weight, and must not be subject to serious deterioration in bad climatic conditions.

Wood is an ecologically-sound blade making material although it is becoming harder to obtain, and more and more expensive. Its use encourages over-exploitation of timber resources—especially in the Third World, where little replenishment is

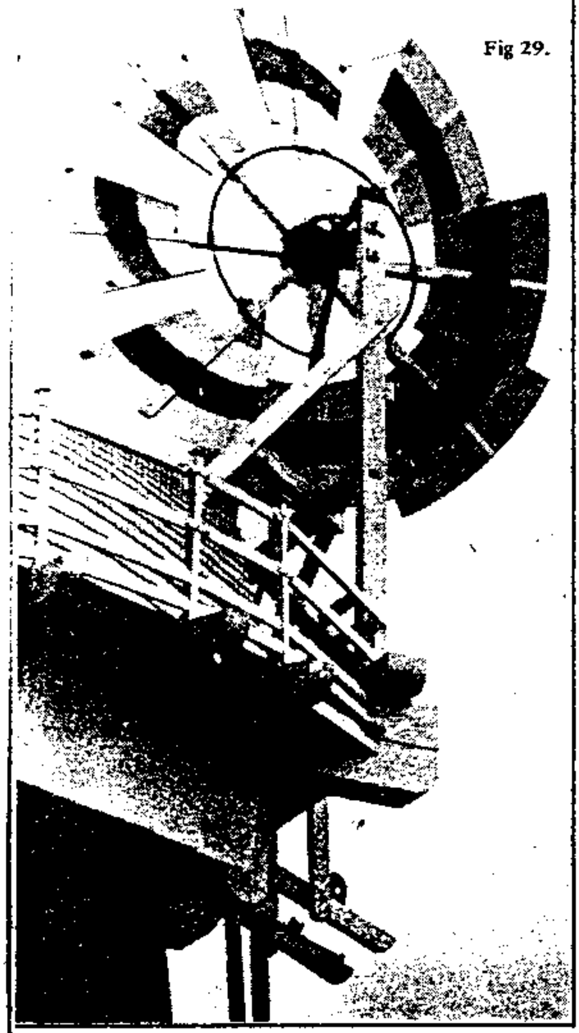
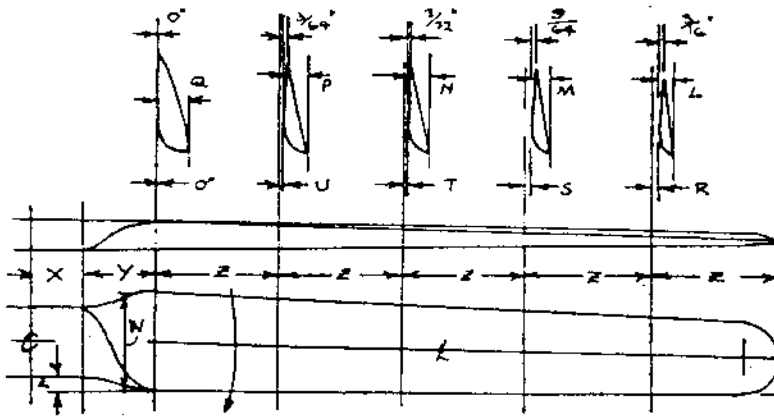


Fig 29.

Fig 30. Leejay design wooden propeller blades for diameters from 6ft to 10ft.



	Z	Y	X	W	V	U	T	S	R	Q	P	N	M	L
6ft. dia. prop	6"	3½"	2½"	4½"	2¾"	1/16"	1/8"	3/16"	1/4"	3/4"	21/32"	9/16"	15/32"	3/8"
7ft. „ „	7"	4"	3"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"
8ft. „ „	8"	4"	4"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"
10ft. „ „	10"	5"	5"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"

Blades are carved out of the plank by means of plane, saw, spokeshave and sand paper. The blades should be protected by sealing against moisture with about five coats of enamel or varnish, and rubbing with wet and dry emery paper between each coat. The tips also have to be protected by means of metal foil or a standard metal tip designed for aircraft propellers.

DEREK TAYLOR

taking place and soil erosion is the consequence. Why not plant some trees and put some wood back?

Timbers approved for aircraft propellers are: walnut; some mahogany; Queensland silk wood; ash; iroko; and silver spruce. As a general rule, timber used for propeller construction should not weigh more than 40 lbs per cu ft. Specifications for walnut, mahogany, ash and spruce, together with details of methods for testing timbers, may be obtained from the British Engineering Standards Association. Wooden blades need protection at the tips, due to the high tip rotation speed, and there are several sizes of standard brass tip available.

Wooden blades can be made by anyone with a plane, spokeshave and patience, and are very suitable for small wind machines (see Fig 30). But various other materials and systems have been developed to reduce the weight.

Fabricated blades The process of making this type of blade will be familiar to any model aircraft builder. It consists of covering a skeletal framework with a fabric which is then toughened by aircraft dope, plywood—or even paper, if a tough enough grade is found. Great care is needed for this method of construction and it is generally not worthwhile for propellers under 2 metres in diameter.

Fibreglass blades Fibreglass is a relatively light, fairly easily manipulable and mouldable material, and fibreglass skills are nowadays quite well distributed throughout the population, thanks to do-it-yourself car-body repairing and boat-building. Such blades are weather-resistant and light in weight.

Expanded paper blades In this method of construction, honeycomb paper is cut with a bandsaw to the required shape, then the honeycomb is expanded along the length of the blade shaft (usually a metal tube), and 'jigged' to give the blade the desired angle of attack. When the honeycomb is in the required position, the blade is covered with a fine-weave fibreglass cloth, followed by fibreglass resin. This simple and cheap method of constructing precision airfoils was developed by Hans Meyer and Ben Wolff of Windworks.

Expanded polystyrene and urethane core blades This method is similar to the previous one, and consists of cutting the core into the required profile (this can be done with a hot wire), and then covering it with fibreglass cloth and resin. The process is similar to that used for surf-board construction.

Metal blades Metal blades are not really suitable for self-build, small-scale propeller-type wind machines. But simple, bent-metal blades can be used in multiblade designs. Metals and plastics are not only large consumers of energy in their production, but the processes involved tend to be very polluting, so these materials should be avoided as far as possible. Otherwise, only recycled scrap metal should be used.

◆ *Sails* Sails usually consist of a sheet of canvas—as employed, for instance, in Greek-type sail mills, the sails of traditional English mills, and sail panemones of the Chinese type. But they can be of the 'Venetian Blind' type; or with roller shutter sails (some of the later traditional mills and early electric mills were of this type); or with wooden sheets, as on the 'battle axe' or 'Jumbo' mills.

TOWERS

The power available from wind increases with height and is more constant above the level of surrounding obstacles such as trees and houses. It is not a good idea to instal a horizontal-axis windmill permanently on a roof unless the roof has a streamlined top. So it is more-or-less necessary to have a supporting mast or tower of some sort.

Telegraph poles (see Fig 31) if available, and scaffold tubes to some extent, are suitable for small-size machines but otherwise a lattice tower will have to be constructed.

The type of tower chosen should be one that calls for the minimum of technical skill in construction. A simple lattice tower with three or four legs, depending on relative costs, can be made of timber, as in Jim Sencenbaugh's self-build design (Fig 32), or one of the Brace timber lattice masts (Fig 33). Or, more commonly, of steel (Fig 34)—although this is not so suitable for the self-builder, unless an old electricity pylon or a floodlight, railway signals or radio mast can be scrounged.

Monolithic concrete towers have been used for many of the Danish wind generators, and although they are relatively attractive in appearance (they resemble somewhat the old traditional windmills) they are rather expensive and suffer from vibration problems (at least when constructed on a large scale).

The Brace Research Institute has done some work on concrete *block* towers, which worked out cheaper than steel towers, but like masonry towers they may suffer from vibration problems, and obviously they are more permanent and less portable than lattice masts.

Hans Meyer has designed an attractive 30 ft tall octahedron module tower made of 250 ft of one inch electrical conduit tubing (see Fig 35); it could also be made of bamboo struts.

Another useful tower idea is to use a telescopic mast, as Villinger in Germany have done. Brace have also explored the possibilities of these masts.

The actual erection of a mast can be made much easier by the use of a 'gin pole', as shown in Fig 36.

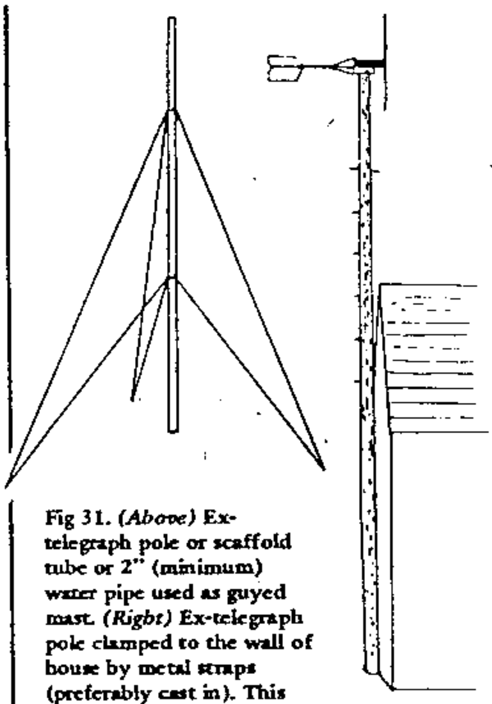


Fig 31. *(Above)* Ex-telegraph pole or scaffold tube or 2" (minimum) water pipe used as guyed mast. *(Right)* Ex-telegraph pole clamped to the wall of house by metal straps (preferably cast in). This method must be done extremely carefully and only with small wind machines as brick and masonry walls are weak in shear. Metal tube such as scaffolding or 2" water pipe could also be used for small units.

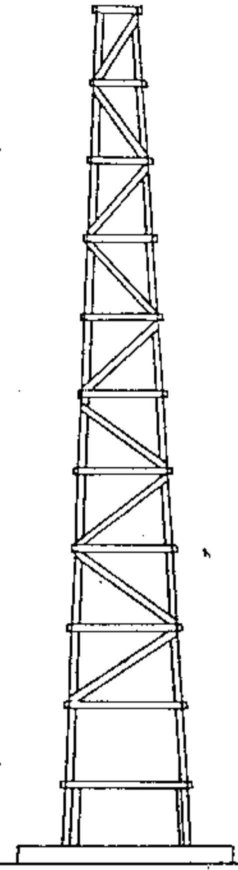
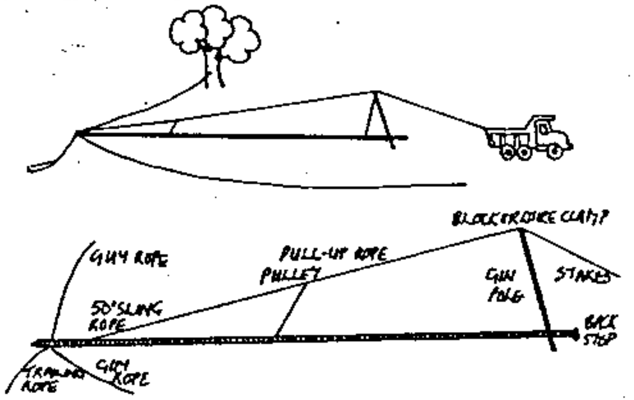


Fig 32. Timber lattice tower, plans for which are available together with working drawings and specifications for 'Sencenbaugh O_2 Delight' wind generator, from Jim Sencenbaugh, 678 Chimalus Dr., Palo Alto, California, USA for $15.

Fig 36. Erection of mast with the use of a gin pole, from *Alternative Sources of Energy*, No. 14 p. 9.



GENERATORS

For small scale wind machines the most popular generators are car alternators or dynamos, both of which are widely available from car breakers. Another useful idea is to run electric motors in reverse as generators.

◆ *Car alternators* Car *alternators* have several advantages over *dynamos* for use with wind turbines. They start producing an electrical charge at low revs, they are lighter, generally have higher outputs, and offer less rotational resistance than dynamos.

They consist, basically, of a magnet within a coil of wire. When the magnet is rotated by the rotor, an alternating current (AC) is produced which is then rectified to direct current (DC), electronically, by diodes.

Alternators should not be used without a battery in circuit, otherwise they may burn themselves out. Some types of alternators need to be 'energized', before they will start to charge, so the battery used will have to have some charge in it; in such cases a wind pressure operated micro switch must also be in circuit, which will energize the field coils from the battery.

Because of their greater sophistication and their use of electronic components, alternators tend to be rather more expensive than car dynamos—although I bought a brand new Prestolite 35amp alternator for £15 and a second-hand Lucas 11AC 45amp alternator for £8.

Types of car alternator available in the UK Lucas: 10AC—35amps; 11AC—45amps; 11AC—60 amps (uprated version). All work at 12 volts and are battery-excited. Lucas: 15ACR—28amp; 16ACR—

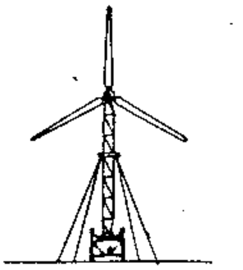


Fig 33. Brace tubular lattice tower (rotatable). Plans are available from Institute.

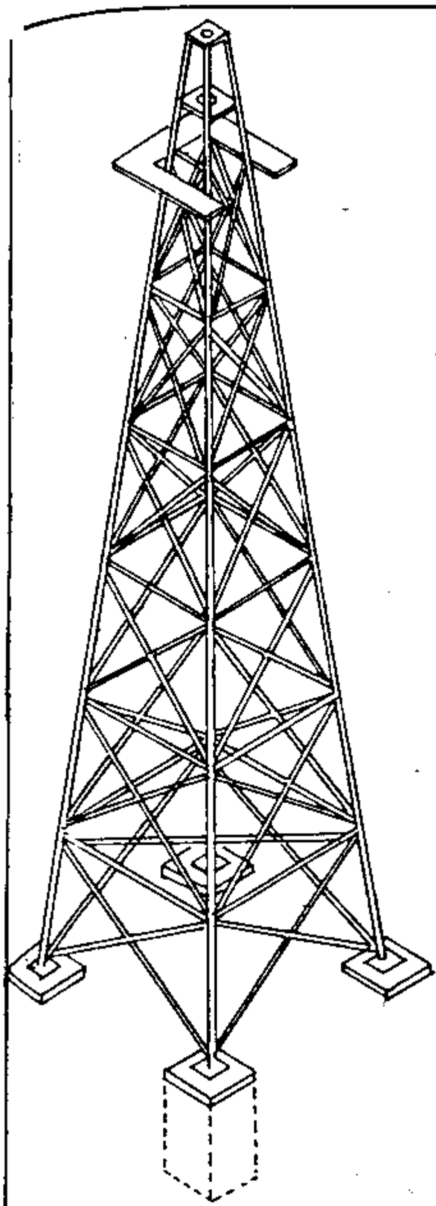


Fig 34 (Above). Typical metal lattice tower used for windmills. This particular example is made from galvanised steel angle designed in various heights from 19'0" to 61'0" for their 'Hercules' wind pump by H.J. Godwin Ltd, Quenington, Gloucestershire.

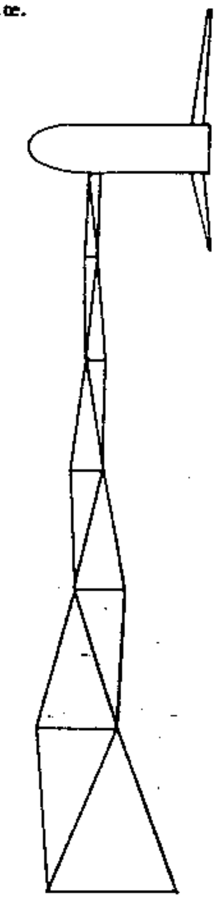


Fig 35. 30'0" High Octahedron Module Tower Designed by Windworks for their '12 Footer' wind generator plans, and made from 250'0" of 1" electrical conduit tubing.

34amp; 17ACR–36amp; 18ACR–43amp; 20ACR–66amps. These work at 12 volts, are self exciting. Refer to Lucas manual on *Alternators* for details (Joseph Lucas Ltd, Birmingham B18 6AU, England). Prestolite (Smiths): 1235–35amps; 1245–45amps; 1260–60amps; all work at 12 volts and are battery excited. Dodge Dart: 45 amp (max) at 12 volts, battery excited. Motorola: 85A2004R–85amp at 12 volts, battery excited.

For outputs greater than one alternator can produce, you can couple several to the windmill. This approach has a certain advantage over the use of larger generators—namely that you can run just one alternator when the wind speed is low, which offers less resistance to the windmill.

◆ *Car dynamos* Car dynamos are more widely available and cheaper than alternators (you can pick up a reconditioned dynamo for £5) and the circuits are simpler, but they 'cut in' at a higher rpm than do alternators, so higher gear ratios are required. Their output is much lower (the maximum output for most car dynamos is around 22amps at 12 volts), they tend to be much heavier than alternators, and they offer more resistance to the rotor. But they have often been used successfully —it really depends on how much power you want, what's available and how much you have to spend. Dynamos are also suitable for reversing and running as 12 volt DC motors, which could be useful for providing 12 volt power tools.

The most common car dynamos in Britain are the Lucas C40 range.

Another possibility is to cannibalize a petrol or diesel generating set and use the generator, geared-up sufficiently, coupled to the windmill. But unless you happen to find a dumped one, such generators are not cheap, and they usually produce 240 volts AC, which is difficult to store in batteries.

Although scrapped cars are a good source of alternators and dynamos, and although they are put to better use on a user-controlled non-polluting wind machine than on a polluting and energy-consuming motor car, the concept of autonomy in wind-produced electricity is undermined by this dependence on high technology industry for electrical components. Until some progress is made towards the construction of slow-speed alternators and dynamos from scratch, wind generator builders are not going to make much of a dent in the capital-intensive industries, however much they pretend they are independent of them.

ENERGY STORAGE

◆ *Batteries* At the moment, the main type of storage available is the electric battery; and the choice is more-or-less limited to batteries of the lead-acid or alkaline (nickel-cadmium or nickel-iron) type. Lead-acid batteries have the shorter life but alkaline types are more expensive.

The lead-acid battery *can* be designed to be recycled easily. This still cannot be done with most of the present designs of car battery, where the cases have to be axed apart, then thrown away, and only the lead reclaimed. Several lead-acid types are available—to suit every application, from cars to tractors, lorries, buses and industrial emergency power supplies.

The capacity of batteries is measured in ampere hours (AH). A 300AH, 12 volt battery can supply 300 amperes at 12 volts for an hour, that is 3.6kWh (12 x 300) of energy. The battery's life will depend not only on the sort of battery but also on the discharge rate. If a battery has to supply a heavy load, it discharges rapidly and it will have a short life. The life of a battery is usually measured by the number of charge-discharge cycles it can cope with. If a battery has a lifetime of approximately 1,000 cycles (car batteries have a typical life of 750–1,200 cycles) and each cycle takes four days, then the battery will last for about 4,000 days. For maximum life, the lead-acid battery should never be more than half discharged.

◆ *Pumping water uphill* Because of its fairly low efficiency and the relatively large volume of water needed to store a given amount of energy, this system seems to be suitable only for use in conjunction with a small-scale water power installation, or on sites near to large volumes of water, such as lakes, rivers and reservoirs, or sites where there is a large difference in height, such as wells, mine shafts, or quarry pits. Basically, a pumped storage system works by raising water from one level to another by means of a wind driven pump, and then, when electricity is required, letting it drop to the original level through a water turbine connected to a generator. The technology required is relatively simple and fairly well developed, but overall storage costs may be high.

◆ *Compressed air* This method depends on storing the wind's potential as compressed air, retaining it in a gasometer, and, when energy is required, releasing it to drive air turbines, coupled to a generator for electricity production or integral with the appliance for which energy is required. The technology of air turbines is quite advanced, especially in dental and mining equipment. The main problem is the prohibitive volume of the storage and the need for a robust pressure-vessel.

◆ *Fly-wheels* Fly-wheels are a method of storing potential energy mechanically, in the momentum built up by a spinning mass. There have been several developments in fly-wheels in recent years, mainly on a high-technology level. High-speed fly-wheels need stringent quality control in manufacture to avoid the risk of failure, which can be catastrophic. Some work has been done on running fly-wheels in a vacuum, which improves the efficiency considerably by eliminating air resistance. But fly-wheels are still uneconomic for most applications at the moment.

◆ *Hydrogen* If the electricity produced from a wind generator is used to break down water by electrolysis, hydrogen is produced. This can be used as fuel to drive engines (and if these are fitted with water jackets to reclaim waste heat, their efficiency is improved). Hydrogen-powered engines may be designed for dual-fuel use, to operate with methane or alcohol, produced from fermentation of organic wastes, as well as hydrogen. The engine may be coupled to a generator for electricity production; or the gas can be used for cooking, and possibly for limited heating applications.

Hydrogen can be stored in the form of gas in gasometers. But the stuff has to be treated with extreme caution as it is extremely inflammable and highly explosive. Work is being carried out into storing the hydrogen in the form of solid hydrides, which are much less inflammable. Hydrogen as a fuel is more environmentally desirable than most other fuels as it causes very little pollution: on combustion only water is produced.

Research is also going on into producing electricity directly from hydrogen using fuel cells, in which hydrogen and oxygen are brought together in a chamber, and water and electricity are produced. But because fuel cells use rare metals as catalysts and operate at high pressures, the technology involved is very advanced and currently prohibitively expensive.

CONCLUSIONS

Well I hope that I have convinced you that the wind has enormous potential which is totally under-exploited. I've tried to cover most of the aspects and some of the problems. But before you dash off and build your windmill and tap into this new-found energy, make sure your home is well insulated, re-examine the appliances you really need, and which could be muscle operated, and decide whether you really require heat energy or electricity. All these decisions will affect the size of the windmill. The other thing to aim at is a combined system of energy provision—ie solar, wind, waterpower, biological waste fermentation, and muscle power, etc so that the whole energy system in the dwelling does not break down when one source is not producing.

Finally make sure your windmill blades and mast are well anchored as a broken flying blade or falling mast can be lethal and cause a lot of damage.

Happy windmilling.

Derek Taylor

GLOSSARY OF WIND POWER TERMS

Aerofoils (or Airfoil)
Wing, sail or blade which is shaped to produce lift at right angles to the direction of airflow. In cross section the upper surface is curved in a convex camber, while the lower surface usually has either a concave camber or flat surface, unless it is a symmetrical aerofoil, in which case it has a convex camber on both surfaces.

Anemometer
A device used for measuring the speed of the wind.

Chord (or Chordwidth or Chordlength)
The distance from the leading edge to the trailing edge of the aerofoil, ie the width of the blade. A constant chord width is a blade whose width is constant from root (or hub) to the tip.

Horizontal Axis Windmill
A windmill whose drive shaft is horizontal as in traditional European windmills.

Inverter
An electronic device for converting direct current to alternating current.

Power Coefficient
The ratio of the power output from the windmill to the power available from the upwind of the windmill. It can be construed as a measure of the efficiency of the windmill. It will vary from windmill to windmill but is unlikely to exceed 0.63.

Golding gives this expression

$$cp = \frac{\rho \frac{A}{4} V_1^{\,3} \left[\left(1 + \frac{V_2}{V_1}\right)\left(1 - \left(\frac{V_2}{V_1}\right)^2\right]\right.}{\rho \frac{A}{2} V_1^{\,3}}$$

$$= \frac{\left(1 + \frac{V_2}{V_1}\right)\left(1 - \frac{V_2}{V_1}\right)^2}{2}$$

Where ρ = density of air
V_1 = velocity of wind upwind of windmill
V_2 = velocity of wind downwind of windmill

Overall power coefficient = electrical power output ÷ power in the wind for swept area

Rated Wind Speed
The lowest windspeed at which full power is produced. At higher windspeeds this output is limited by the controlling mechanism to this full rated windspeed. The outputs of small wind units vary depending on the rated windspeed for which they are designed, and this rarely exceeds 30 mph.

Rectifier
An electronic device which converts alternating current into direct current.

Tip Speed Ratio

$$\frac{\text{speed of rotation of blade tip}}{\text{windspeed}}$$

Vertical Axis Windmill
A windmill whose drive shaft is vertical.

Watts
A unit of power equal in electrical terms to Volts x Amps:
1 kW = 1,000 watts = 1.34 horse power; (the power given out by a one-bar electric fire).
1 horse power = 0.746 kW;
1 kWh = 1 kW consumed for 1 hour.

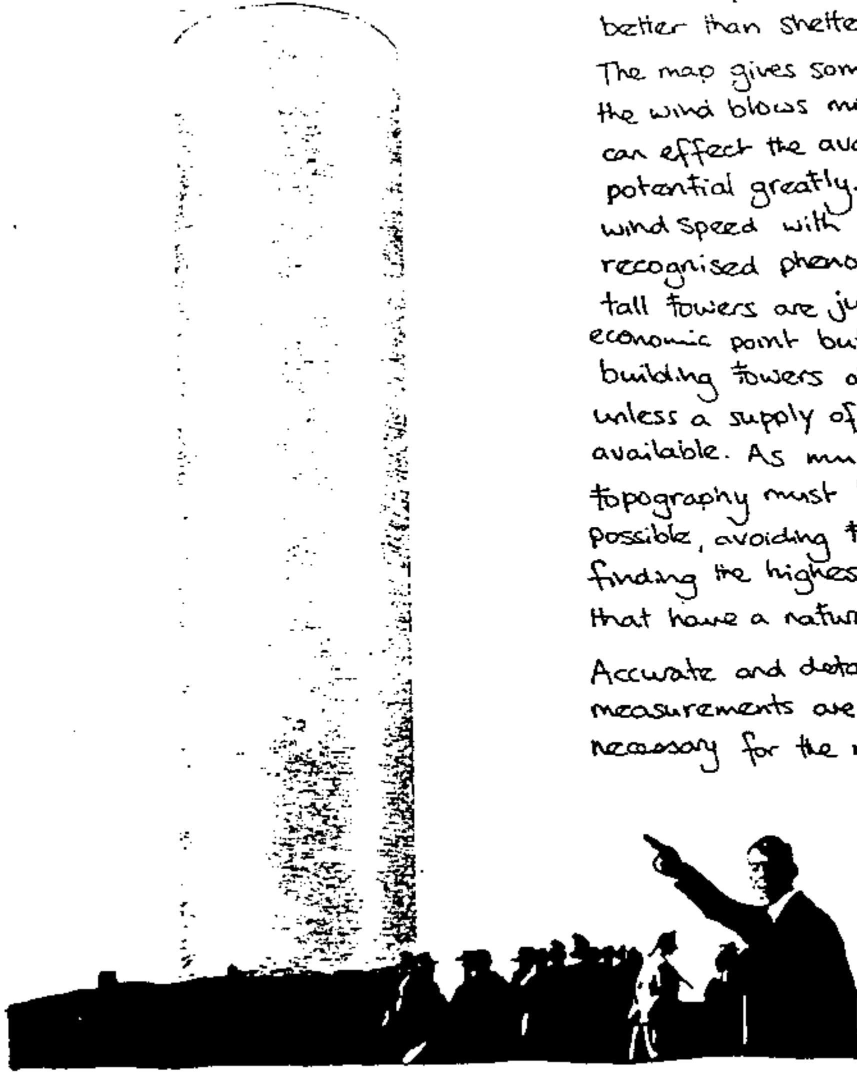
WIND

is possibly the best free energy source in the North East of America + British Isles. There are few places where some kind of wind driven machine will not be of use; but of course open windswept places are far better than sheltered valleys.

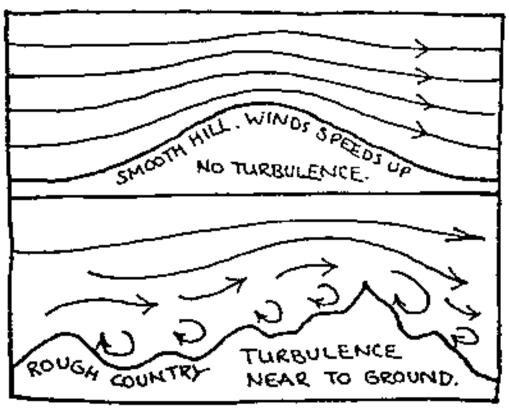
The map gives some overall idea of where the wind blows most. Local conditions can effect the available wind power potential greatly. The increase of wind speed with height is a well recognised phenomena. How much tall towers are justified is a complex economic point but it is generally not worth building towers of more than 50 foot unless a supply of suitable material is available. As much use of the local topography must be made as is possible, avoiding turbulent spots and finding the highest and most exposed places that have a natural wind funneling effect.

Accurate and detailed wind speed measurements are, however, only necessary for the more sophisticated and larger windmills rather than the 'run of the mill' homemade machine.

A 2 blade turbine of 6 foot diameter will equal the human output of works in a moderate 10 m.p.h. breeze



left: test of prototype Madaras rotor, Burlington, New Jersey. 1933.



The power that exists in kinetic form in a current of air of cross-section A is;——

$$\text{Power (usable)} = K \times A \times V^3$$

*K = constant of efficiency .06
V = wind speed.

POWER AT A GLANCE in watts

WIND VELOCITY in M.P.H.							
5	0.6	:	2	4	5	10	15
10	5	11	19	30	42	75	120
15	16	36	64	100	140	260	400
20	38	85	150	240	340	610	950
25	73	160	300	410	660	1180	1840
	2	3	4	5	6	8	10

DIAMETER OF MILL in feet. (2 blade high speed type)

thanks to Ed Trunk + Mother Earth News 17.

WIND ONE

Preliminary Notes:

Wind Measurements on a site are of 3 classes. 1. long term measurements to determine possible power output. 2. Medium term to establish wind structure in various weather conditions to enable a choice of wind unit. 3. Short term to determine detailed mechanical characteristics esp. with respect to gusts.

Apart from average wind velocities an important measurement is the maximum wind speed which determines the stresses that must be withstood by the machine.

Much valuable information on wind speeds and directions already exists in the records of national meteorological services, although these are general and do not take interest in the most exposed windiest sites. Uses are.

i) Areas of highest wind speeds.
ii) Direction of prevailing wind.
iii) Measure of constancy, or variability of year to year wind speed.
iv) As an indication of the annual wind regime
v) Measure of the maximum speeds and duration of calm spells.

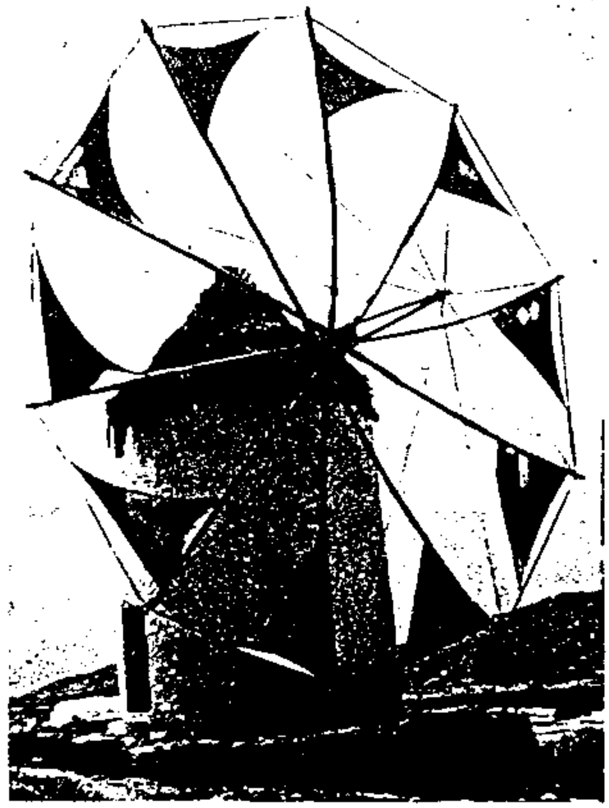


photo courtesy of the Museum of English Rural Life, Univ. of Reading. Shows Mediterranean type mill with adjustable sails.

Note: SAFETY WARNING DANGER
Great care must be taken with home-made wind machines near habitation, especially in towns, on account of their persistent habit of disintegrating at high speeds and showering a wide area with a deadly shrapnel of windmill parts. Test your machine thoroughly in hurricanes out of harms way. Always turn off machines when you are not around unless a foolproof automatic governing and cut-out device has been attached.

❋ Sails are safest.

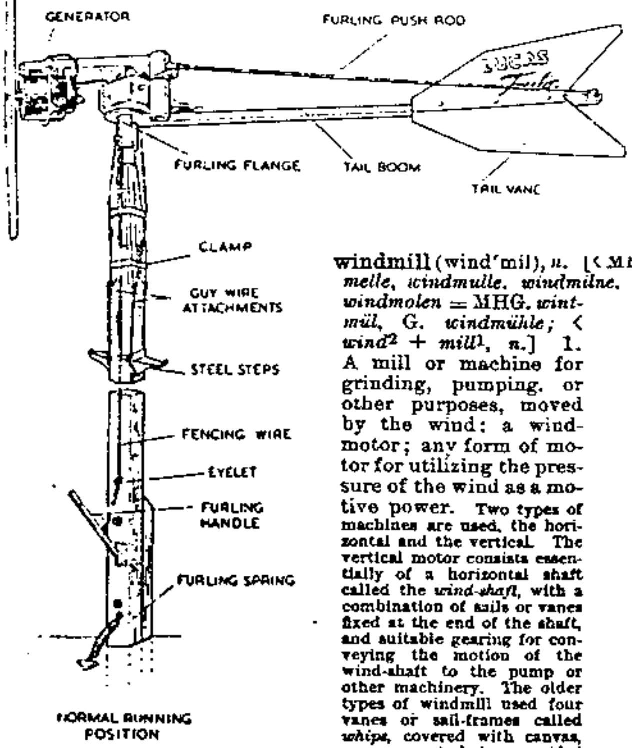
❋ 2½" ordinance Survey maps show wind pumps like this: Wd.Pp. Even if they don't exist now there may be old bits in the barn or old folks with useful memories. Investigate.

❋ Wind speeds are likely to be higher in winter than summer.....which is useful.

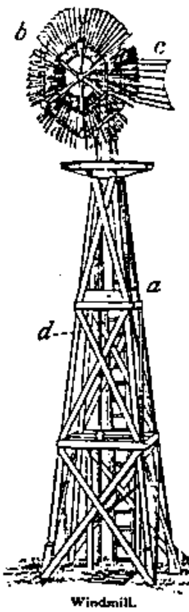
HOLLANDSCHE MOLENS — WIND MILLS

At one time there were over 12,000 mills operating in Holland — average output 8hp.

CLASSIFICATION of WINDMILL TYPES.



Construction of Lucas "Freelite" wind-driven generator 1940s

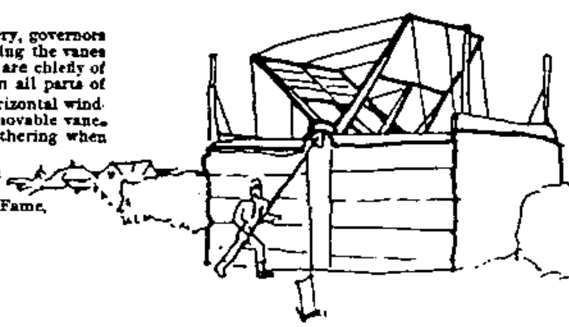


Windmill.
a, frame; *b*, sails; *c*, vane; *d*, pump-rod.

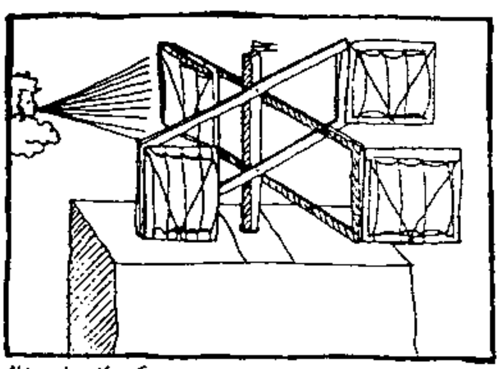
windmill (wind′mil), *n.* [< ME. *windmille, windmelle, windmulle, windmilne, wyndemylne* = D. *windmolen* = MHG. *wintmül*, G. *windmühle*; < *wind*² + *mill*¹, *n.*] 1. A mill or machine for grinding, pumping, or other purposes, moved by the wind: a wind-motor; any form of motor for utilizing the pressure of the wind as a motive power. Two types of machines are used, the horizontal and the vertical. The vertical motor consists essentially of a horizontal shaft called the *wind-shaft*, with a combination of sails or vanes fixed at the end of the shaft, and suitable gearing for conveying the motion of the wind-shaft to the pump or other machinery. The older types of windmill used four vanes or sail-frames called *whips*, covered with canvas, arrangements being provided for reefing the sails in high winds. To present the vanes to the wind, the whole structure or tower carrying the windmill was at first turned round by means of a long lever. Later the top of the tower, called the *cap*, was made movable. Windmills are now made with many wooden vanes forming a disk exposed to the winds, and fitted with automatic feathering and steering machinery, governors for regulating the speed, apparatus for closing the vanes in storms, etc. These improved windmills are chiefly of American invention, and are largely used in all parts of the United States for pumping water. Horizontal windmills employ an upright wind-shaft, and movable vanes placed in a circle round it, the vanes feathering when moving against the wind.

> I saugh him carien a *wind-melle*
> Under a walshe-note shale.
> *Chaucer*, House of Fame,

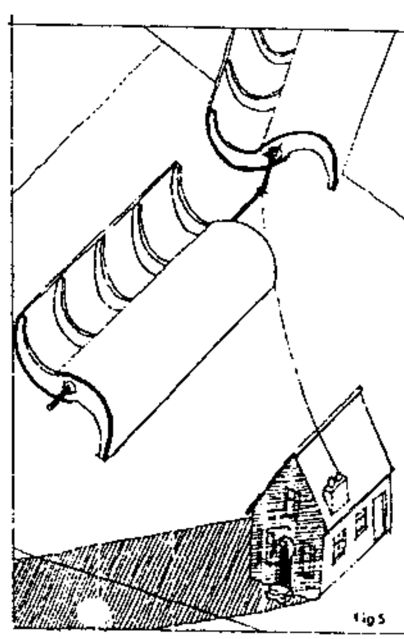
Old Windmill at Bridgehampton, New York.



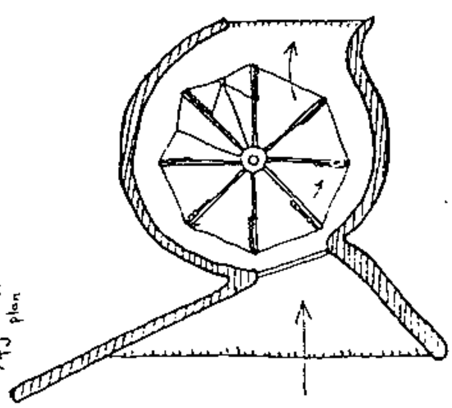
Lincoln, Nebraska 1890s



Hinged sails of canvas. Veranzio 1595



Steebles Flying Rotor 1980s



Afghanistani ducted mill, 1970
plan

TYPES

WINDMILL EFFICIENCY

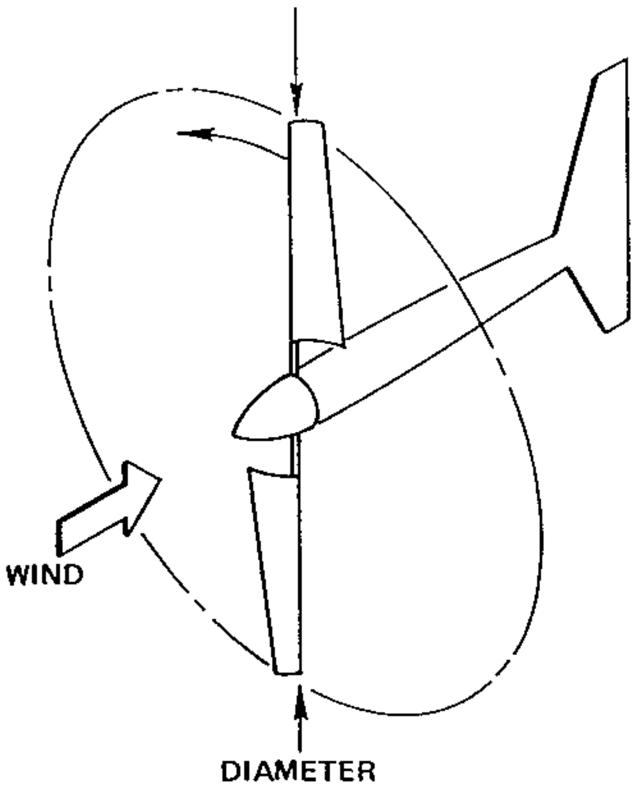


Figure 3A Horizontal Axis Windmill

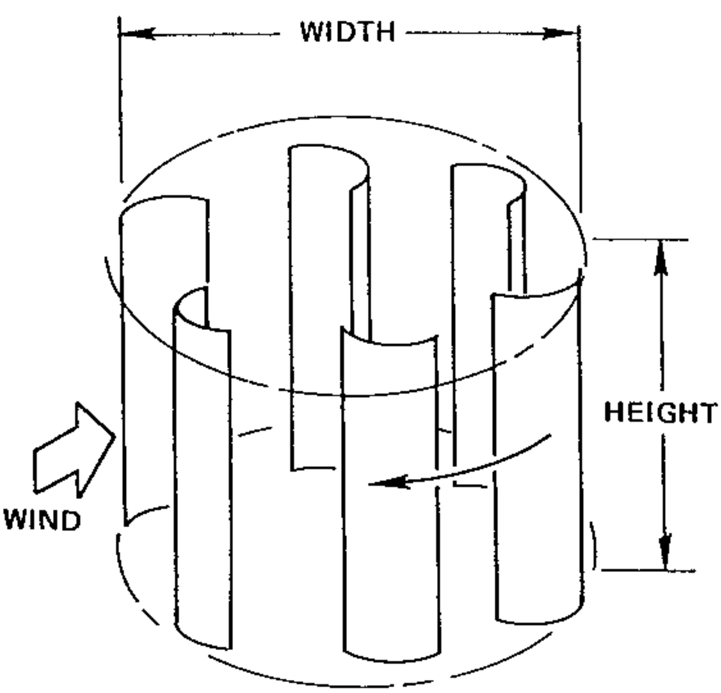


Figure 3B Vertical Axis Windmill

The previous calculations called for a value of the efficiency factor. Since no manmade device is ever 100% efficient at doing whatever it is designed for, we must either assume a low value of efficiency in the interest of conservative design (a sort-of guarantee that we'll get the power we need), or find some means of reliably estimating a value of E that corresponds to our particular windmill design. A windmill extracts power from the wind by slowing the wind down. If the wind could be stopped completely by a rotating device, then 100% of the wind power could be extracted. The wind cannot be stopped; it is only slowed down by about a third of its original speed, which means that the actual theoretical maximum wind power available to a windmill is 59% of the total.

Now, how much of the 59% of the total wind power is actually extracted? This depends on the design of the windmill, the gear losses, the degree of accuracy with which the builder of the machine reproduces the necessary shape and size, and so on. Obviously 59% is still only theoretical. Practical values of overall efficiency, the E in our formula, lie between 0.1 (or 10%) and 0.4 (40%), not much more. By using real values for E in our calculations for horsepower or watts, the result will be real, attainable values of windmill power.

We shall explore several examples of these calculations in use following an explanation of how to estimate E. The actual value of E depends on the type of windmill design used and a factor of speed ratio, which we shall discuss now.

Windmills, as discussed in this text, generate power while rotating. Rotation means that windmill components near the center or rotation will be moving relatively slowly, while portions near the outer edges (tips) will be moving faster, in proportion to the distance from the center of toration (radius). See Figure 4.

This gives a chance to discover a speed ratio which will be used in future calculations: u/V ratio (called u-over-V ratio) is simply the speed of any area of a windmill such as the tip of the blade divided by the wind speed. Both speeds must be of the same units like miles per hour, or feet per second. Obviously, the u/V ratio at the tip -written u/V(tip) is a larger number than, say, the u/V ratio halfway between the tip and the center of rotation. Typical windmill calculations will use the u/V ratio for the tip, or outermost area of the machine. Speed ratio values you might see are 1 to 2 for slow speed machines, and 5 to 7 or 8 for the more modern high speed machines.

Now before proceeding with calculations of E, the following is a comparative discussion of types of windmills as related to the value and estimation of E. As will be seen, the type of windmill selected to satisfy power requirements affects the efficiency, and hence, size of the machine. A low efficiency windmill will have to be larger than a comparable high efficiency windmill to generate a certain amount of power.

TYPES OF WINDMILLS

There are two primary classes of windmills:

1. Those with power shafts mounted vertically.
2. Those with power shafts mounted horizontally.

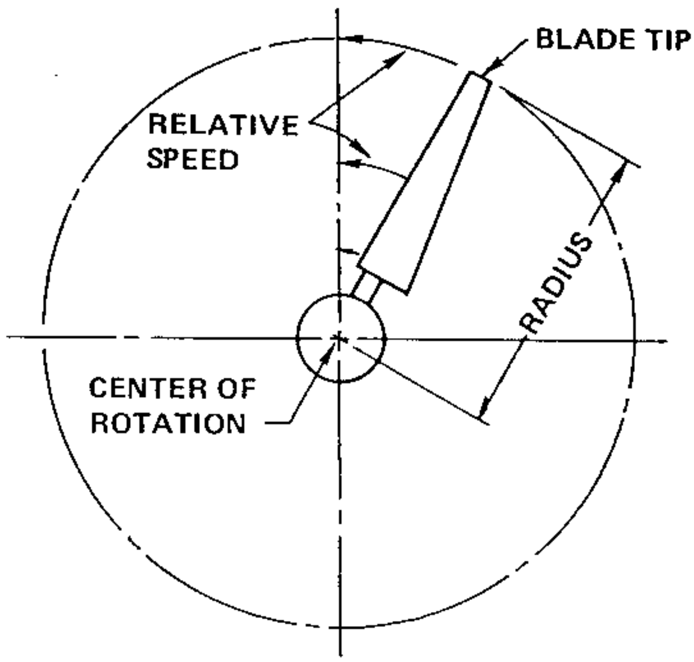
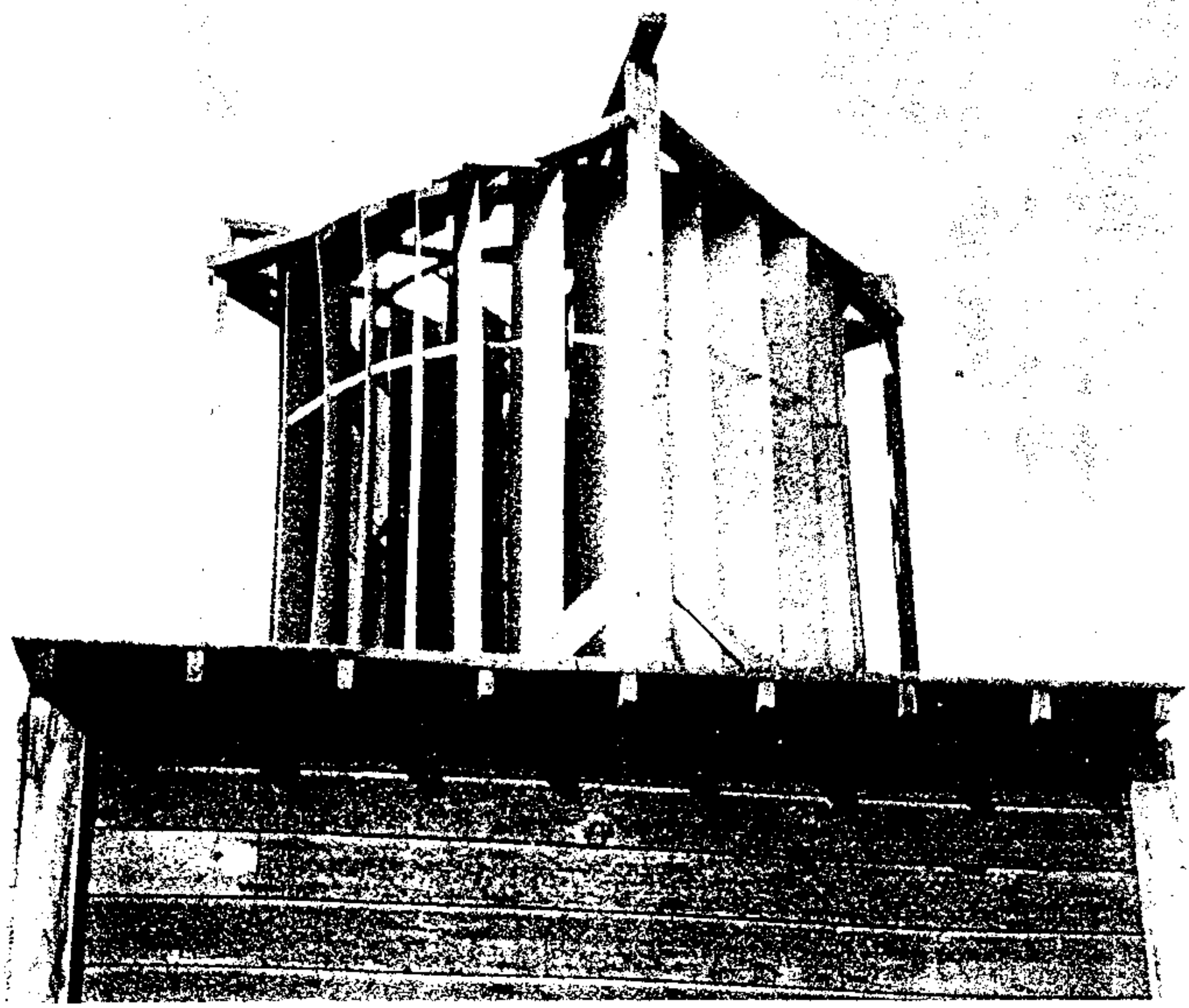
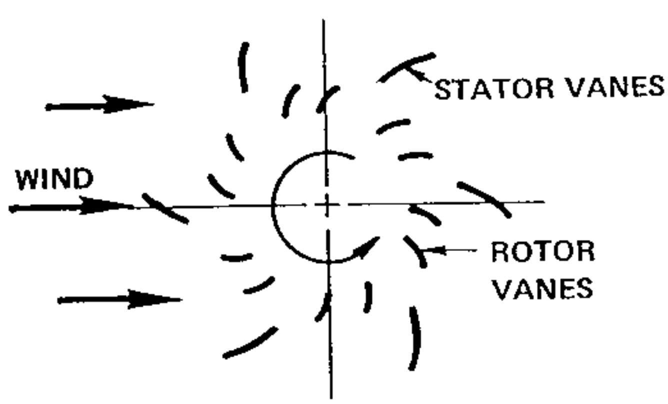
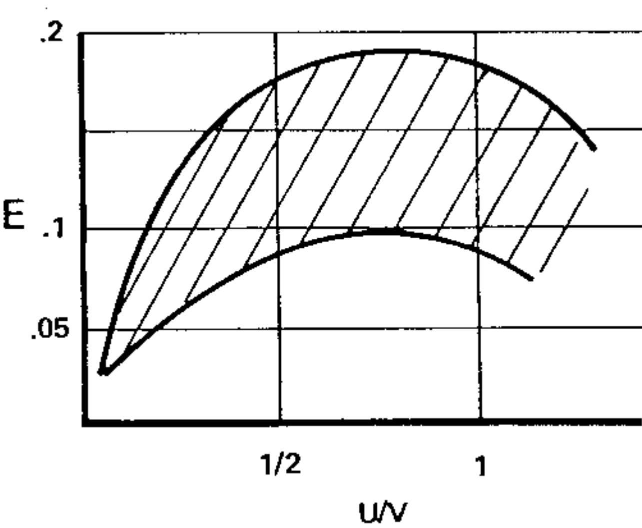


Figure 4

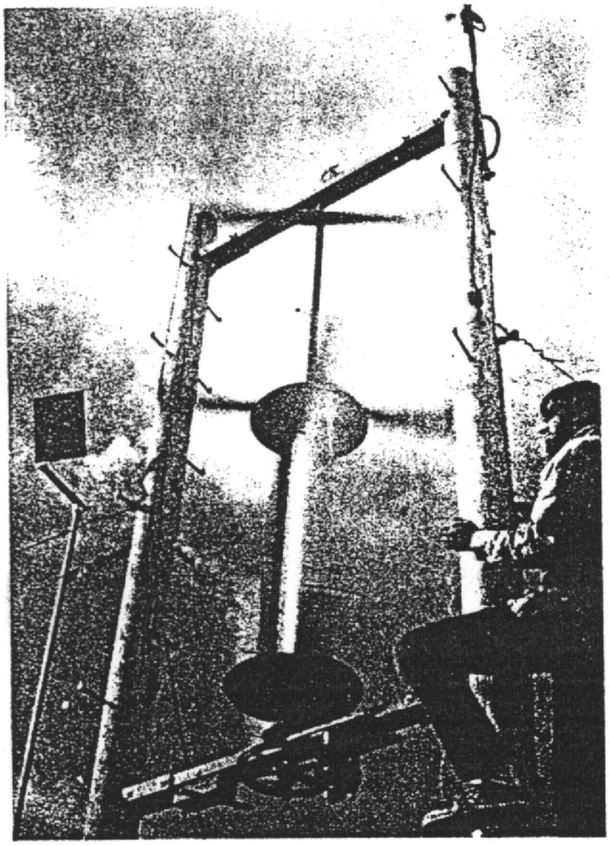
Appendix A WINDMILL DATA

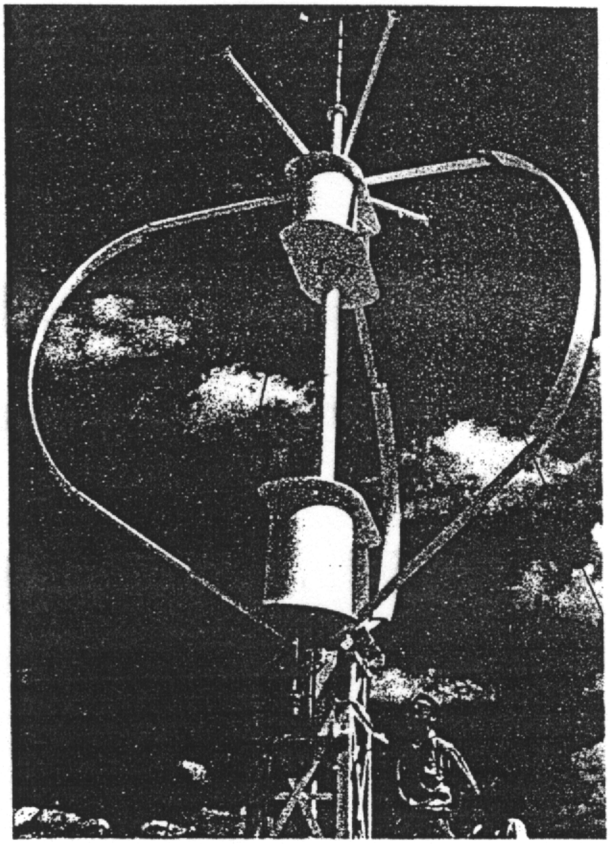


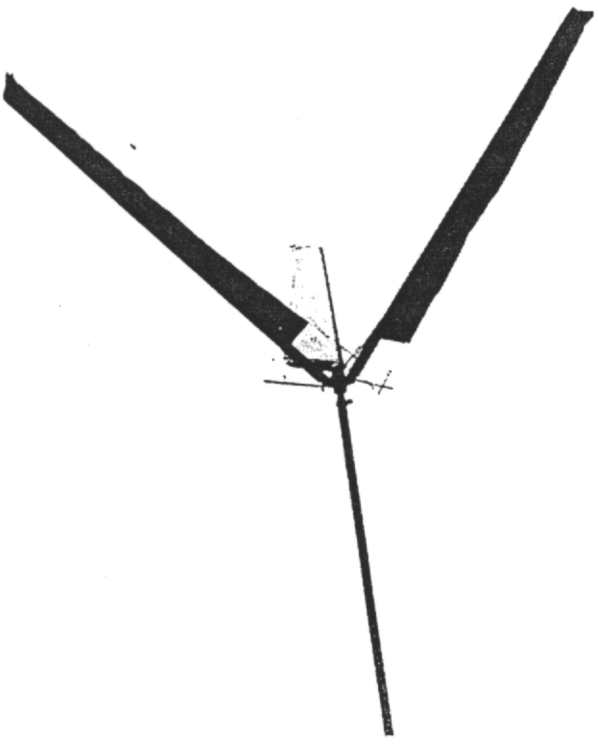


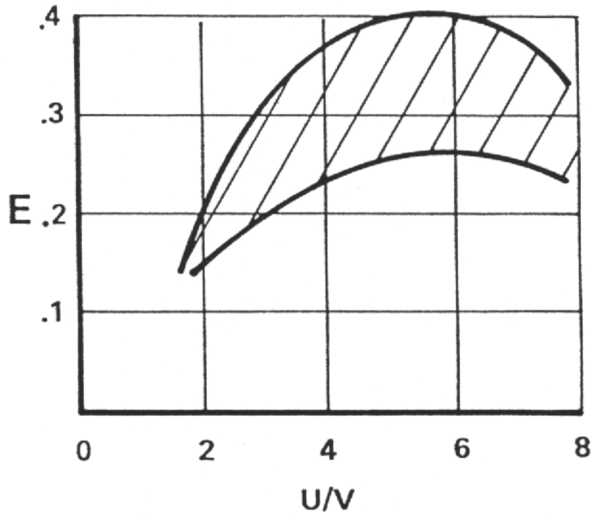


AUGMENTED TURBINE WINDMILL



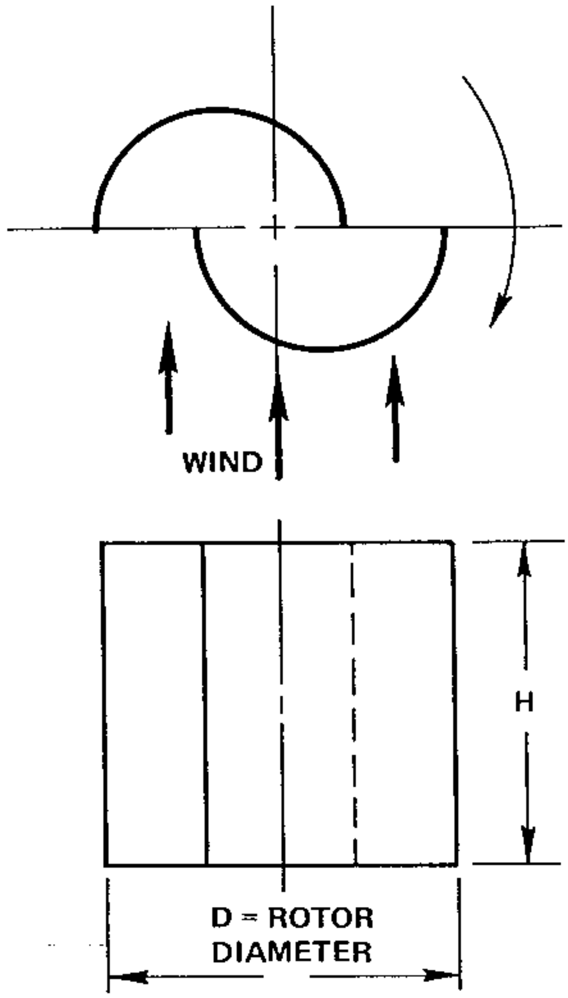






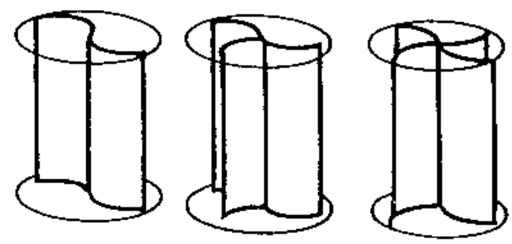
HYBRIDS

SAVONIOUS ROTOR

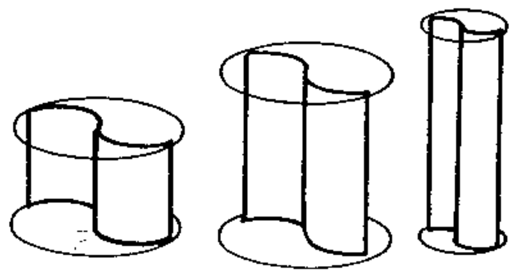


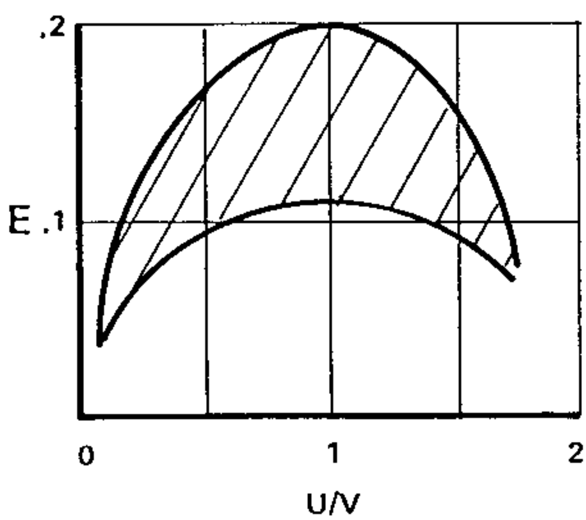
SINGLE TIER
SAVONIOUS

NUMBER OF VANES

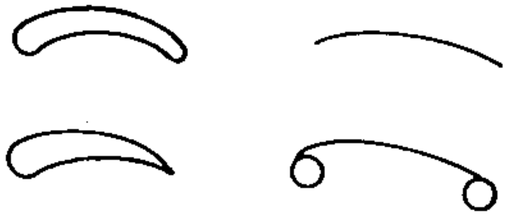


ASPECT RATIO

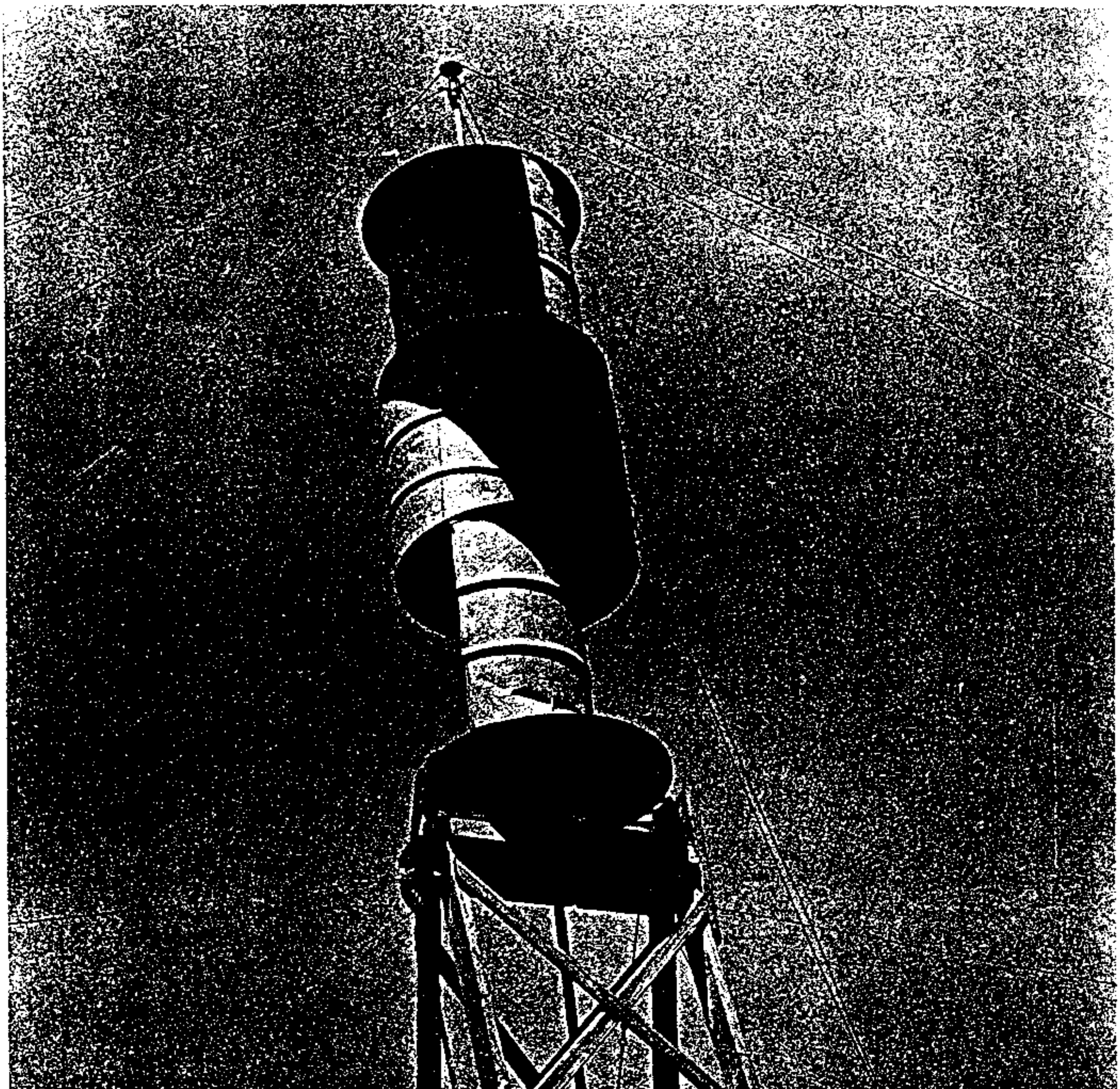


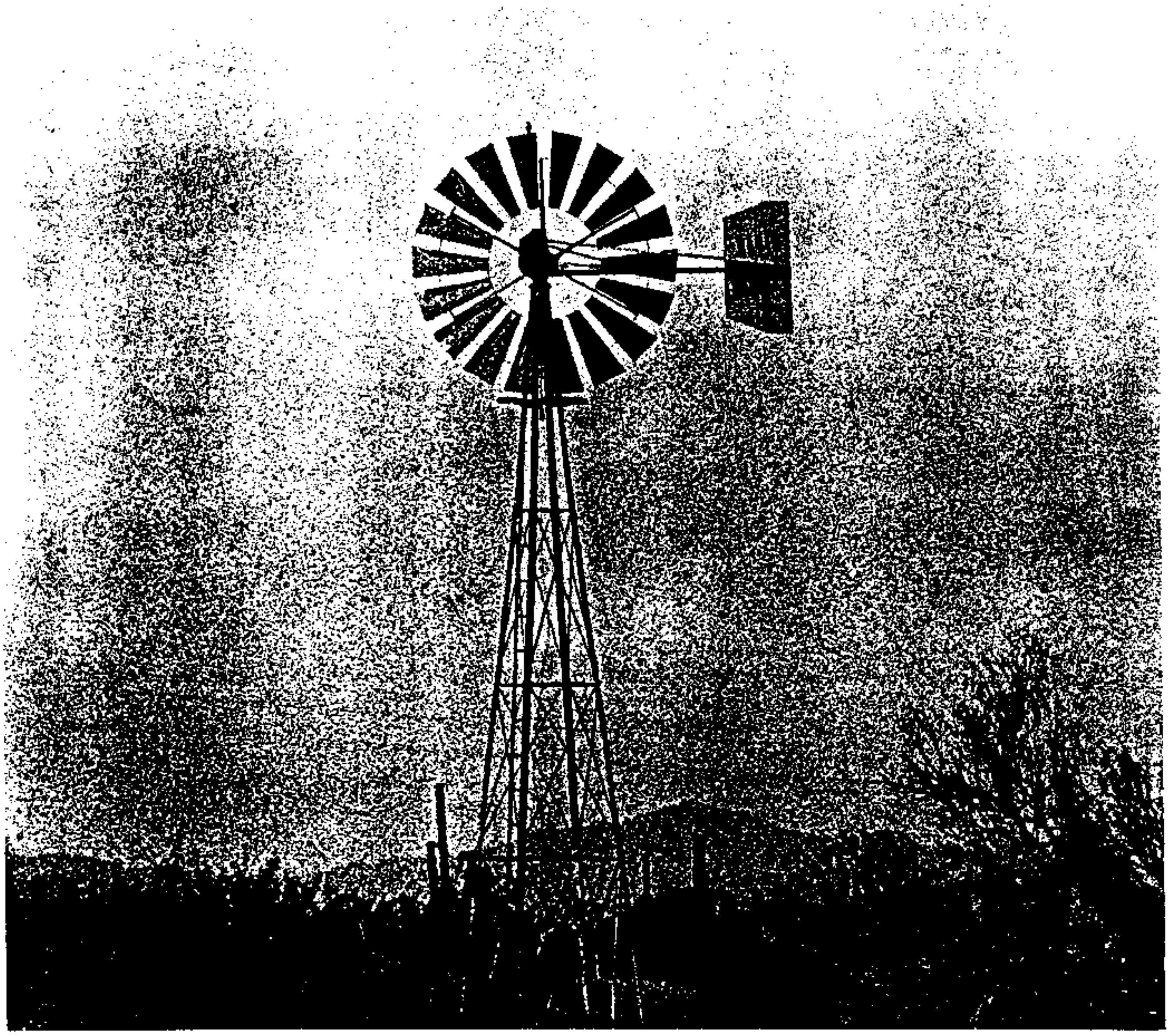


VANE FORM

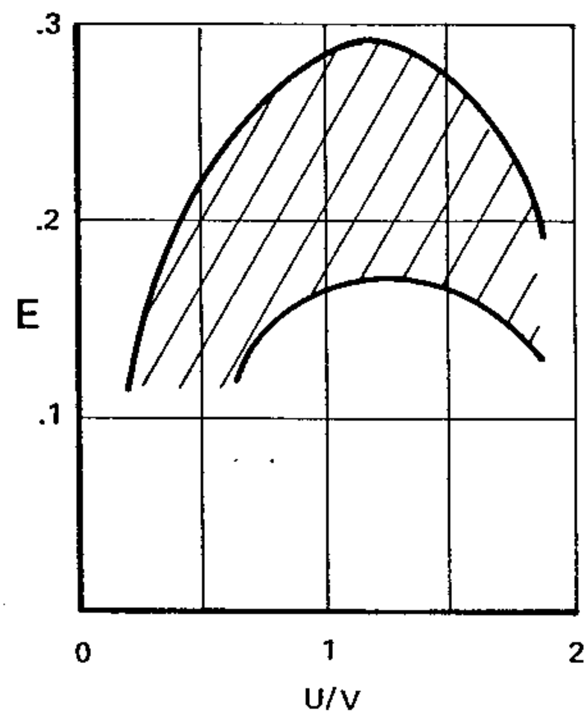


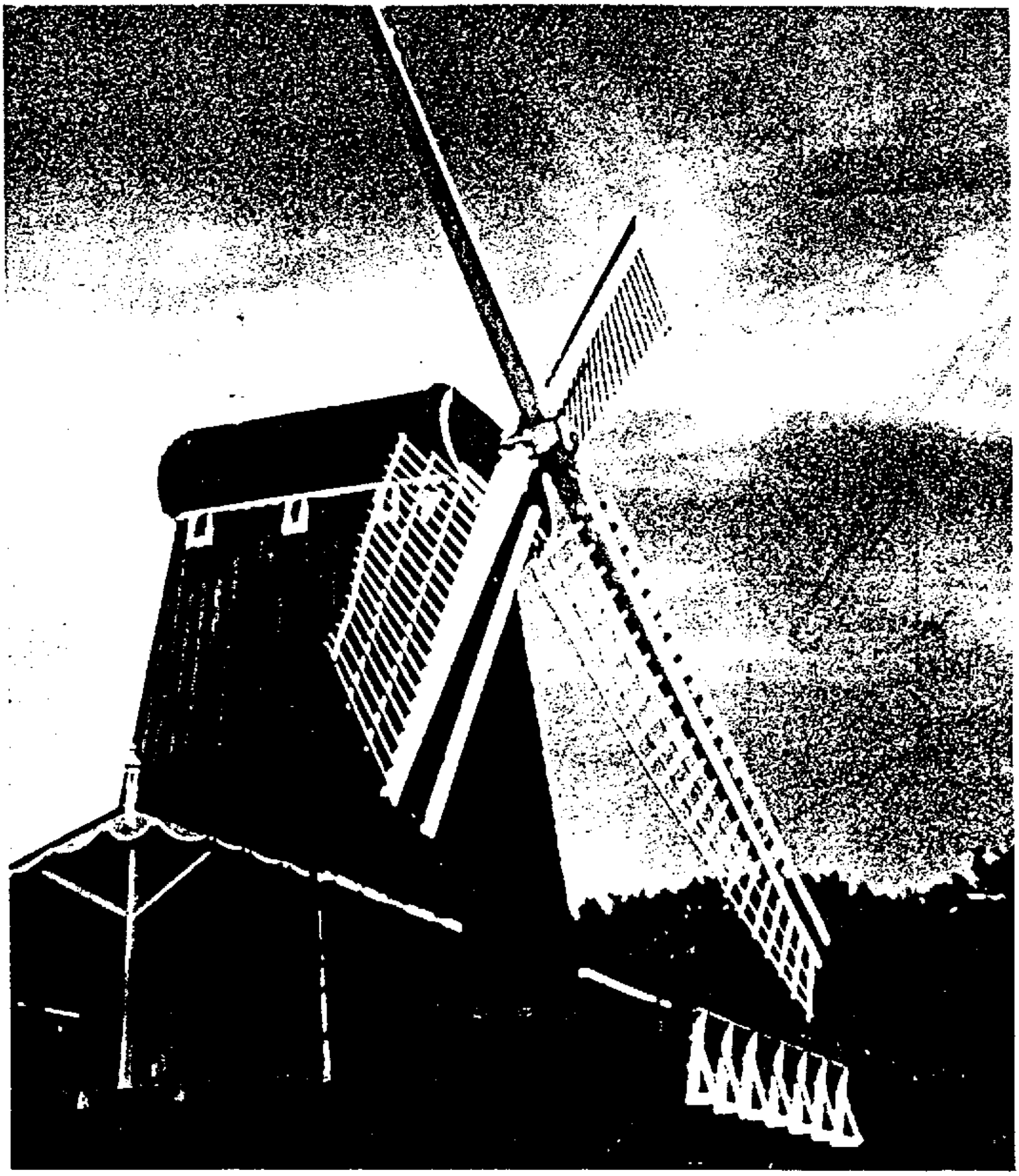
CONFIGURATIONS



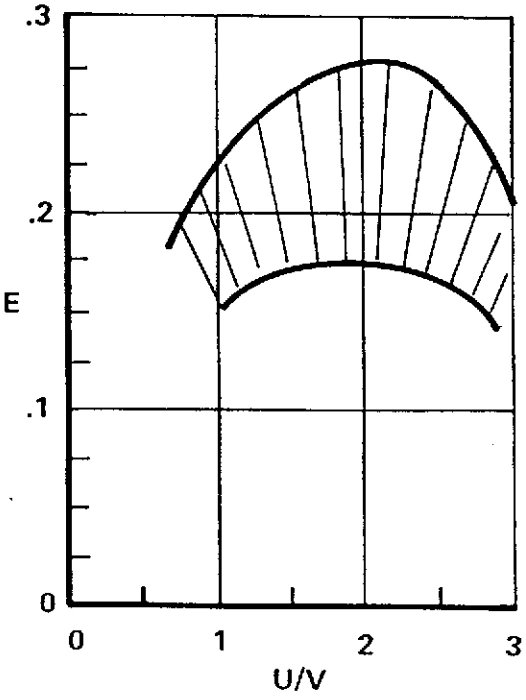


MULTI-BLADE WATER PUMP WINDMILL



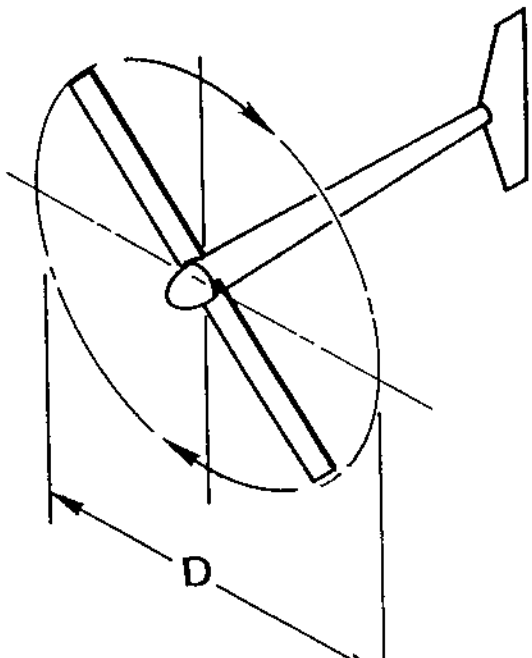


DUTCH WINDMILL

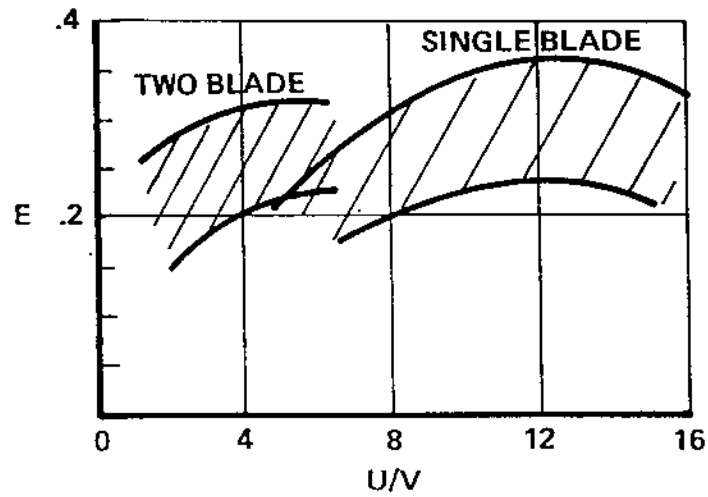


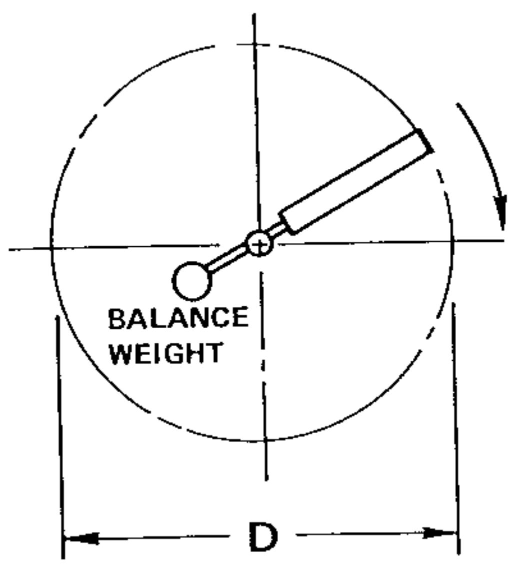
HIGH-SPEED

HORIZONTAL AXIS WINDMILLS

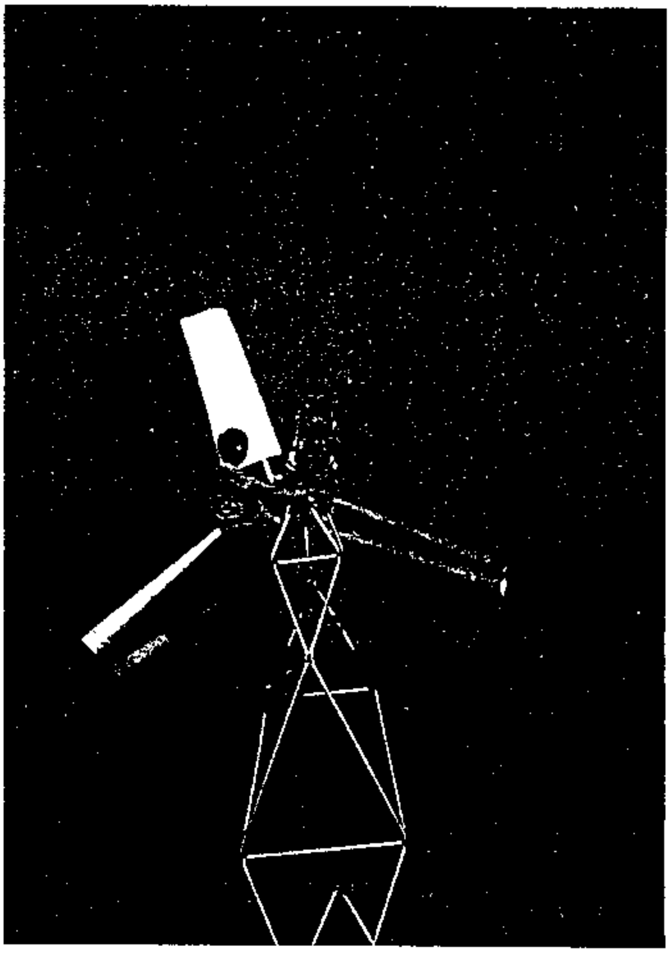


TWO BLADE



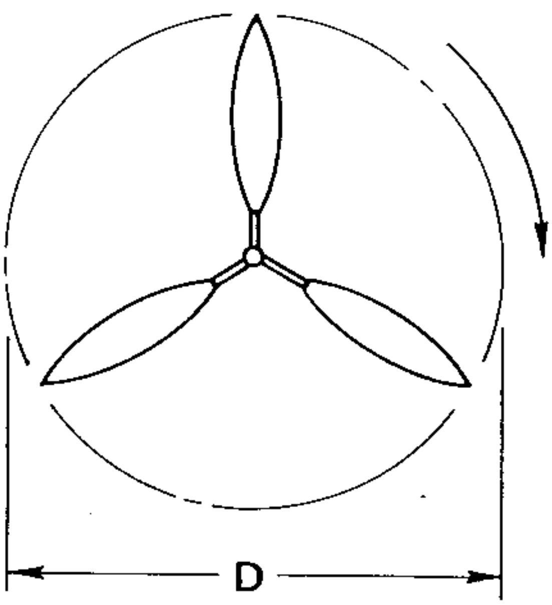


SINGLE BLADE

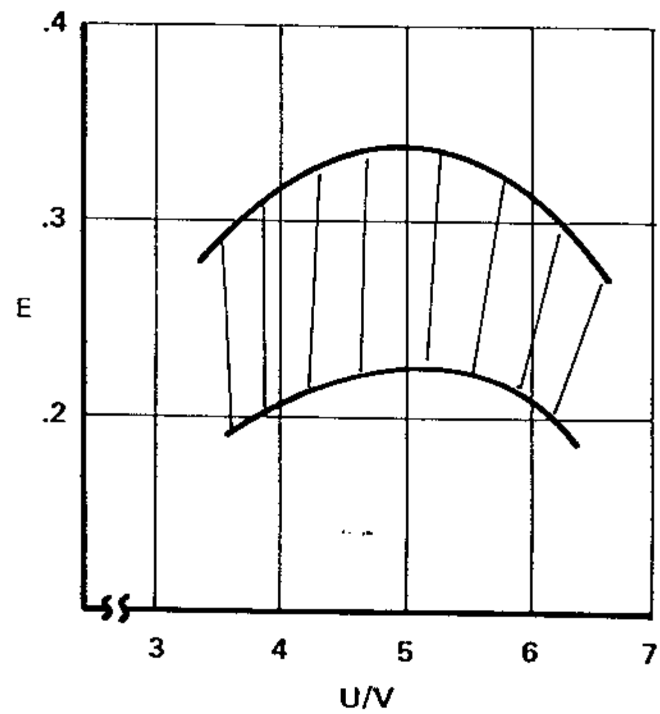


HIGH-SPEED

HORIZONTAL AXIS WINDMILLS



THREE BLADE



Appendix B AIRFOIL DATA

Following is a discussion of the method by which you can lay out an exact airfoil shape according to some numbers which are presented in this section of the book. A graph is presented which shows the lift coefficient performance for each of the airfoils listed. This graph will help you in Blade Angle computations. Other airfoils are available, some better than those listed here, many less suitable. Check the bibliography in this book for sources of further airfoil information.

HOW TO LAY OUT AN AIRFOIL

The numbers presented for each type of airfoil are percentages of the airfoil's chord length. When you have determined chord lengths, you can calculate dimensions from which to develop the exact airfoil shape much as you would plot a graph.

EXAMPLE

A few of these numbers for the Clark Y airfoil are:

Station	Upper	Lower
0	3.50	3.50
1.25	5.45	1.93
2.5	6.50	1.47
5.0	7.90	.93

and so on . . . .

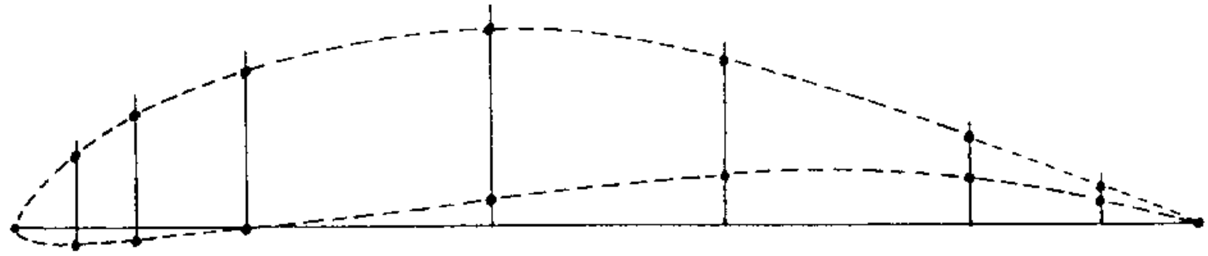
For simplicity let's assume a chord length of 10 inches. Then you multiply each number in the box by the chord length. Remember that these are percentages before multiplying by chord length, -that is, 3.50 percent is really 0.035, and 1.25 percent is really 0.0125. Move the decimal point two places to the left. You may run into some source of airfoil numbers listed as the real multiplier number rather than as a percentage. In this case, use the numbers as they are. Then , multiply:

Station	Upper	Lower
0 x 10 = 0	0.35 x 10 = .35	0.35 x 10 = .35
.0125 x 10 = .125	.0545 x 10 = .545	-----ETC

Now you simply plot the airfoil on a large sheet of graph paper. Start on a straight horizontal line. Always measure from Station = 0 to the right to each next station point, then measure up or down to the upper or lower points. Measure up from this line by the upper value. Make a dot at this point. Then, at the same station, measure from the horizontal line to the lower value. If the lower value has a minus (-) sign, measure below the line. If not, the lower value is measured above the line. Some sources of airfoil information will have different station values for the upper point than for the lower value. For these airfoils, you will have to compute the different additional station values. Keep them separate.

By making all the dots for the upper and lower values, you will generate a series of dot targets which, when connected with a curved line, will form the airfoil shape.

The "LR" value is the leading edge radius. Again, it's a percentage of the chord. For the Clark Y, LR = 1.5%, or 0.015. For a 10 inch chord, leading edge radius = 10 x .015 = .15 inches. Use this value to shape the curve at the leading edge with a compass or draftsman's circle guide. Some airfoils will not show the leading edge radius value. This is really a reference number. You can draw the curve without it.

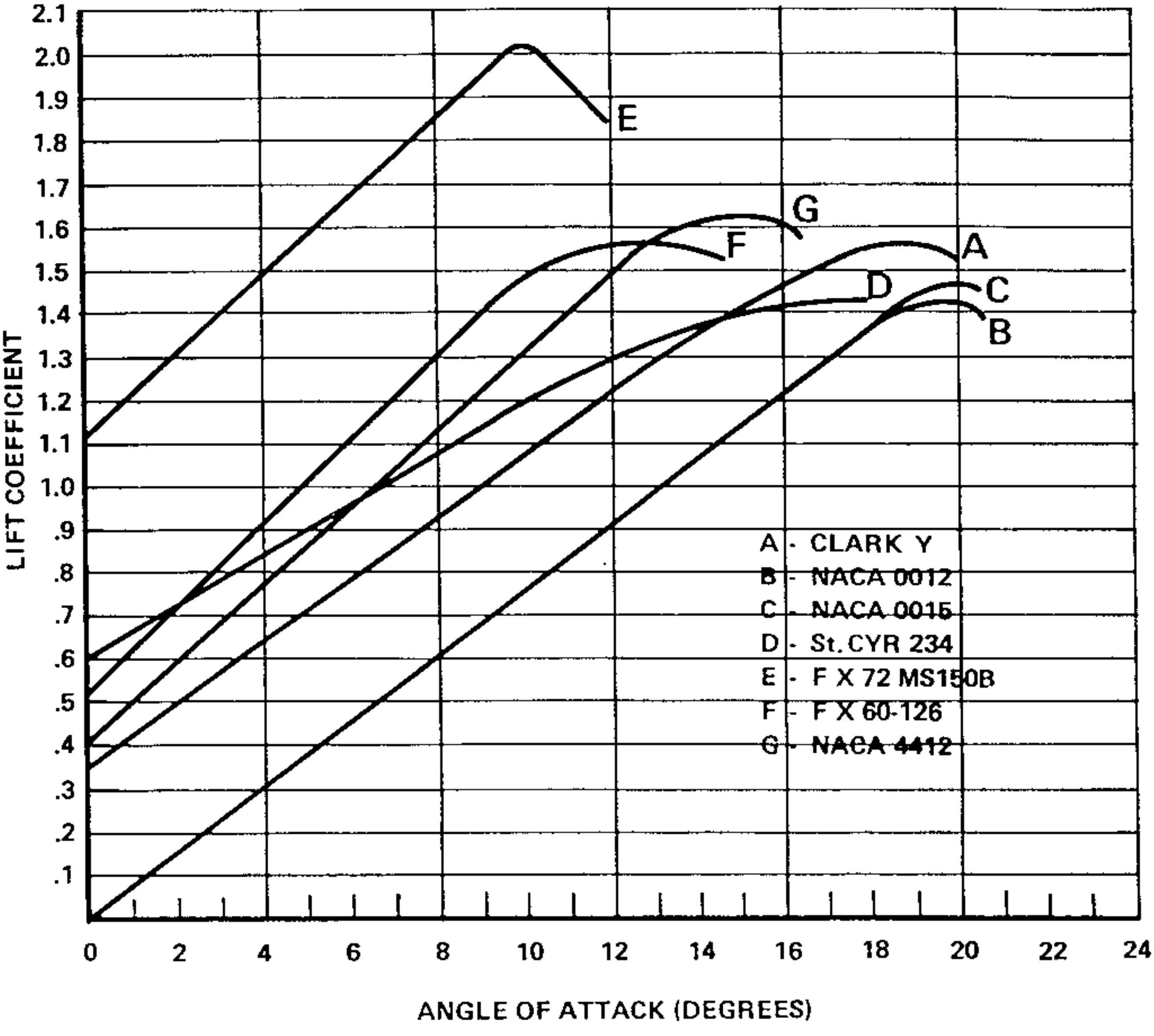


EXAMPLE FX 72-MS-150B

SELECTED AIRFOIL ORDINATES

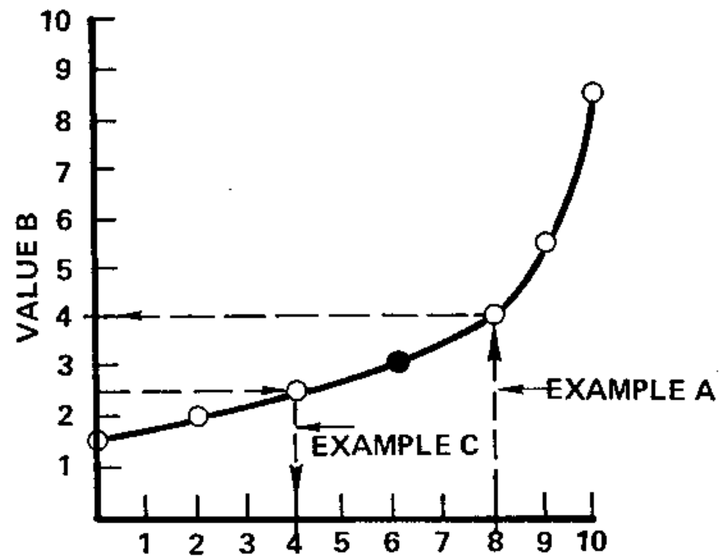
	CLARK Y		St. CYR 234		NACA 0012		NACA 0015		NACA 4412	
STA	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
0	3.5	3.5	6.42	6.42	0	0	0	0	0	0
1.25	5.45	1.93	9.55	3.75	1.89	-1.89	2.37	-2.37	2.44	-1.43
2.5	6.5	1.47	11.0	2.7	2.62	-2.62	3.27	-3.27	3.39	-1.95
5.0	7.9	.93	12.7	1.4	3.56	-3.56	4.44	-4.44	4.73	-2.49
7.5	8.85	.63	13.8	.85	4.2	-4.2	5.25	-5.25	5.76	-2.74
10	9.6	.42	14.6	.5	4.68	-4.68	5.85	-5.85	6.59	-2.86
20	11.36	.03	16.2	.2	5.74	-5.74	7.17	-7.17	8.8	-2.74
30	11.7	0	16.55	.65	6.0	-6.0	7.5	-7.5	9.76	-2.26
40	11.4	0	16.1	1.1	5.8	-5.8	7.25	-7.25	9.8	-1.8
50	10.52	0	15.2	1.35	5.29	-5.29	6.62	-6.62	9.19	-1.4
60	9.15	0	13.3	1.9	4.56	-4.56	5.7	-5.7	8.14	-1.0
70	7.35	0	10.8	1.35	3.66	-3.66	4.58	-4.58	6.69	-.65
80	5.22	0	7.75	1.05	2.62	-2.62	3.28	-3.28	4.89	-.39
90	2.8	0	4.0	.5	1.45	-1.45	1.81	-1.81	2.71	-.22
100	0	0	0	0	0	0	0	0	0	0
	LR = 1.5				LR = 1.58		LR = 2.48		LR = 1.58	

	FX 60-126		FX 72-MS-150B	
STA	UPPER	LOWER	UPPER	LOWER
0	0	0	0	0
1.7	2.77	-1.37	3.05	-1.23
2.65	3.44	-1.8	4.01	-1.24
5.16	4.81	-2.48	6.15	-1.14
6.69	5.46	-2.76	7.26	-1.03
10.33	6.59	-3.26	9.43	-.72
19.56	8.33	-3.75	13.32	.13
30.86	9.13	-3.39	16.05	1.16
40.24	9.04	-2.55	16.86	2.09
50.0	8.43	-1.42	16.16	3.27
59.75	7.4	-.3	14.21	4.25
69.13	6.08	.55	11.55	4.64
80.43	4.05	1.07	7.5	4.07
91.57	1.78	.85	3.23	2.21
100	0	0	0	0



AIRFOIL LIFT AND ANGLE OF ATTACK DATA

Appendix C HOW TO READ A GRAPH



SAMPLE GRAPH 1

Graphs are used to simplify calculations. I have presented many graphs in this manual so that computations which are normally difficult will be made easily. So that all users of this text have graph reading ability, this page is presented.

CONDITION 1 - You know VALUE A and you want to find VALUE B on Sample Graph 1.

<u>EXAMPLE A</u>

If VALUE A equals 8, start on the horizontal line at 8 and look (or draw a line) vertically up to the curve. Next, look (or draw a line) horizontally to the scale at the left. Notice that the answer VALUE B equals 4.

NOTE - You may have more than one curve which applies to your problem. You select the curve which applies, or add a curve which does.

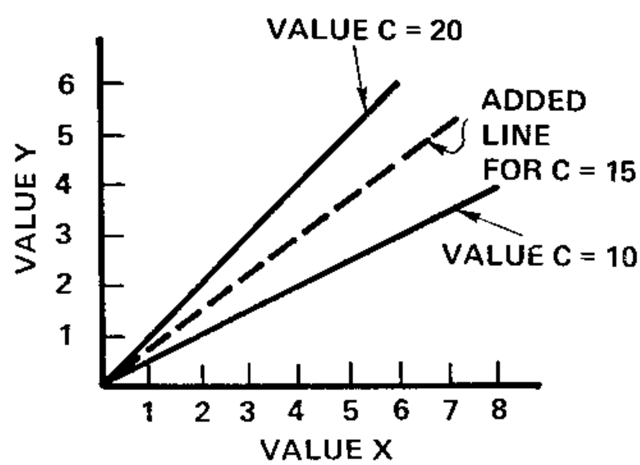
<u>EXAMPLE B</u>

Look at Sample Graph 2. Suppose that VALUE C in your problem equals 15, which is half-way between the line for C=10, and C=20. Simply add a line roughly half-way between the two and proceed as above.

CONDITION 2 - Refer to Sample Graph 1. You know VALUE B, and need VALUE A.

<u>EXAMPLE C</u>

Start at VALUE B (B=2.5 in this example). Look to the right to the curve, then down. Notice that the answer is VALUE A = 4.



SAMPLE GRAPH 2

Appendix D

DETAILED WINDMILL PERFORMANCE

1 - Power = Force x Velocity

2 - Force = Pressure x Area

3 - Pressure = $\rho \times V^3 / 2$

where ρ = Mass density of air = 0.0024 slugs / $foot^3$ at sea level

V = wind speed measured in feet per second

4 - Power = $.0012 \times V^3 \times A$

where A = windmill frontal area measured in square feet

V = wind speed measured in feet per second

This is the theoretical power available in a wind of speed = V, acting across a windmill of frontal area = A. Power units here are foot-pounds per second.

5 - One Horsepower = 550 foot-pounds per second

6 = Horse Power = $.0012 \times V^3 \times A / 550 = 0.0000022 \times V^3 \times A$

Again, this is theoretical horsepower.

7 - The mathematical horsepower which a windmill can extract from the above value is 59.3% of the total. However, no windmill is perfect, and the actual maximum horsepower available from a windmill will be more like 10% to 40% of the total. For calculations, E will be efficiency factor.

8 - Actual Horsepower available from a wind = $0.0000022 \times (k\ V)^3 \times A \times E$

where V = wind speed

k = a constant to adjust V

if V is measured in miles per hour, K = 1.47

if V is measured in feet per second, K = 1.0

A - frontal area of the windmill measured in square feet

E = the efficiency factor

9 - For calculation of electrical power: One horsepower = 746 watts

10 - Actual watts available from a wind = $0.0016 \times (k\ V)^3 \times A \times E$

Appendix E

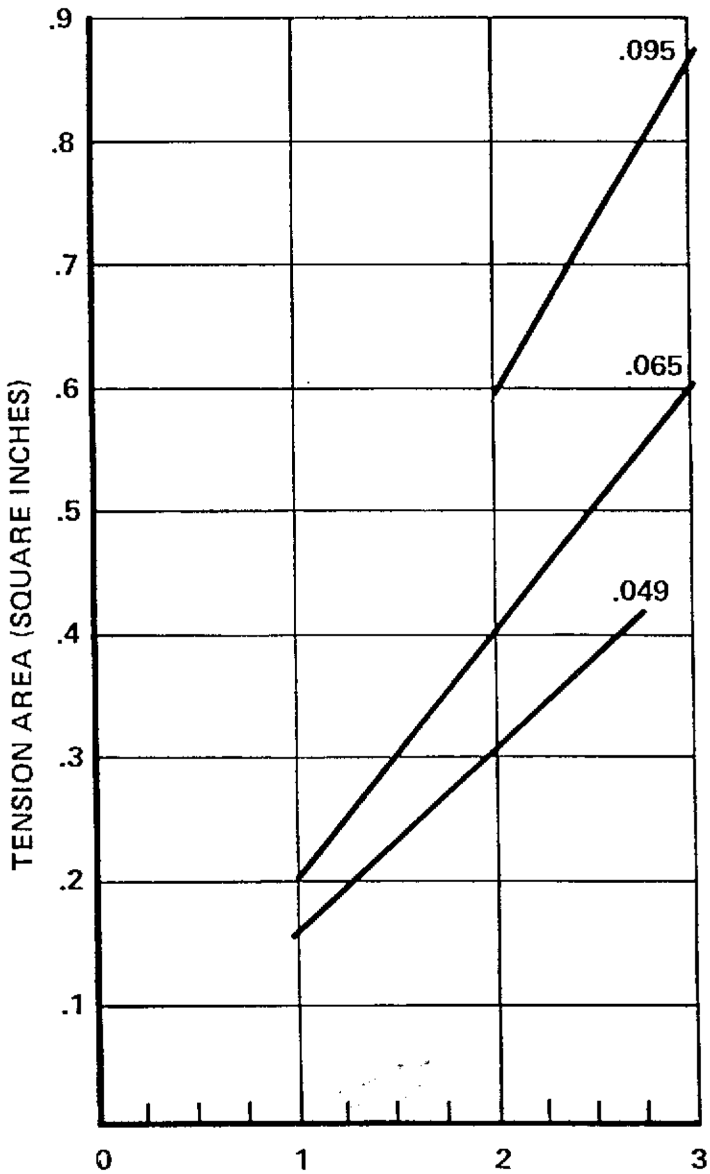
STRENGTH OF CONSTRUCTION MATERIALS

TUBE TENSILE STRENGTH

To compute tube tensile strength, measured in pounds of force, multiply tension area from Graph A below times the tensile strength factor for the metal alloy of the tube. See next page for tensile strength factors.

EXAMPLE

A 2-inch diameter by .065 inch wall thickness tube of Aluminum alloy 2024 T-4 is selected. Calculate the tensile strength. From Graph A, note that tension area equals .39. Tensile strength factor for this alloy is 60,000. Then Tensile Strength = .39 x 60,000 = 23,400 pounds.



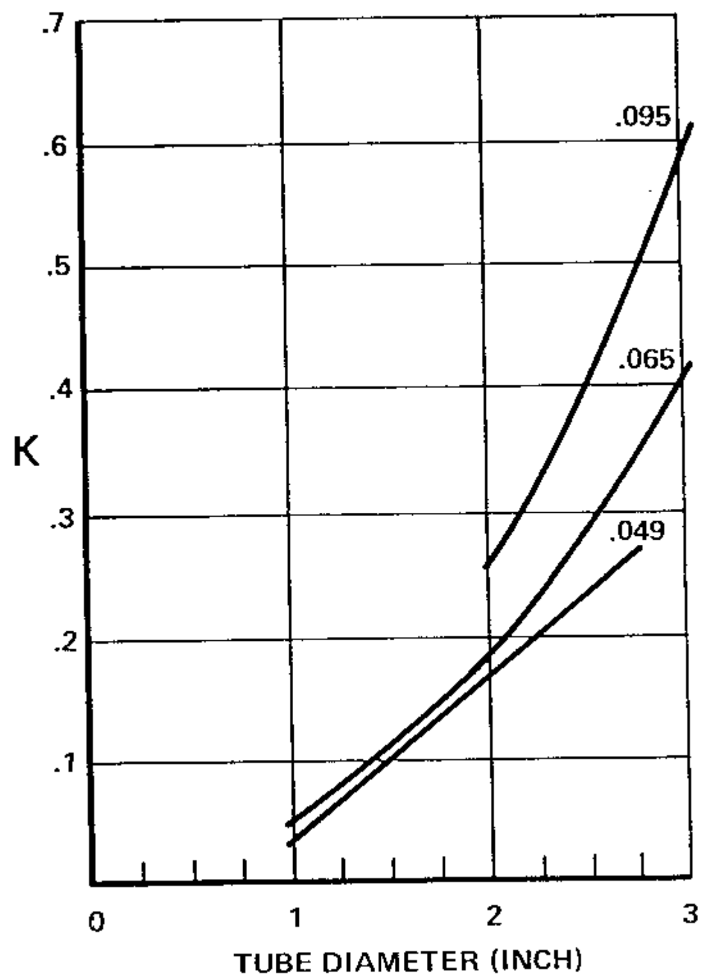
GRAPH A TENSION AREA FOR TUBE DIAMETERS AND THREE WALL THICKNESS VALUES

TUBE BENDING STRENGTH

To compute approximate tube bending strength, measured in inch-pounds, multiply K-value from Graph B below times the tensile strength factor.

EXAMPLE

A 2-inch diameter by .065 inch wall thickness tube of Aluminum alloy 2024 T-4 is selected. Calculate the bending strength. From Graph B, note that K = 0.19. Tensile strength factor for this alloy equals 60,000. Then Bending Strength = 0.19 x 60,000 = 11,400 inch-pounds.



GRAPH B K VALUE FOR TUBE DIAMETERS AND THREE WALL THICKNESS VALUES

TENSILE STRENGTH FACTORS

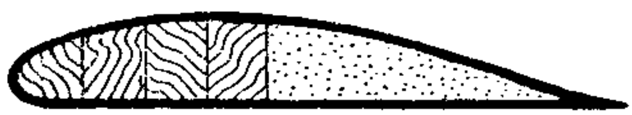
Alloy	Tensile Strength Factor
Aluminum	
2024 T-4	60,000
6061 T-6	42,000
7075 T-6	75,000
Steel 4130 4130	90,000

TENSILE STRENGTH OF WOOD BLADES

Wood blades - as discussed earlier in this manual - are laminated and carved from quality materials like aircraft grade spruce. The Tensile Strength Factor for wood varies between 7000 to about 12,000 pounds per square inch. This value depends on the type of wood used, and the moisture content. Wood strength increases rapidly as the material dries out. For average wood used in the 10% to 15% moisture content range, a safe check of blade strength can be made with a tensile strength factor of 8,000. You need to know the tensile area of the blade. Then multiply this area times the strength factor to compute blade tensile strength.

EXAMPLE

The blade sketched has a tensile area for the structural wood forward portion (you can disregard any strength value in the balsa or foam trailing edge in this example) of approximately 12 square inches. Blade strength = 12 x 8,000 = 96,000 pounds. This is the maximum centrifugal tension load this blade can withstand.



CABLE STRENGTH

Cables are used for tower guy wires, windmill bracing, and so on. Data presented is for 7 x 19 flexible aircraft stranded cable - available in surplus outlets, or the source listed in the Bibliography of this book.

CABLE DIAMETER (inches)	BREAKING TENSILE STRENGTH (pounds)
1/16	400
3/32	750
1/8	2,000
3/16	4,200
1/4	7,000

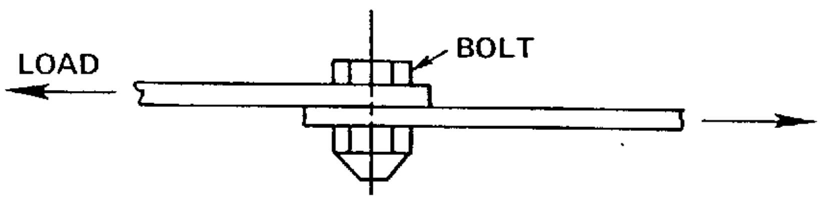
BOLT STRENGTH

Data presented are for aircraft quality (AN) bolts.

BOLT DIAMETER (inches)	SINGLE SHEAR STRENGTH (pounds)	TENSILE STRENGTH (pounds)
3/16	2,100	2,200
1/4	3,600	4,000
5/16	5,700	6,500
3/8	8,200	10,100
7/16	11,200	13,600
1/2	14,700	18,500

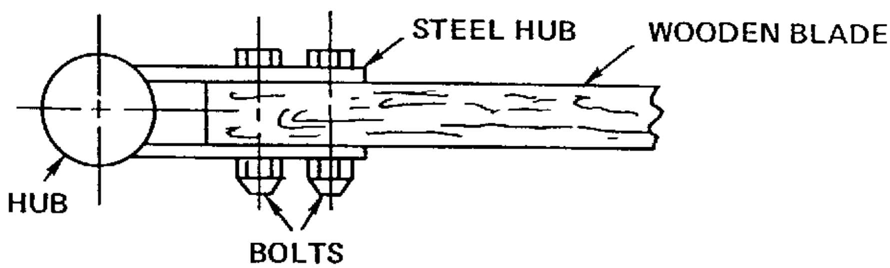
EXAMPLE 1

Two strips of steel are to be bolted together. The maximum tensile load in the strips is 8,000 pounds. The bolt will take this load in single shear. The minimum size bolt for this load is one 3/8 inch aircraft quality bolt, or two 5/16 inch bolts. Hardware store bolts will have to be larger in diameter.



EXAMPLE 2

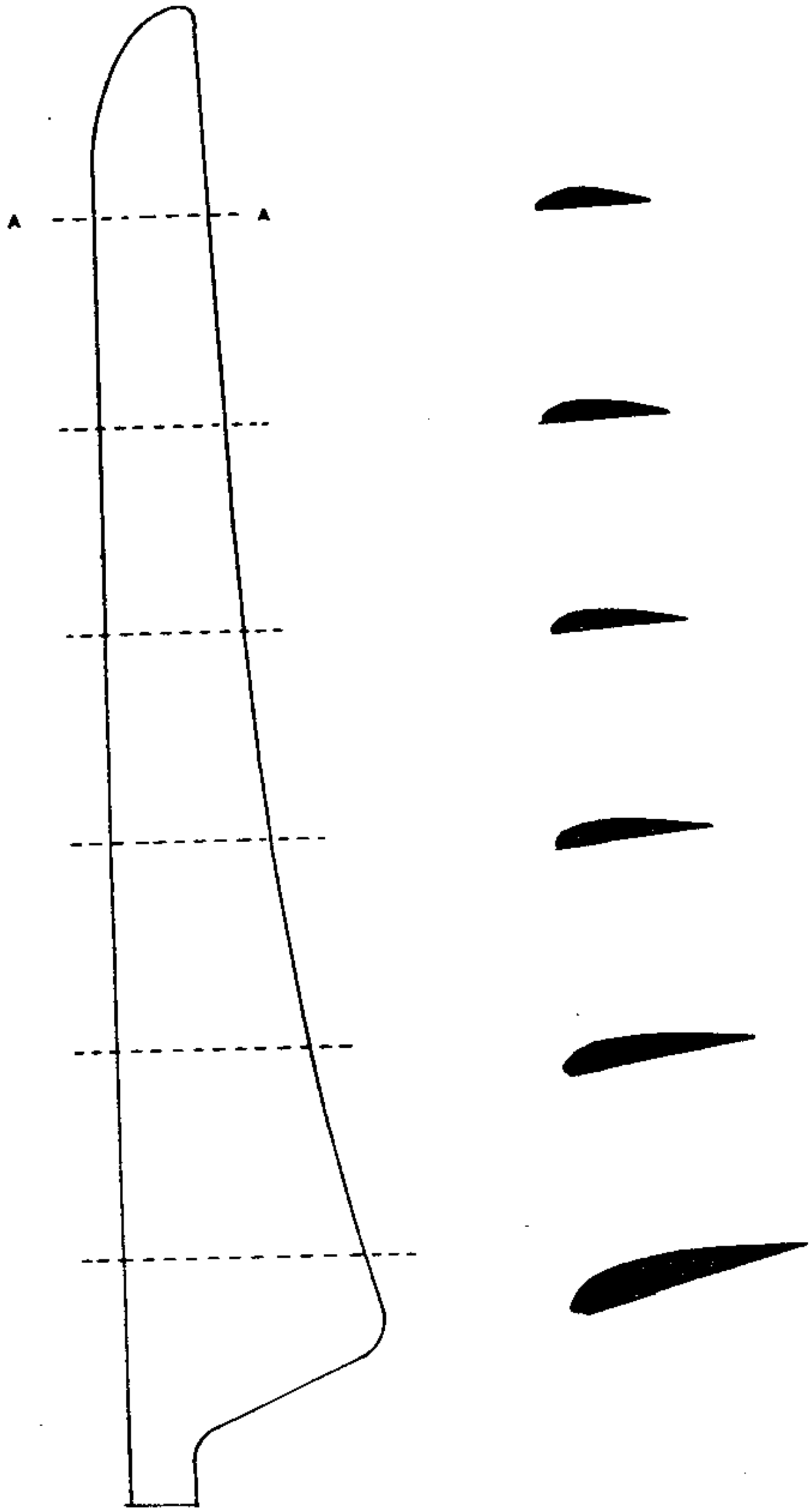
A wooden blade is to be bolted to a steel hub. The centrifugal force is equal to 20,000 pounds. The bolts are loaded in shear as illustrated below.



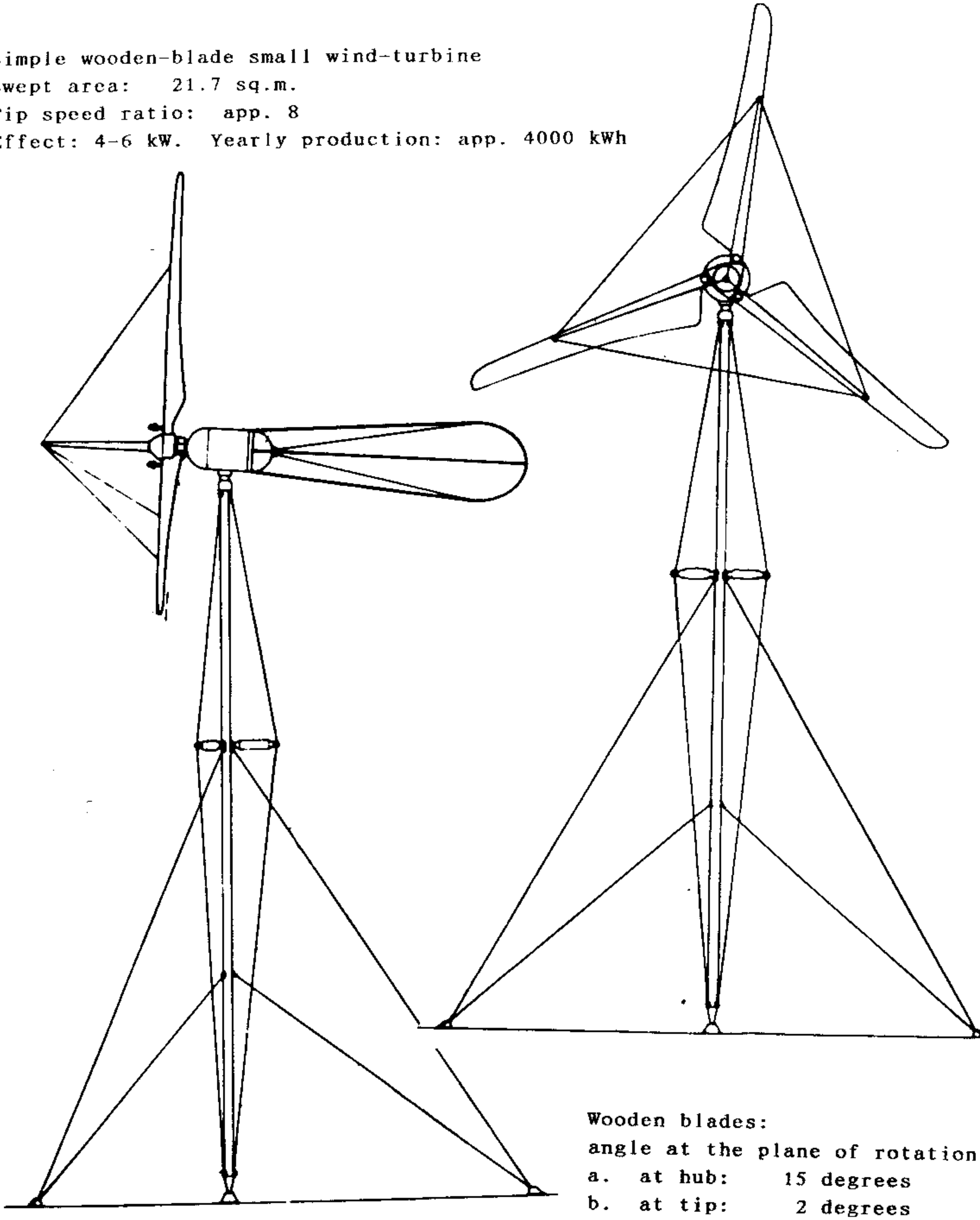
Notice in the sketch that the blade load ends up in two hub parts, which means that half of the load goes into each side of the blade. Thus 10,000 pounds is loaded at two different places along the attachment bolt - called double shear. Two 5/16 inch bolts could handle this load. In the case of wood blade attachment, lots of smaller bolts are recommended.

Freja 1974: School of Architecture Copenhagen Denmark. 1974.

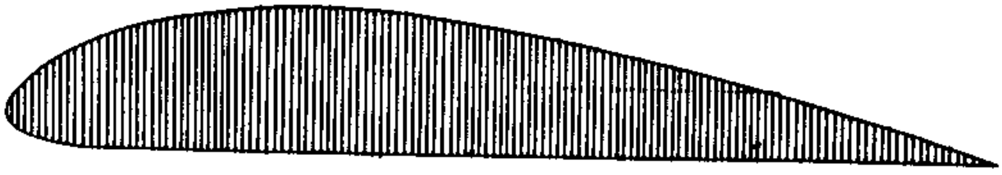
FORSLAG TIL EN VINDMØLLE:



Simple wooden-blade small wind-turbine
Swept area: 21.7 sq.m.
Tip speed ratio: app. 8
Effect: 4-6 kW. Yearly production: app. 4000 kWh



Wooden blades:
angle at the plane of rotation
a. at hub: 15 degrees
b. at tip: 2 degrees



A - A

<u>The "Sokol" electrical machine</u> (2D-12MA) with a submerged centrifugal pump is designed for lifting water on farms, irrigated and reclaimed sections, and also for providing electrical power to small far-removed objects. The basic zones for the machine's use are Kazakhstan, Azerbaydzhan, near the Volga, the Arctic, the coastline areas of the Caspian, the Altay and others.

The distinguishing feature of the machine consists of the fact that, due to the use of a new system of moment-centrifugal regulation, it can be also used together with a non-wind electrical station for working in parallel with a network.

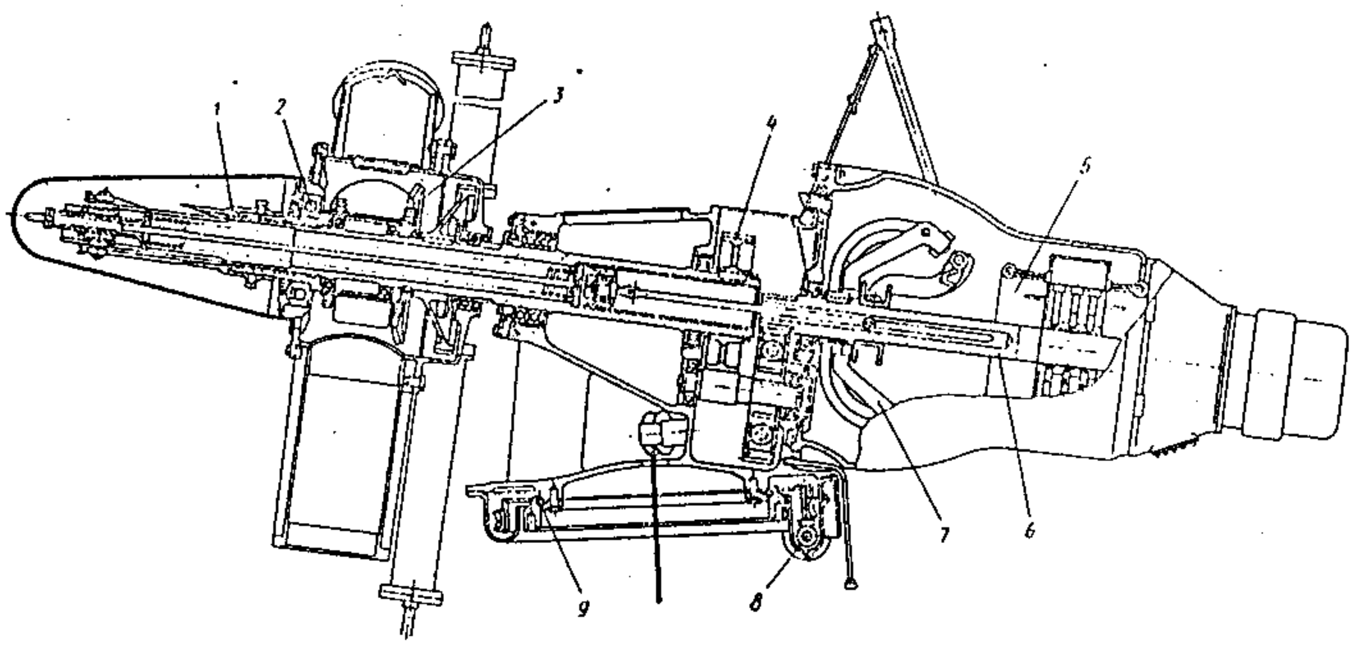


Fig. 81. Head of the "Sokol" machine: 1. main shaft; 2. bearing; 3. gear; 4. reduction gear; 5. generator; 6. generator shaft; 7. centrifugal regulator; 8. orientation mechanism; 9. support bearing.

The machine has a three-bladed windmill 1 (Fig. 80), in the hub of which is built in a moment regulator 2; head 3, consisting of the reduction gear, generator and rotating support; orientation mechanism with two wind roses 4; pipe mast 5 with two levels of guys 9 and manual control winch 6. The equipment for the machine includes electrical panel 7 for control and automation, type EPN-6-16-110 pump 8, lifting boom and pile foundations.

The windmill is fastened onto main shaft 1 (Fig. 81) by the hub on bearings 2 so that a slight angular motion relative to the shaft is possible when the moving aerodynamic moment exceeds the calculated value. The fiberglass blades are fastened into the hub on bearings so that all the roots are kinematically connected together through rod 3 of the main shaft. To decrease flyout of the windmill relative to the tower axis, the shaft is installed at an angle of 10° to the horizontal.

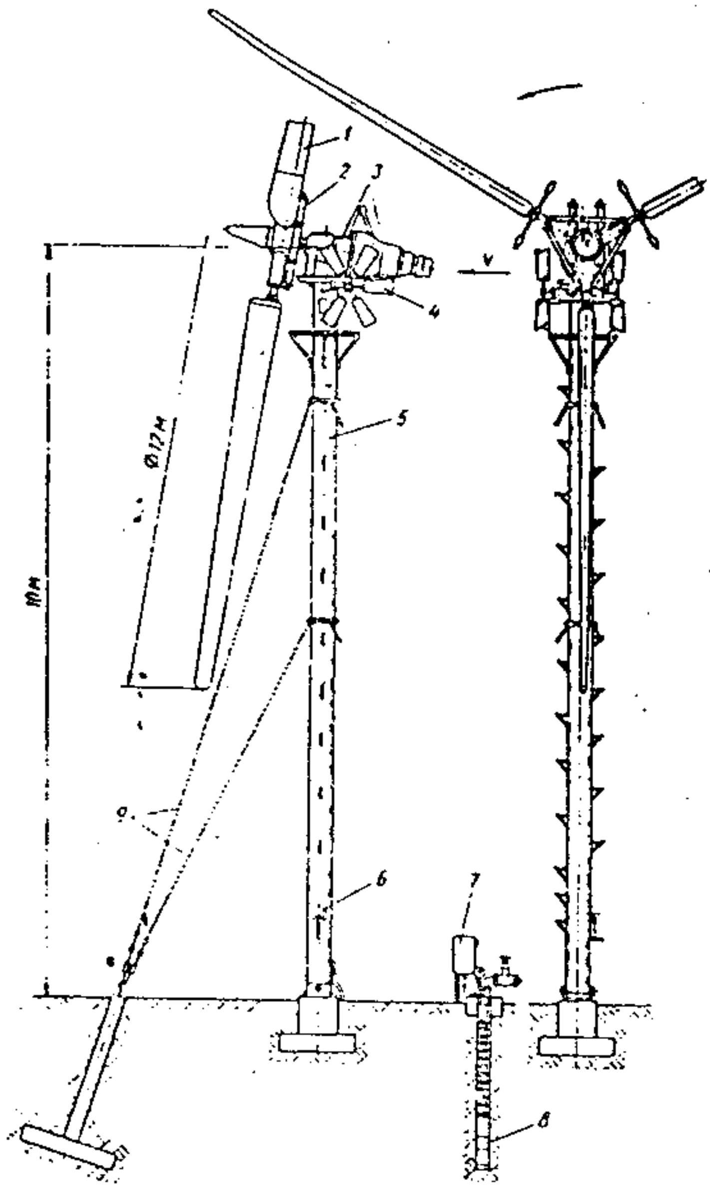


Fig. 80. Overall view of the "Sokol" machine.

The two-stage reduction gear 4 ($i = 17.1$) is connected to the rotor of the synchronized generator 5 on the shaft 6 of which is mounted centrifugal regulator 7. The reduction gear, generator and supporting device have a common body, into which the two-stage worm orientation mechanism 8 is also built. Two wind roses are located in front of the windmill. The support bearing device 9 is the same

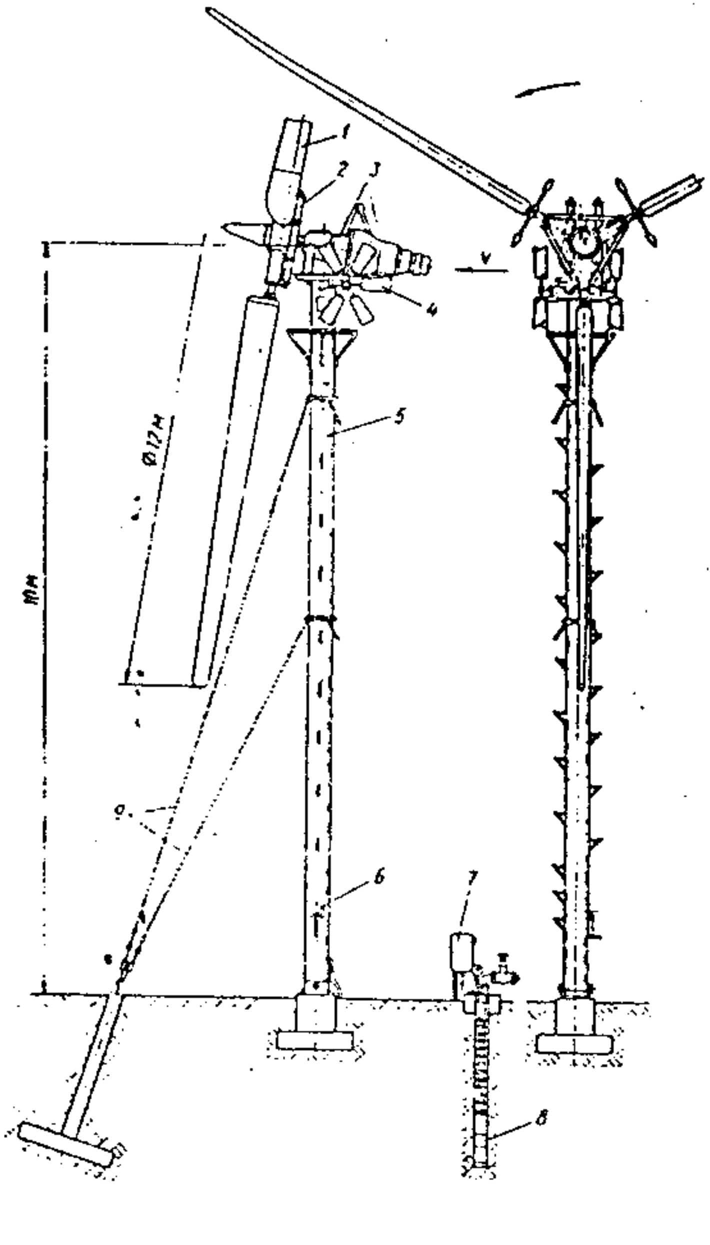


Fig. 80. Overall view of the "Sokol" machine.

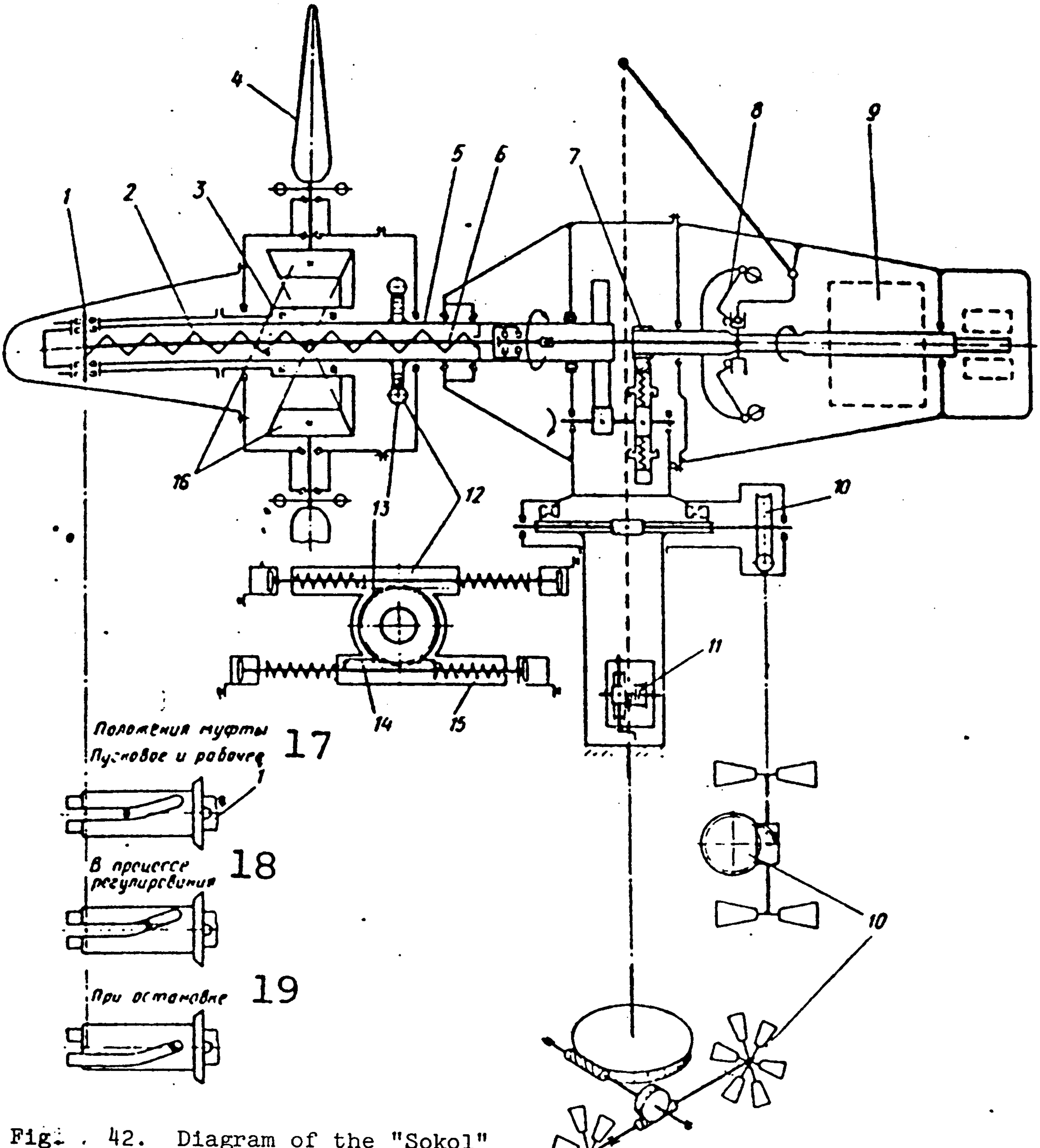


Fig. 42. Diagram of the "Sokol" electrical wind machine: 1. Sleeve with slot; 2. Regulator spring; 3. Kinematic connection gear; 4. Windmill; 5. Main shaft; 6. Regulator rod; 7. Reduction gear; 8. Centrifugal regulator; 9. Generator; 10. Orientation mechanism; 11. Starting-stopping windlass; 12. Moment regulator; 13. Toothed wheel; 14. Toothed racks; 5. Moment regulator spring; 16. Stroke spring; 17. Starting and working positions of sleeve; 18. In the process of regulation; 19. When stopping.

as in unified machines. The tubular tower (metal or reinforced concrete) has a hinge at the bottom.

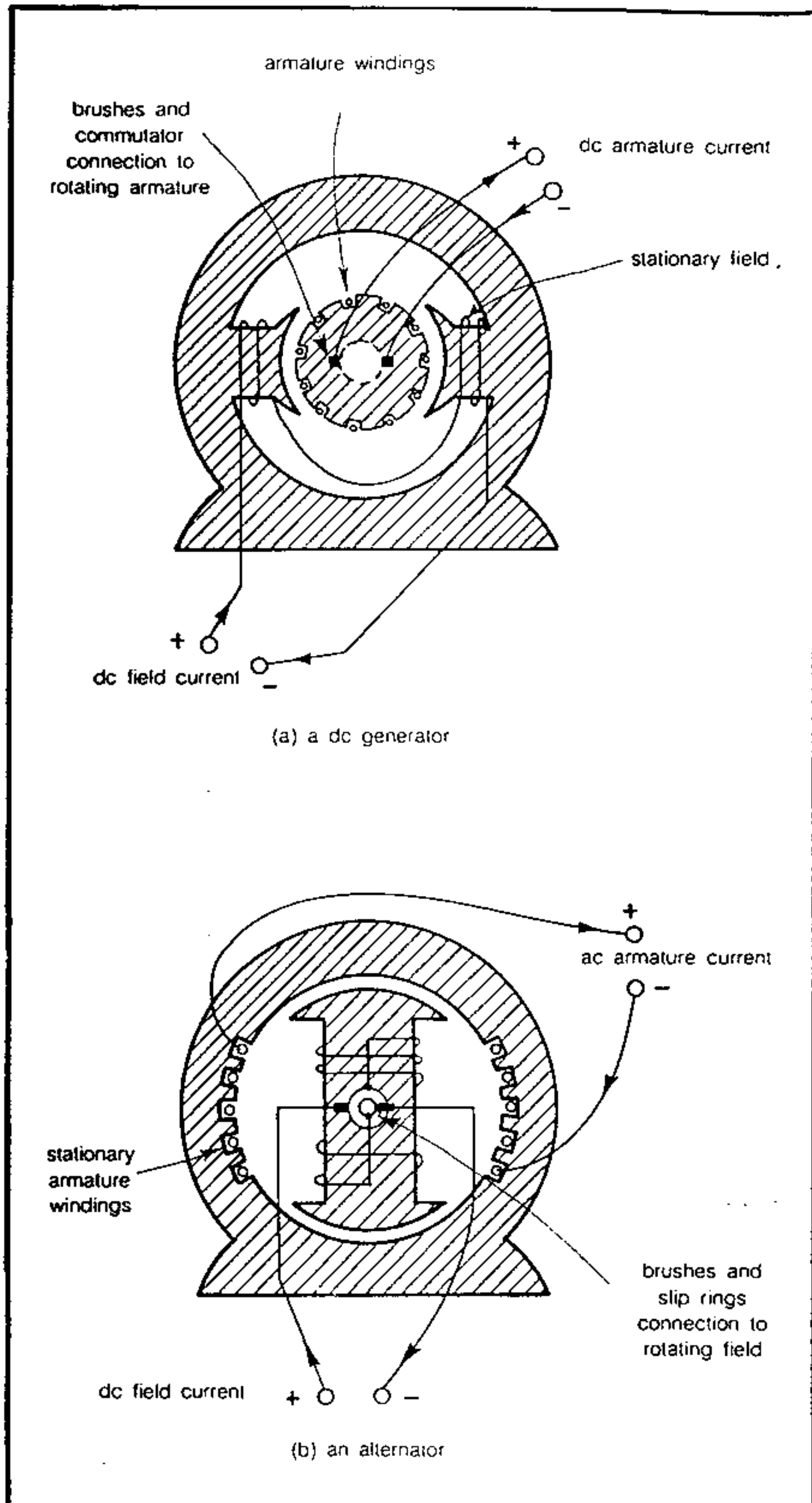
The motor works in the following manner. Before the beginning of operation, the blades are automatically set at the optimal starting angles (about 40°) and as the angular velocity of the windmill increases, they rotate to the working angles (13°). The springs of the moment regulator, enclosed in the housing (see Fig. 42), have a preset tension which corresponds to the nominal moment M_n. If the moment of resistance of the load M_r becomes greater than M_n, the hub of the windmill, overcoming the force of the spring, turns relative to the shaft, and the gears of the roots (see Fig. 81), rolling along the shaft gear, turn the blades so that the moment developed decreases. In the reverse situation, the hub is rotated by the action of the springs.

At $M_r < M_n$, the rotation frequency of the windmill begins to increase and centrifugal regulator 8 (see Fig. 42) comes into operation. Sleeve 1 of the regulator is connected with pull rod 6, passing inside the main shaft. Overcoming the resistance of spring 2, this sleeve is shifted to the right by the force of the regulator, and, through rollers and a sleeve with inclined slots connected with gears, rotates the blades so that the original rotation frequency is reset.

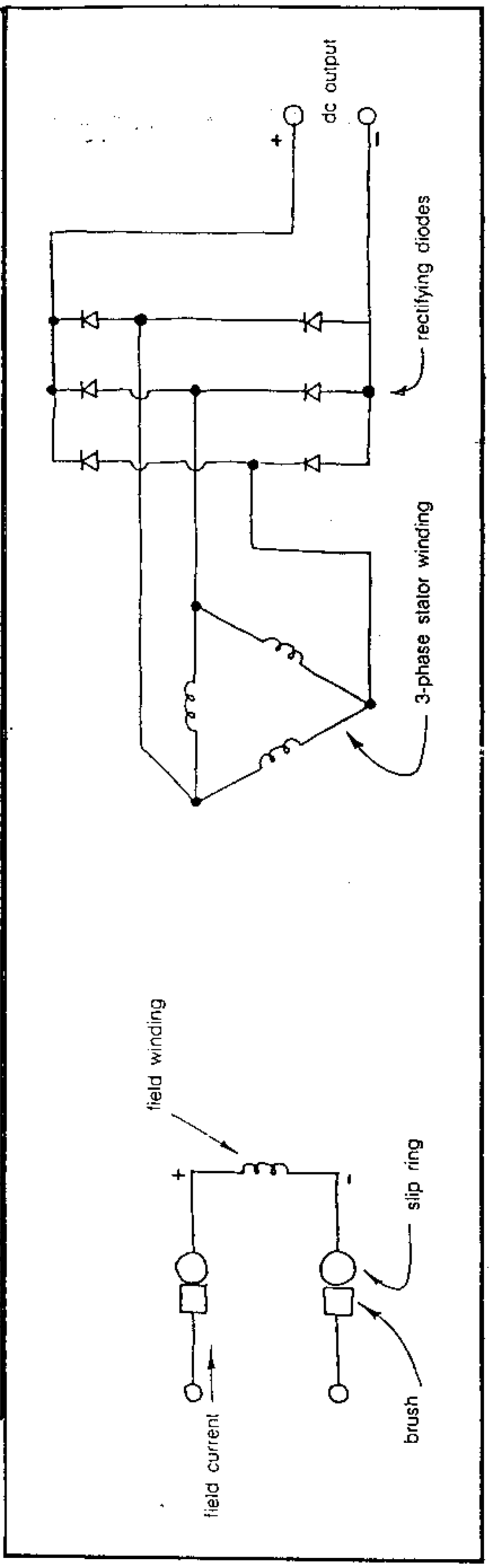
The motor is stopped with winch 11, by pulling on a cable connected with a lever. Having compressed spring 2, the blades turn so that M_{mo} becomes equal to zero. Depending on the velocity of the wind, the machine has the following characteristics:

Wind velocity in m/sec	4	5	6	7	8 and higher
Power in kW	0.8	1.6	4.5	7.3	12
Productivity in m^3/h:					
at H_Σ = 50 m	--	5.9	11.3	14.1	16
at H_Σ = 100 m	--	4.6	9.7	12	15

Other Homes & Garbage: Leckie et al. USA. 1975. ISBN 0 87156 141 7

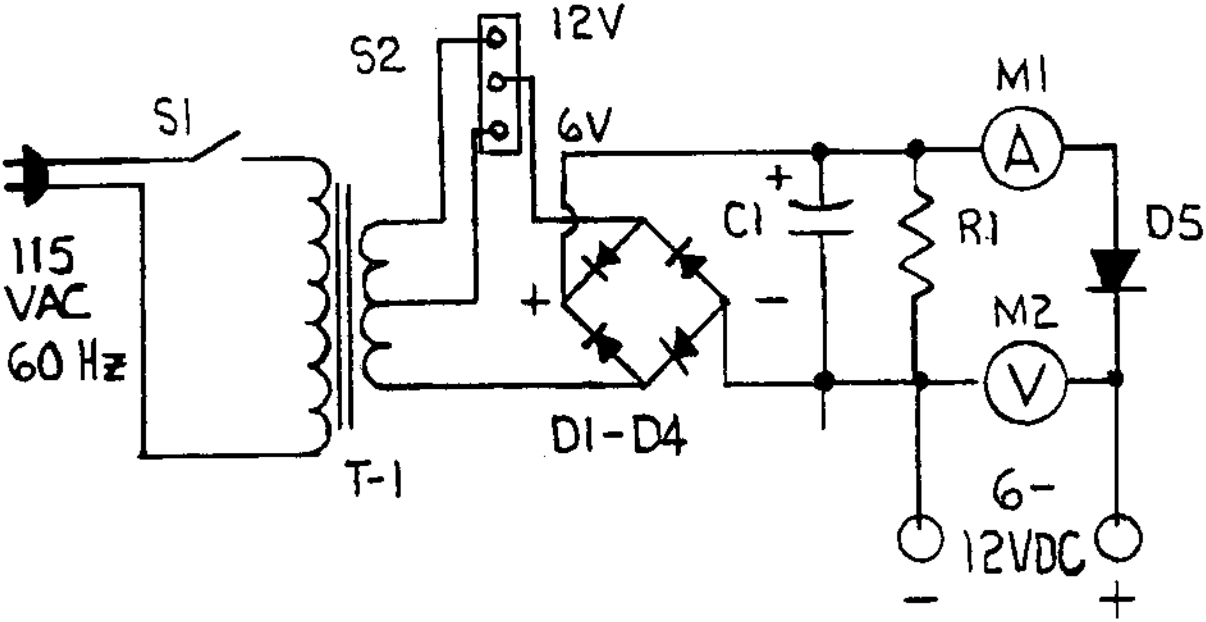


A dc generator (a) has a stationary field and a rotating armature, and an alternator (b) has a rotating field and a stationary armature.



Circuit diagram for an alternator showing the rectification of the 3-phase armature current.

6 OR 12 VDC BATTERY CHARGER



Parts list for Drawing

D1-D4	Diodes, 5 Amp, 25PIV
D5	Diode, 8 Amp, 25PIV
M1	DC Ammeter, 10 Amp Full Scale (minimum)
M2	DC Voltmeter, 15 Volt Full Scale (minimum)
R1	400-800 Ohm, Fixed (carbon) Resistor, 1 Watt
S1	SPST Switch, 1 Amp rating
S2	DPST Switch, 5 Amp rating
T1	Transformer, 12 volt secondary, 5 Amp, and centertapped.
C1	500MFD, 25WVDC, Electrolytic Capacitor

The following suggestions are based entirely on the excellent work recently done and published by Prof. P. la Cour in Denmark on behalf of that Government, which has in that particular placed itself ahead of other countries—considerably to the advantage of many of its villages and isolated dwellings. The reader must be prepared to experiment a little—not indeed in principles but in details of apparatus to suit his own case—but may rest absolutely assured that the method is quite practical and satisfactory.

There are two main difficulties in applying a power so variable and intermittent as wind to the production and supply of electricity. There must, first, be a means of automatically switching on the dynamo to a set of accumulators whenever the former is in a position to deliver current, the same apparatus cutting it out when the power falls away. Secondly, means must be adopted whereby an increase of wind-power beyond the normal amount required to just work the dynamo shall not affect the output by increasing either voltage or current. Both these ends have been attained by La Cour with the simplest apparatus imaginable.

A consideration of the second question raised will show why it is necessary to decide on a definite wind-velocity as being that at which any given windmill shall supply its "normal" output. By rating it low, say a wind of 9 miles per hour, it is possible to keep a dynamo working nearly every day in the year and for twelve hours out of the twenty-four. But the power of the wind at 9 miles an hour is only a quarter of that at 15 miles an hour, and although the latter only blows about half the total number of days in a year, and then for only about nine or ten hours a day, its total output is greater than the other. Another point to be considered is that a very small dynamo is much less efficient, so that a double loss is experienced if too much constancy of work is aimed at. Of course, in a large installation these points have less emphasis, and it becomes desirable to run the plant at a lower wind-rating (in other words, use a comparatively large mill), the only limiting factor being the initial cost of the plant.

In a wind-driven generating plant the following points should be noted. The windmill itself should be self-regulating (as, for example, that described in Chap. V.), and fitted with tail so as to turn to face all possible winds. The dynamo should be shunt-wound, so that an increase in the external resistance tends to raise the terminal voltage. If necessary, this tendency may be increased by having one or two resistance coils in series with the shunt-winding, these coils being automatically cut out as the external resistance rises and current falls. A low-speed machine is certainly preferable, the speed of a windmill being rather low itself. The accumulator is a vital point: it should have a large capacity, as on this depends its ability to maintain a supply over a longer period of calm; yet as it is undesirable for any accumulator to remain long at a low state of charging, care must be taken to avoid draining it—especially if a spell of calm weather seems likely.

The whole of the electrical apparatus is shown diagrammatically in fig. 73, the only part needing much description being the automatic switch, further illustrated in three views in fig. 74. This consists of two electro-magnets, EM, each like an ordinary bell-magnet, and wound with fine wire, but with an extra winding of a few turns of thick wire, exactly like a compound-wound dynamo field magnet. A horse-shoe permanent magnet, PM, is suspended so that its poles lie opposite and near to the poles of the electro-magnets, and swings by means of the pivot screws which work in a *brass* (or non-magnetic) block, B. This block also carries the copper rod CR, each end of which turns downward into the wooden cups 1 and 2, containing mercury, matters being so arranged, however, that the end 1 is always in the mercury whichever way PM is swung, while 2 only touches the mercury when that end of CR is drawn downwards.

The switchboards present no special features. By following out the connections it will be seen that any agreed number of cells can be switched on to the dynamo, while any independent number can be caused to supply the lamps. This latter arrangement is desirable to allow for drop of voltage during discharge, also to provide for losses in mains and for an extra cell or two in case of accident to others.

The action of the automatic switch is as follows: Assuming the dynamo to be still, or running at too low a speed to furnish current, it will be seen that the battery is energising the electro-magnets EM through the fine wire-coils, the current passing also through the armature of the dynamo. The winding of EM is such that the current in this direction attracts the poles of PM to the right and so raises the end, 2, of CR out of the mercury. Only a very small current is required, or allowed, to be thus wasted. Supposing now the wind to increase sufficiently to raise the speed of dynamo so much as to be able to supply current, the first effect will be to reduce the current in EM to nil and then to reverse it, altering the polarity of the electro-magnets and throwing the lower end of magnet PM over to the right. This, by dipping the end 2 of CR into the mercury, makes connection between the dynamo and accumulator, the charging of which at once begins. The effect of the thick-wire coils on EM is to hold the magnet switch more securely during charging. The opposite action—that of throwing out the dynamo when the speed fails—is obvious on inspection.

There would be twelve accumulator cells, each of from 150 to 200 ampere-hour capacity, which would be easily capable of dealing with the full current for twenty-four hours' continuous charging. The capacity mentioned is the maximum suitable for the given plant, but the minimum may be anything down to twelve pocket-batteries, if so desired. Within the limits given, the greater the capacity the more the independence of conditions of wind.

With regard to the automatic switch, a little experimenting and adjusting will be needed to ensure its correct working. The electro-magnets may be two ordinary bell-magnets, wound with No. 36 wire, the bobbins being about $1\frac{1}{4}$ inches long and 1 inch diameter outside. A resistance may be needed in series with this winding, or the effect may be tried of connecting up only six of the cells to these coils, the six on the left-hand side in fig. 73 being, of course, selected. All four bobbins will be joined in series. Over the fine wire on each bobbin will be wound from six to twelve turns (to be determined by experiment) of No. 16 or 14 gauge cotton-covered wire, the winding being in same direction as the fine wire in each case, so that the current is a reinforcing one when being supplied from the dynamo. The balance of the permanent magnet can be adjusted by moving the copper rod CR either to right or left.

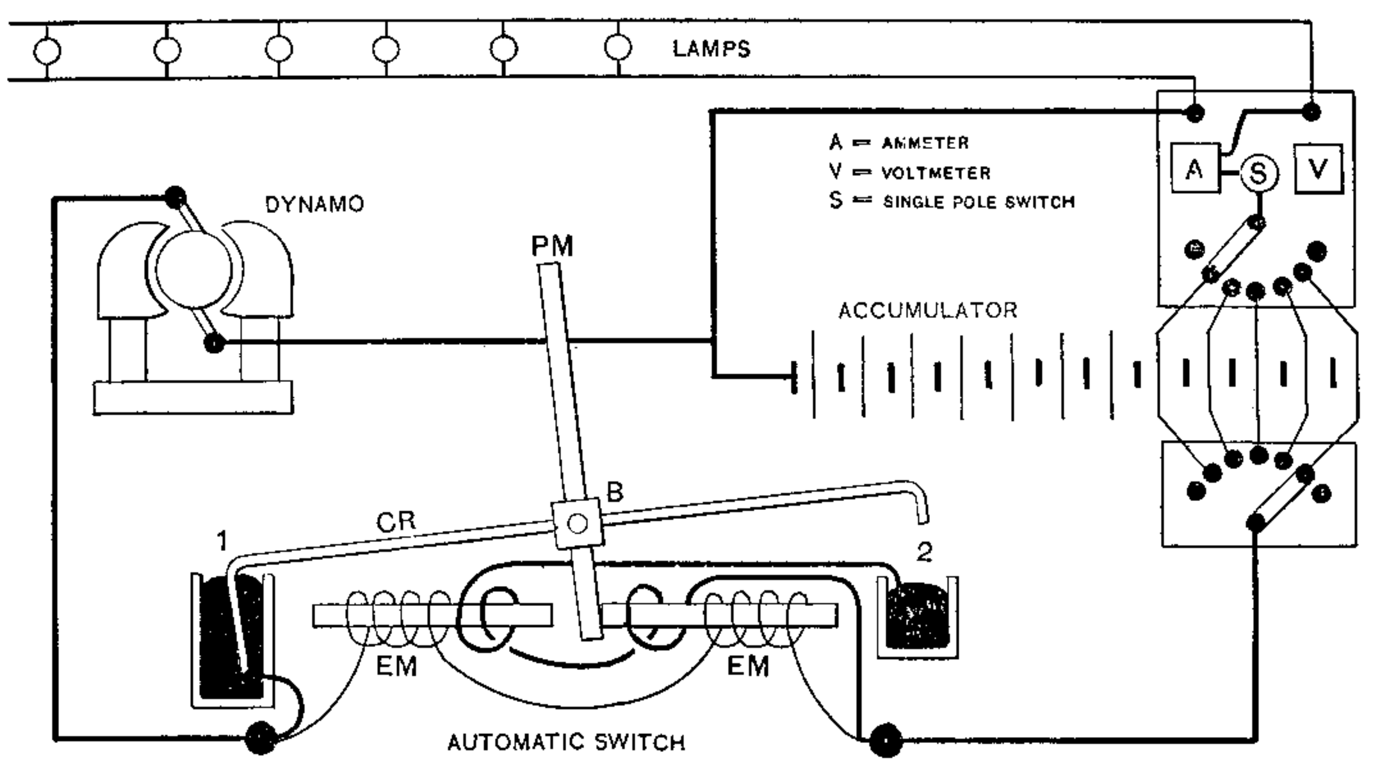


Fig. 73.— Diagram of Connections for a Wind-driven Electrical Installation.

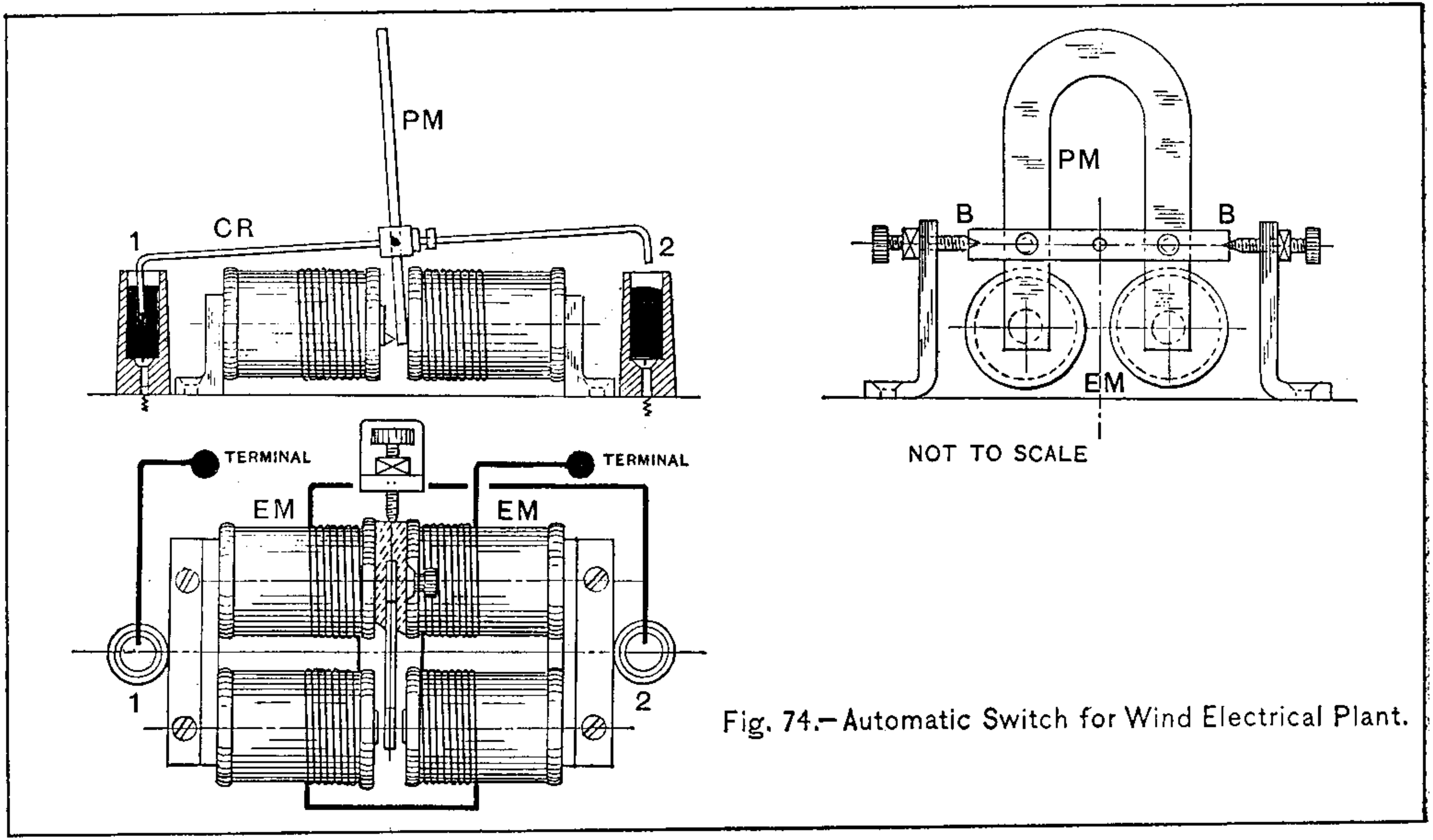
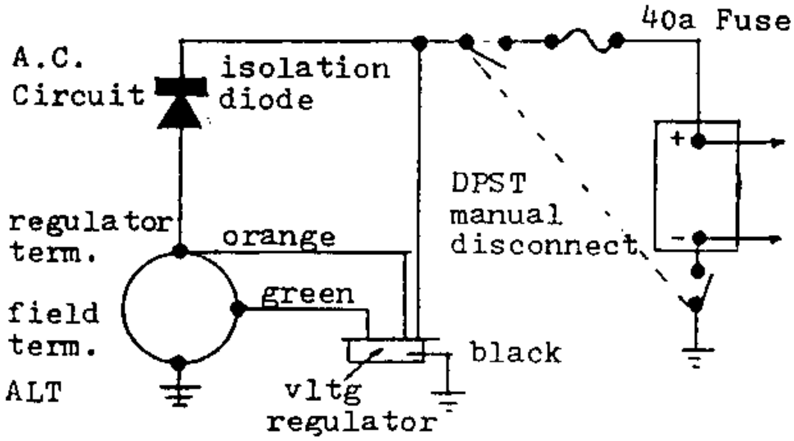
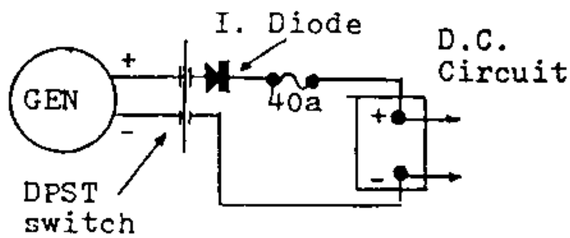


Fig. 74.—Automatic Switch for Wind Electrical Plant.

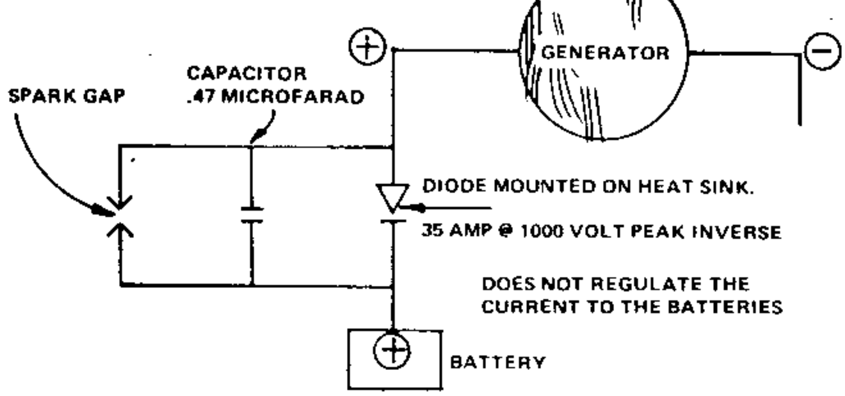
CHARGING CIRCUIT

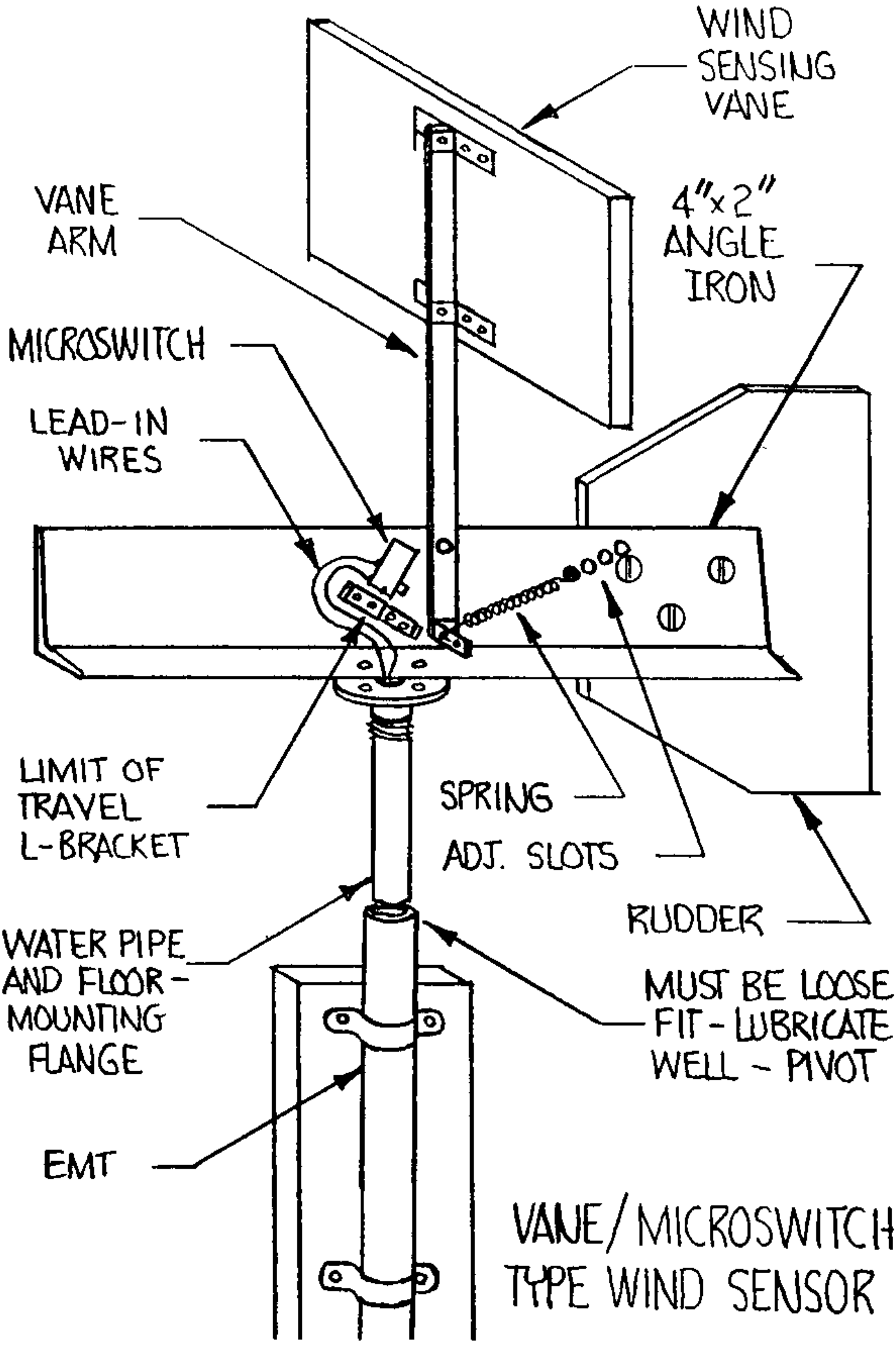
There are two basic charging curcuits, one using a PM DC generator, and one using an automotive alternator. In this case, we shall assume that the alternator is a newer model that has internally mounted rectifying diodes. In the alternator case, you can see that the field terminal requires current from the battery to create a surrounding field around the armature to facilitate charging. The PM DC generator is a much simpler system, and is recommended if one can be found in your area.





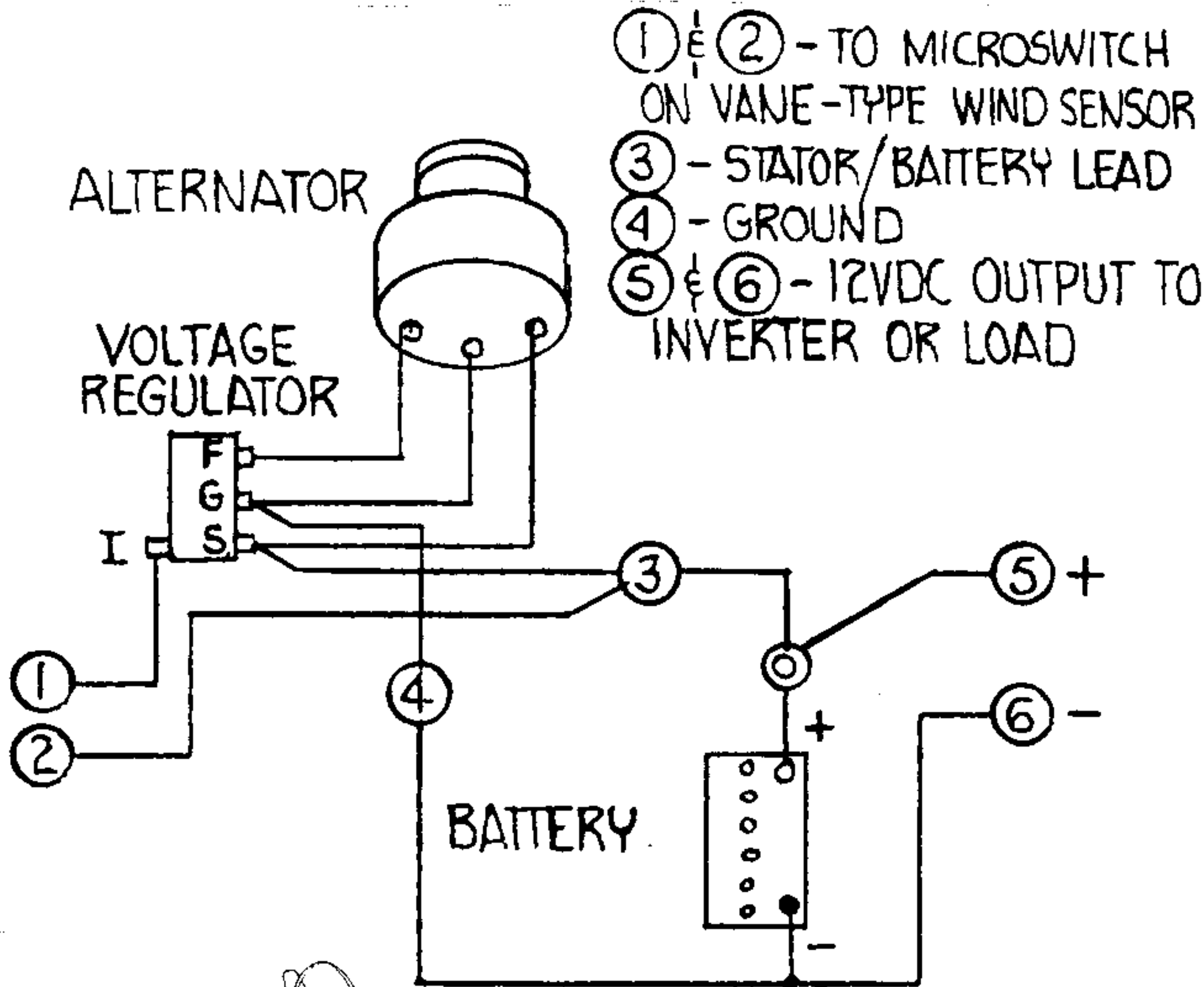
WIRING DIAGRAM FOR PRIMITIVE "CONTROL BOX" ON 110 VOLT WIND GENERATOR (PRIMARILY AN ANTI-MOTOR DEVICE, AND PROTECTION AGAINST LIGHTNING)

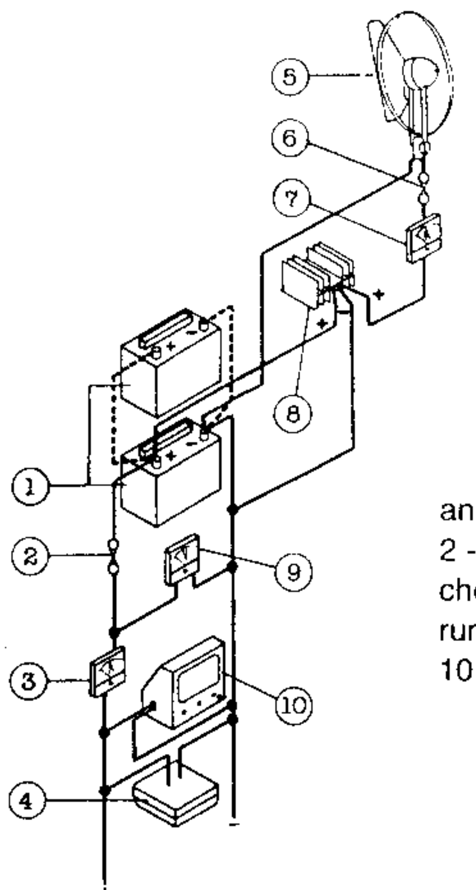




VANE/MICROSWITCH-TYPE WIND SENSOR

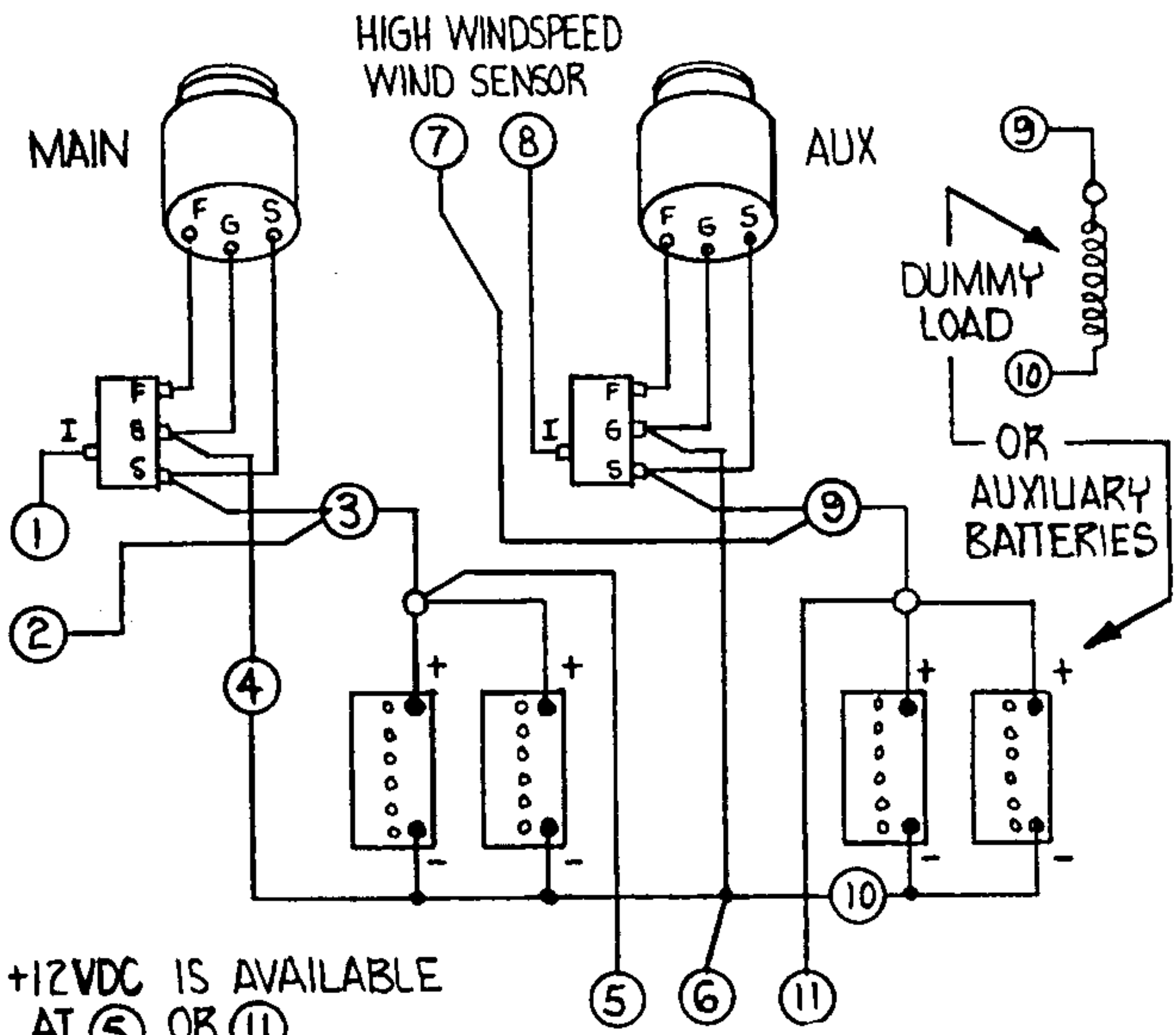
BASIC WIND/ELECTRIC CONTROL CIRCUIT





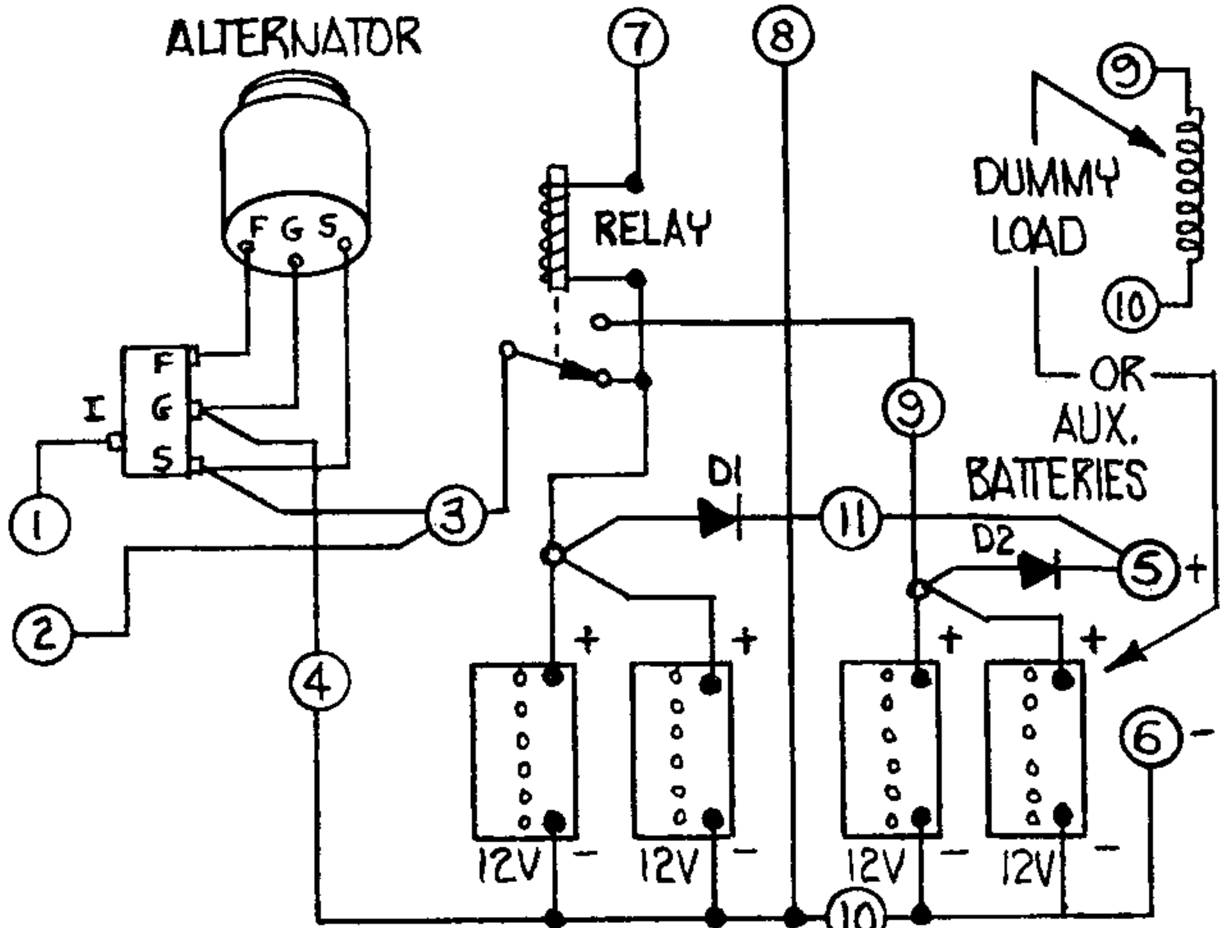
Schaltbeispiel mit Meßpunkten und Meßinstrumenten an einer kleineren Windgeneratoren-Anlage: 1 - Anlagenbatterie; 2 - Sicherung; 3 - Amperemeter (Stromabnahme der Verbraucher); 4 - Leuchte; 5 - Windgenerator (Rutland 500); 6 - Sicherung (5 A); 7 - Lade-Amperemeter; 8 - Laderegler; 9 - Voltmeter; 10 Fernseher (Conrad Electronic)

AUX. ALTERNATOR/BATTERY CONTROL CIRCUIT



+12VDC IS AVAILABLE AT 5 OR 11

RELAY/AUX. BATTERY CONTROL CIRCUIT



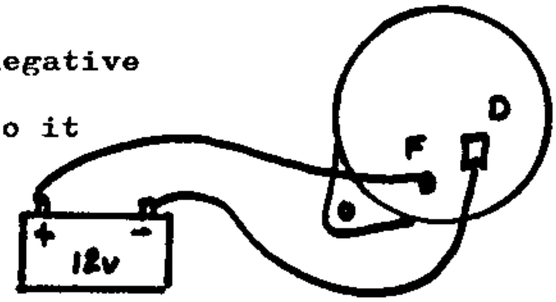
NOTE: IN THIS DRAWING, D1 & D2 PERMIT SIMULTANEOUS USE OF MAIN & AUX. BATTERIES. THIS OUTPUT CAN BE WIRED AS SHOWN IN FIG. 4-8, WHICH IN TURN CAN BE WIRED AS SHOWN IN THIS DRAWING (USING DIODES).

Wind generator-JEPH 10: Jemmett Engineering Pinner Middlesex UK. 1994.

USING A CAR DYNAMO

The most suitable car dynamos to use are Lucas C40 or C41 (22 amp) or Lucas C40LO or C41LO (25 amp).
These dynamos start to charge at 1100-1200 rpm and are self exciting.
However before use they must have the field polarised, negative earth is normal.

To polarise the dynamo to negative earth.
Connect a 12v car battery to it as shown for 2-3 seconds.



Voltage regulated version (see Fig. 6)

This version is wired basically the same as a dynamo on a car.
The wiring diagram shows a C40 dynamo and regulator box from a Mini car. (other dynamos are the same or similar)
It is recommended that a fuse is fitted as shown.

Car dynamos must be driven in the direction of the arrow marked on the case

Un-regulated version (see Fig. 7)

This version is very simple to wire up and requires no regulator box.

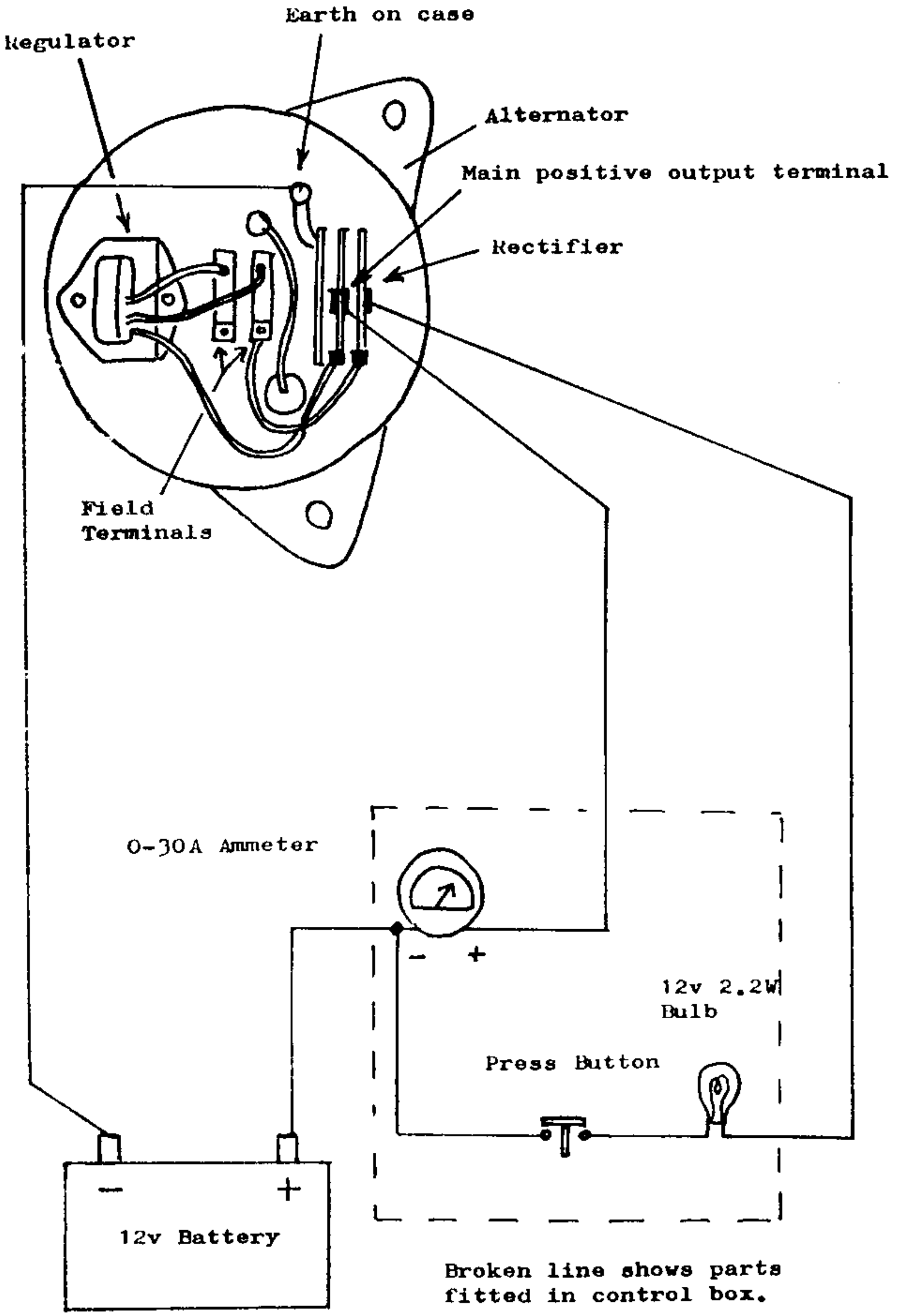
The field is connected directly to the dynamo output by wiring a link between the F and D terminals.

To stop the battery slowly being discharged by the field a blocking diode is fitted.

The diode, ammeter and fuse are mounted in the ground control unit.
The diode (30 amp, 50 volt) is mounted as shown on an insulated aluminium sheet.

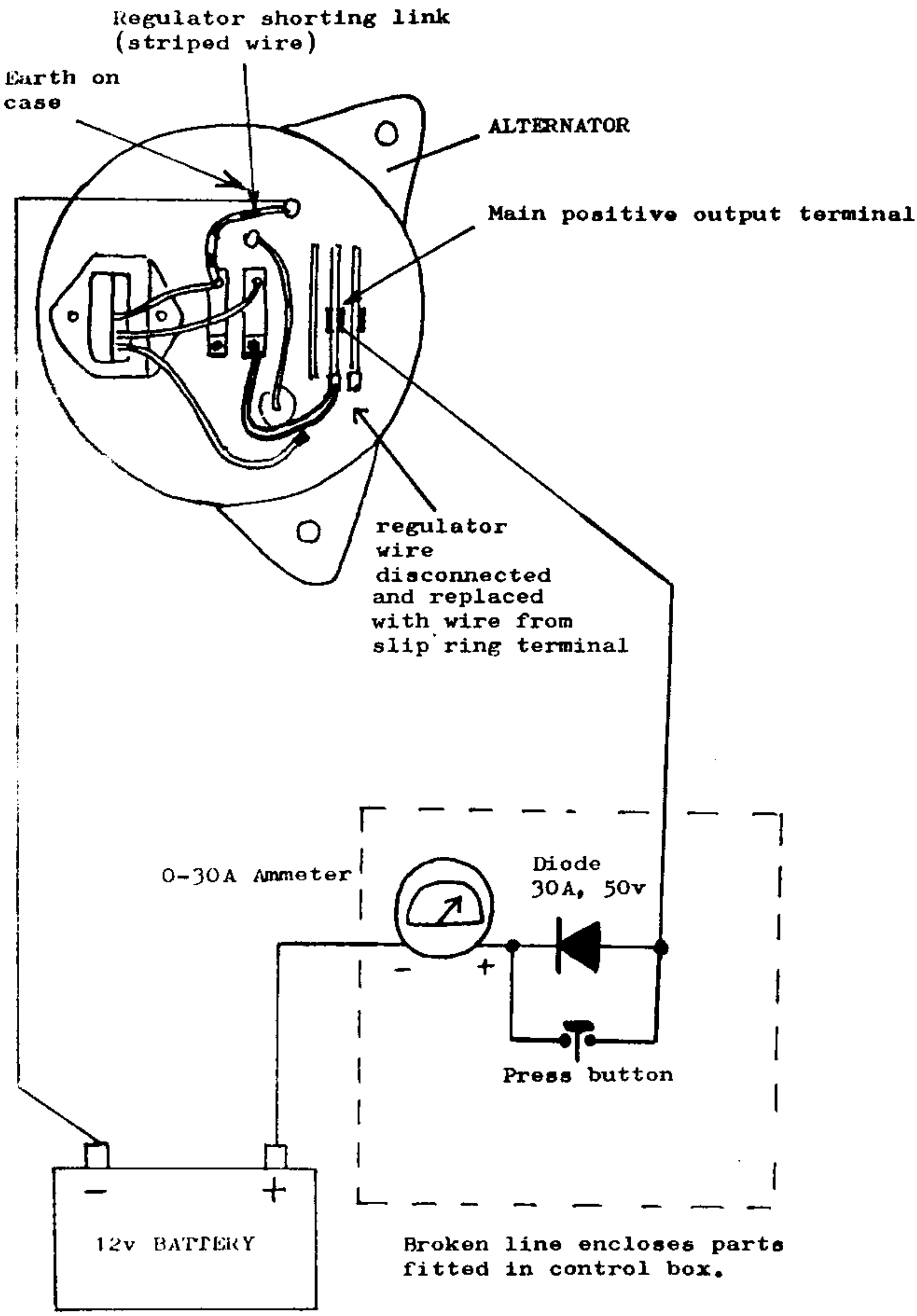
As with alternators, the dynamo must not be run without a battery connected unless a short circuit is put across the dynamo output.

FIG. 4 -- 12 VOLT REGULATED VERSION WIRING DIAGRAM - ALTERNATOR



Broken line shows parts fitted in control box.

FIG. 5 -- 12 VOLT UN-REGULATED VERSION WIRING DIAGRAM



Broken line encloses parts fitted in control box.

FIG. 6 - GENERATOR WIRING DIAGRAM

VOLTAGE REGULATED VERSION

Note: Some control boxes have
a 'B' terminal instead of
'A1' and 'A'.
Wire 'B' the same as 'A1'.

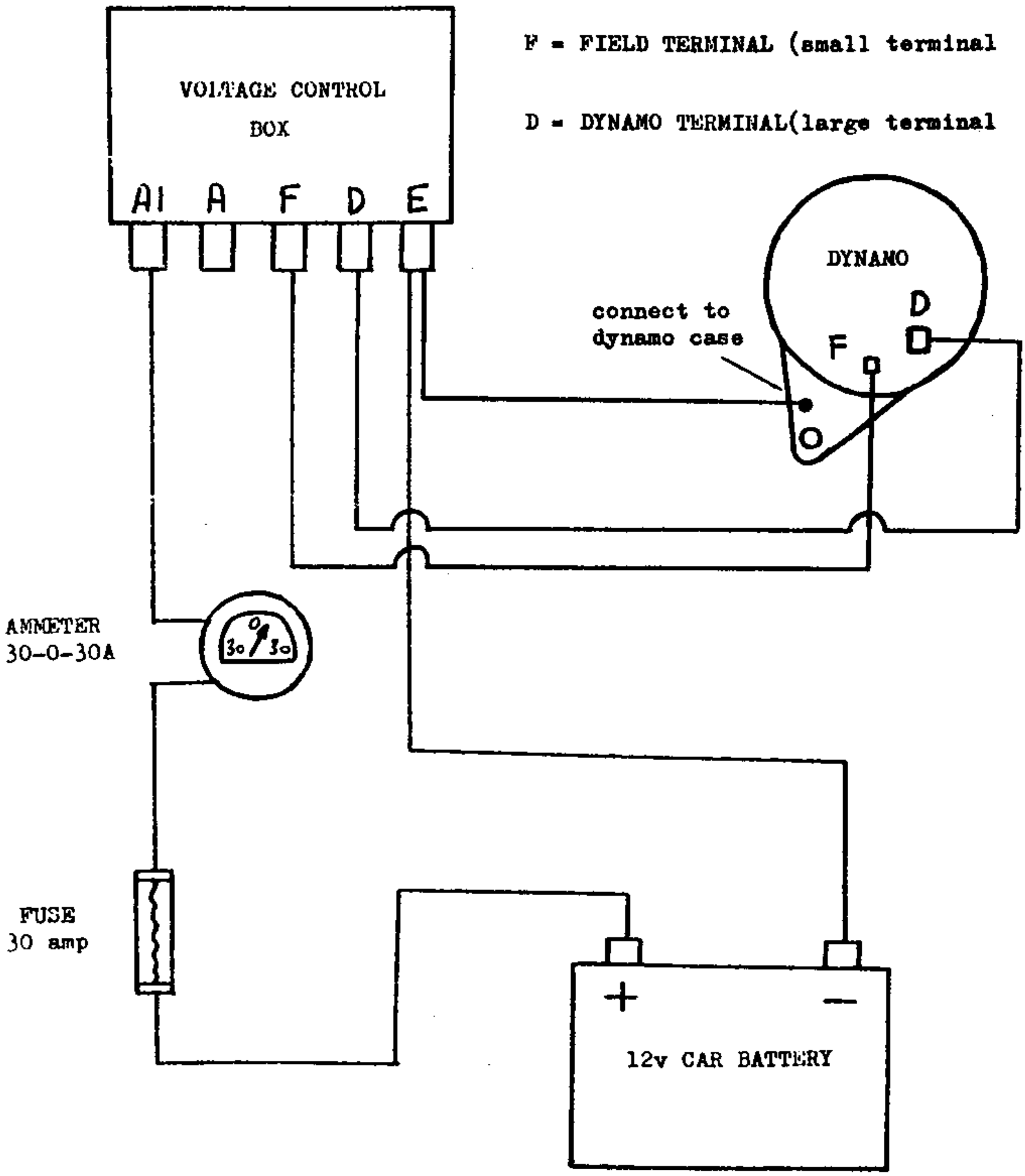
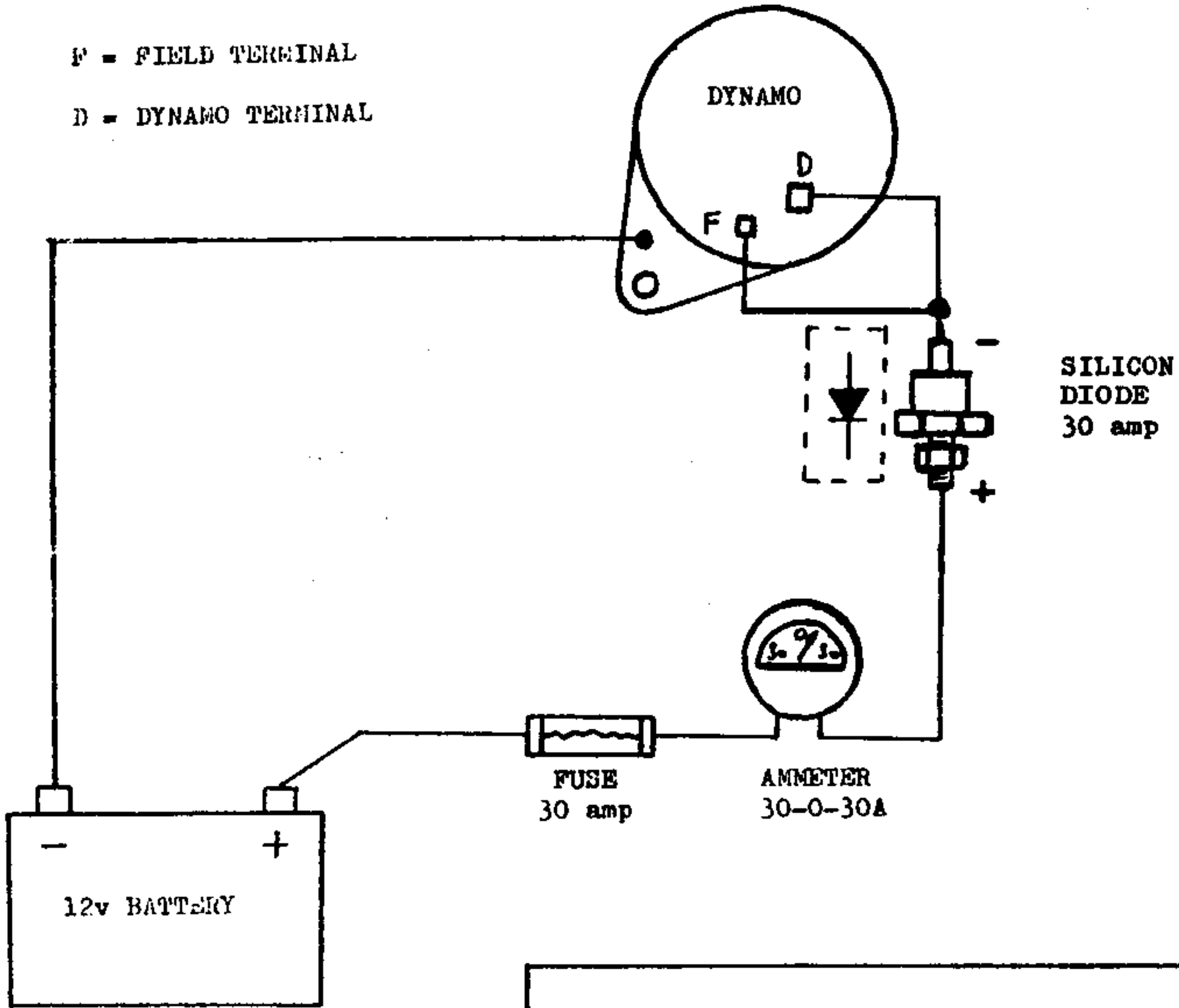


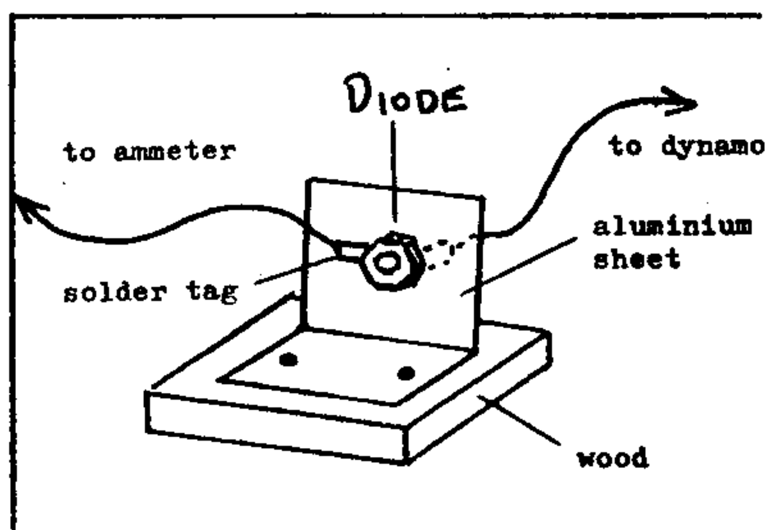
FIG. 7 - GENERATOR WIRING DIAGRAM

UN-REGULATED VERSION

F = FIELD TERMINAL

D = DYNAMO TERMINAL





Diode Mounting

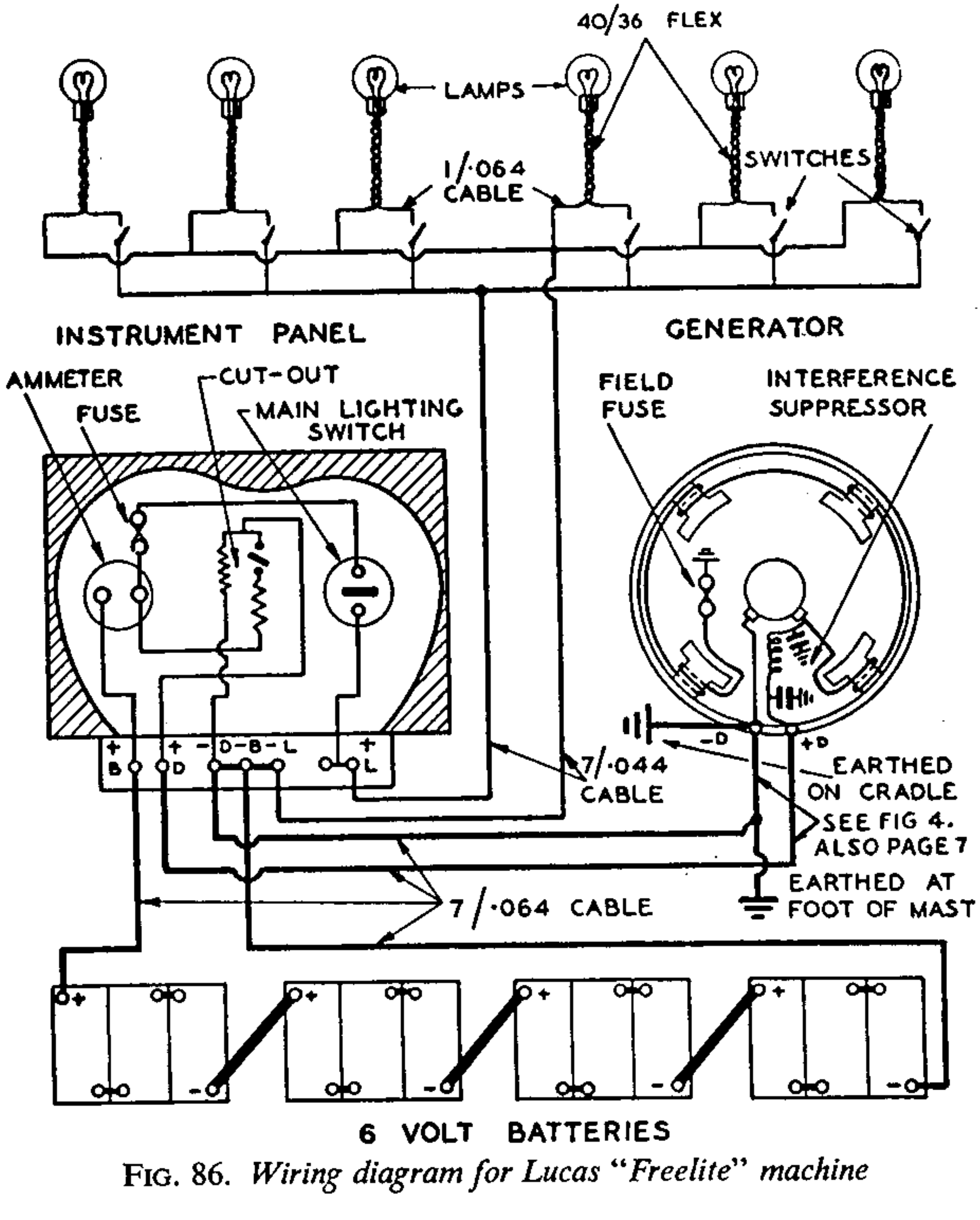
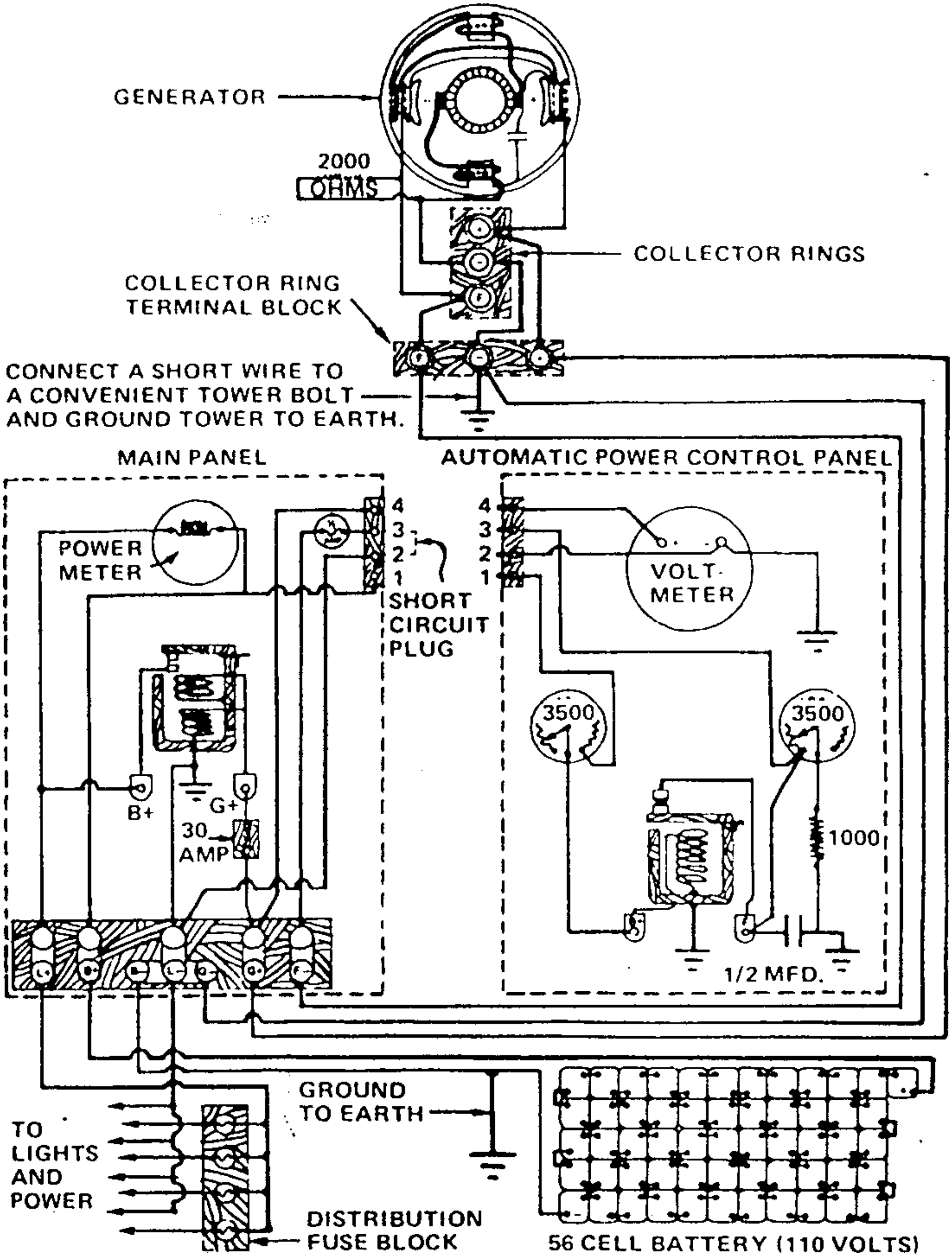
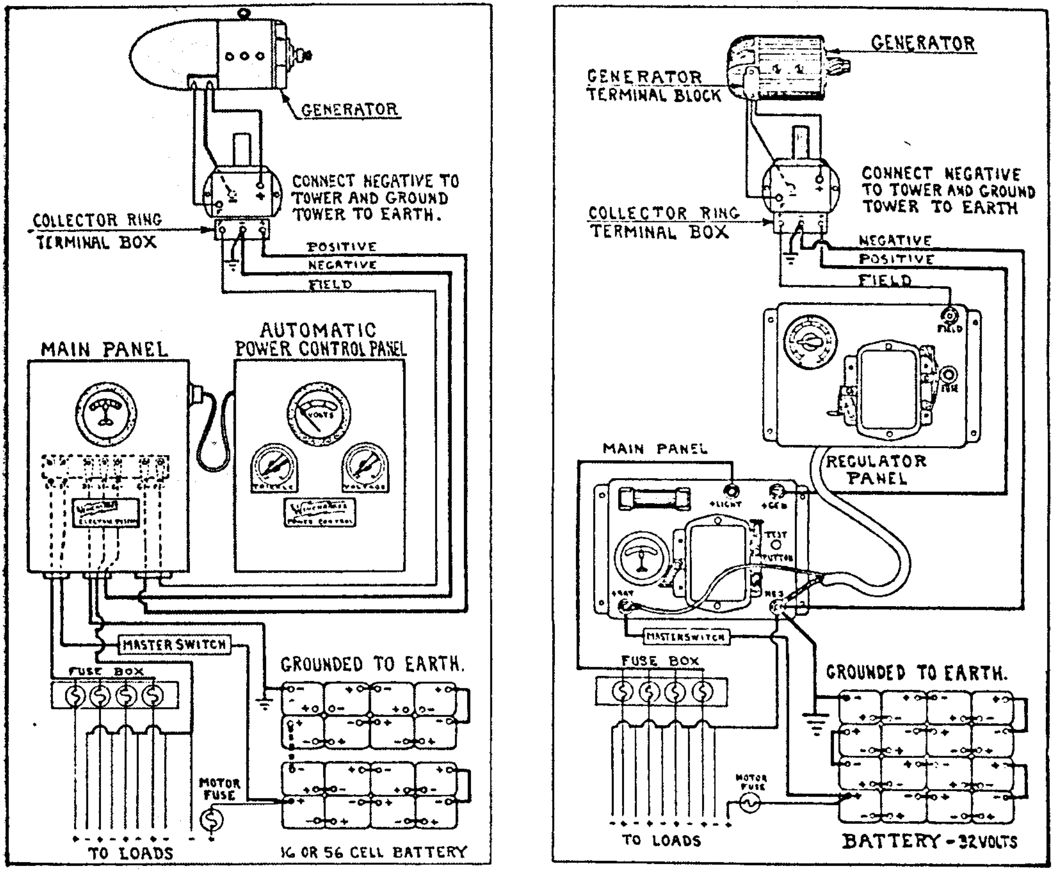


FIG. 86. *Wiring diagram for Lucas "Freelite" machine*



COMPLETE WIRING DIAGRAM FOR MODEL 1107



Two different wiring systems used by Wincharger

A Simple Control Box

With the smaller Winchargers manufactured in the pre-REA period, a very simple and small control box was installed. Fig. 5-20 gives a wiring diagram for this unit and, compared to the ones we'll soon be discussing, you can see that there is not much to it. It didn't do an awful lot but then it didn't have to -- the wind machine that it was controlling was a relatively low-power unit and overcharge on one of these units is almost a joke.

Basically, the control box contains a cutout relay, an ammeter (two-direction type), two fuses (one for the load and one for the windplant generator), and a PTT (push-to-test) switch. Notice that there is no voltage regulator relay; the field coil on the generator is grounded at the windplant. Becuz it was relatively low-power, this control box counts on the spoiler (air-brake) installed on the windplant to slow it in very high winds. If the windplant does put out more than it ought to (in current), it blows the fuse. Truly a "poorman's" control box. If you are building a small windplant (capable of less than 400 watts), this will probably do the job well. The RPM that the propelle would achieve with these small units is phenomenal, but a six-foot blade can take a lot if it's fairly well balanced. Or at least you have to believe it can.

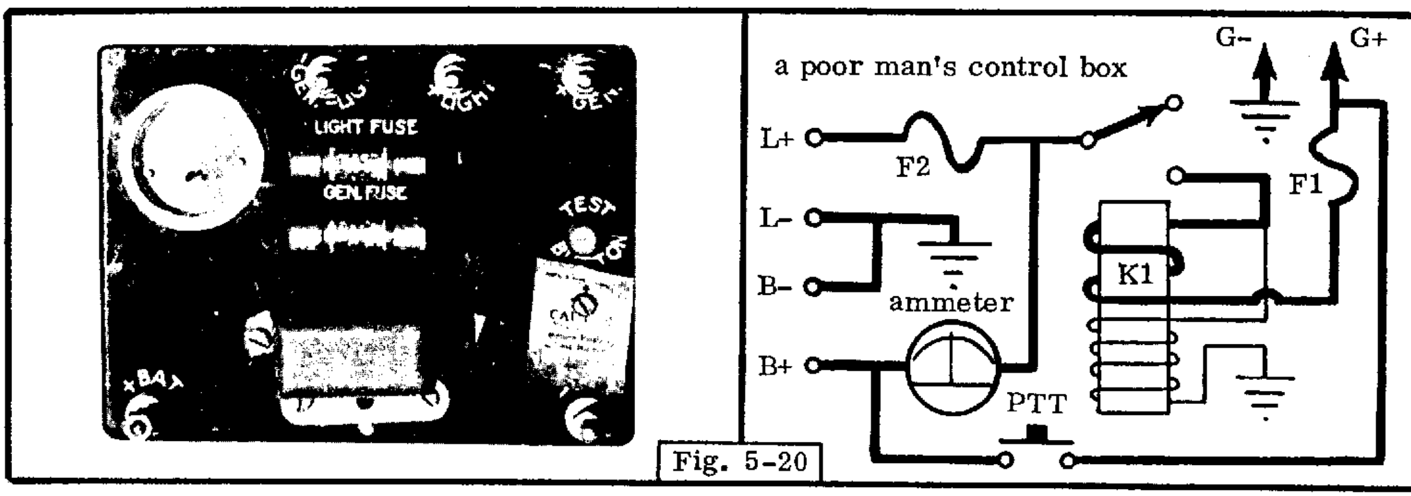
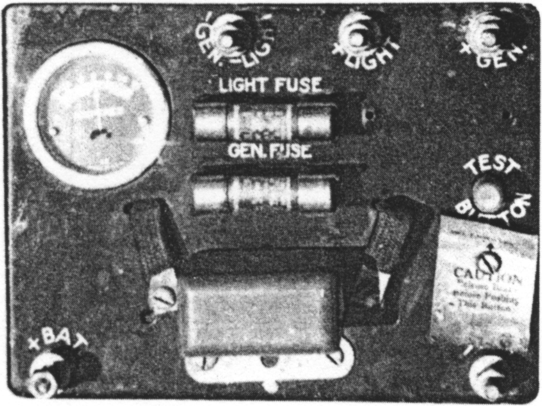


Fig. 5-20

Let's trace the path of current in this unit. The generator current goes through the heavy coil on the relay but is blocked by the open switch, so it goes through the smaller winding of wire on the relay. When the voltage from the generator is sufficient to begin charging, the current in this part of the relay will be sufficient to pull in the relay and close the contacts. Now the current will flow into the batteries thru the ammeter. When the windspeed drops, the windplant will slow; when it's at a lower voltage than the battery voltage, current will flow in a reverse direction thru the heavy wire winding and this will neutralize the magnetic field of the small-wire winding-portion of the relay and the contacts will open. If the wind is not present, and you want to be sure that all is okay with the windplant, you can hit the PTT switch and this will short the batteries out to the generator and motor the windplant; if it starts turning up there, all is okay. If it doesn't, the batteries are dead or the windplant is frozen up or has a broken connection somewhere.


GEN. -LIGHT
+LIGHT
+GEN.
LIGHT FUSE
GEN. FUSE
TEST BUTTON
CAUTION
+BAT

As it might be difficult to find a relay that will energize for your maximum desirable current, an alternative to finding a current regulator relay would be the circuit described by Fig. 5-10; here you can use your own homemade coil of heavy copper or baling wire and insert a relay and rheostat in parallel with the coil. The small amount of resistance in the heavy coil will cause, at high current transfers, a small amount of current to go through the rheostat and relay and in this way the same effect is accomplished as would be in the current regulator relay itself. Adjustment of the rheostat will allow you to set the relay to energize at whatever current flow (through the generator) is in excess of its maximum current rating. The cost of the smaller relay, rheostat, and coil will be, in most cases, far below that of a genuine current regulator relay.

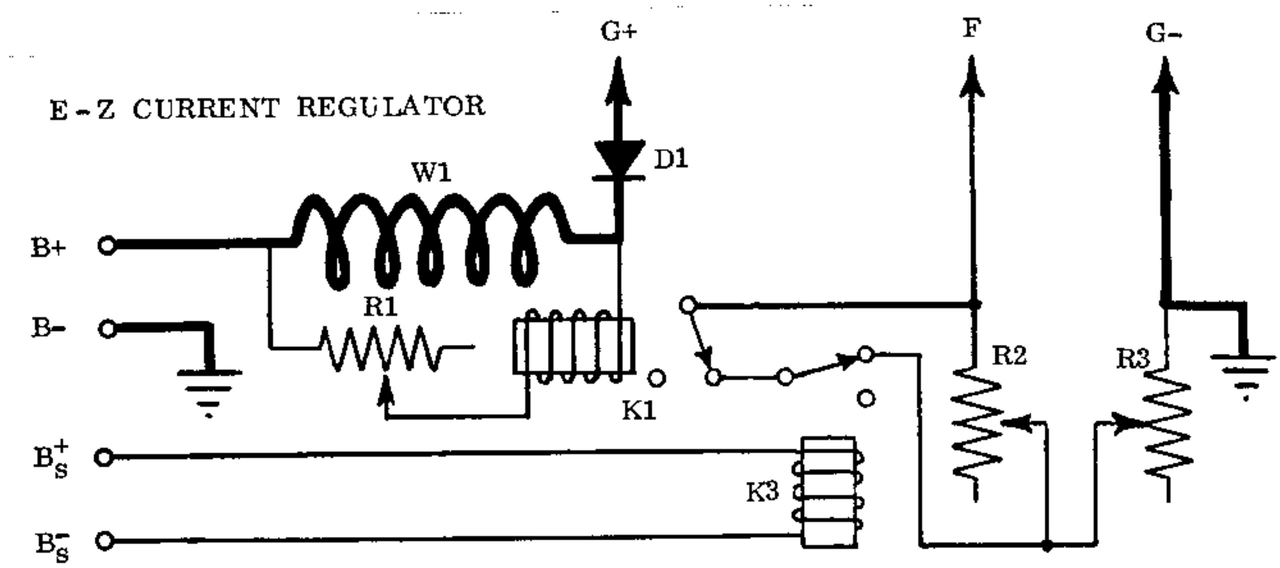
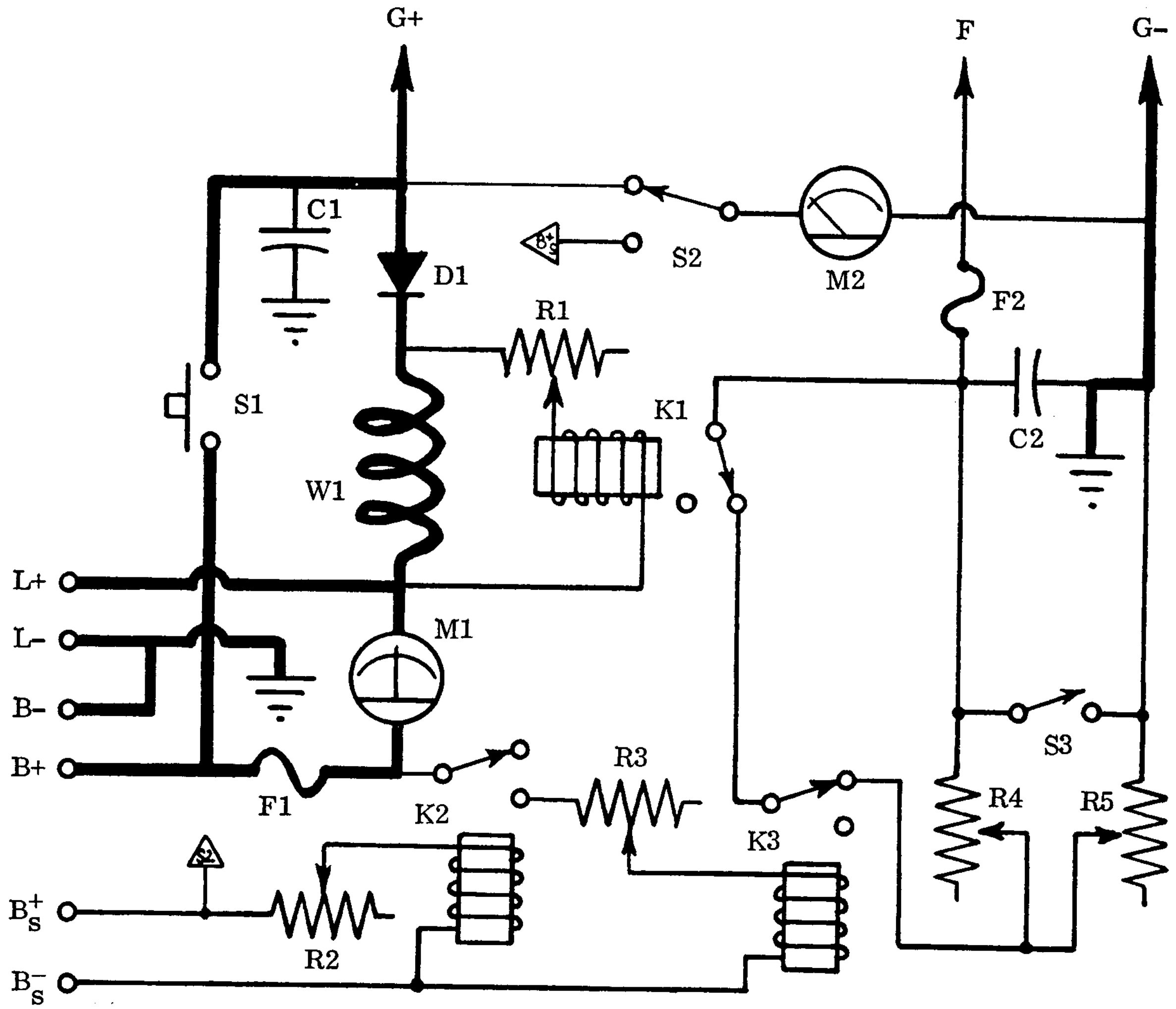


Fig. 5-10

An Owner-Built Control Box

While all of the control boxes discussed thus far have included most of the necessary control functions desired in a wind-electric system, each one of them is lacking in some respect or another, or they utilize components that could be replaced with more available, reliable, or inexpensive circuitry or components that would provide maximum protection and efficiency of energy conversion. Fig. 5-23 is a schematic representation of a circuit that would fulfill all of these requirements for the owner-built control box. A description of its components, functions, and combined effect follows, along with guidelines for component selection, construction, testing, adjustment and troubleshooting.

It's normal for the Diode D1 to get hot in high-current operation -- too hot, unless it is mounted in some kind of heat sink. This will be a finned hunk of aluminum which helps dissipate the heat



AN OWNER - BUILT CONTROL BOX

See text for component descriptions

Fig. 5-23

The main power circuit (from generator to batteries) in Fig. 5-23 is essentially the same as that described in Fig. 5-10; in this instance, however, fuse F1, switch S1, and ammeter M1 are added to complete the requirements. The coil of wire W1, rheostat R1, and relay K1 form the current regulation function. A large amount of current flowing through the coil W1 will, depending on the adjustment of R1, energize relay K1 and cause the field current to be decreased. (It must pass through rheostats R4 and R5.) The optional PTT switch (S1) is added only for those windplants utilizing DC generators; this allows the windplant to be motored by the batteries for testing purposes. Without this switch, the same connection can be made with a temporary wire or a metal tool. The only additional component not previously discussed is capacitor C1, which is a decoupling capacitor and it will serve primarily to bypass noise pulses that can cause interference (in nearby radios, stereos, and your neighbor's TV). M1 is a plus-and-minus reading ammeter (from Fig. 5-11).

The voltage-regulation circuit in the home-brew control box is the same as that described in the text and by Fig. 5-7. If the individual windplant owner is unwilling to install battery-sensing wires ($B+_s$ and $B-_s$) as described in Fig. 5-6, then the wires for relay K2 and resistor R2 can be attached to the B+ and B- terminals. If the battery sensing wires are used, note that the common contact of relay K2 is connected to B+; this can be connected to $B+_s$ instead. R2 allows adjustment of the voltage at which K2 energizes. With K2 energized (voltage is too high), K3 will also energize; R3 will serve to limit the current flowing in the coil of relay K3, but this may not be necessary if the relay coil is rated at the voltage the wind-electric system uses. It will, however, allow a lower-voltage relay to be used without damage.

Rheostat R4 and R5, fuse F2, capacitor C2, and switch S3 form the field circuit in the control box. C2 decouples the field circuit (like C1) and fuse F2 is to protect against field wiring shorts. Note that the field current will pass through the contacts on relay K1, the contacts on relay K3, and pass through R5 to ground; this gives maximum current to the fields (and maximum windplant output) when these relays are not energized. If the windplant produces too much voltage, relay K3 will energize and open its contacts, breaking this path; field current will then be less becuz it must travel through rheostat R4 as well as R5. If the windplant puts out too much current, relay K1 will energize and open its contacts, breaking this path again with the same consequence. Rheostat R4 is adjusted to the maximum taper-charge current for the batteries used and R5 is adjusted (under high wind and low battery conditions) to limit windplant current to the maximum rate the batteries can handle. If a large (amp-hour) capacity battery bank is used, R5 is somewhat optional becuz relay K1 will provide over-current protection; both are needed, however, wherever relatively low-capacity battery storage is used.

Switch S3 is used to bypass rheostat R4 and defeat the action of automatic field control for the windplant; this should only be used if the batteries require an equalizing charge. Care must be taken not to leave this switch in this position for very long. The equalizing charge must be given to batteries to prevent sulphation from building up in some of them, particularly if many cells or batteries are connected in series to obtain higher wind-electric system voltages. If you have a standby generator (Chapter 6), this can do the equalizing charge function every 2-4 weeks, but the windplant can do it as well if the wind is around (no use wasting fossil fuels to do it). How long it has to be done depends on the total amp-hour capacity in the storage batteries, the power the windplant will produce during the equalizing charge, how long the batteries have gone since the last time this was done, and if they have been receiving good charging from the windplant in the meantime. Equalizing charge current will, as a rule of thumb, be twice the taper-charge current so you must pick a day when the wind is moderate but not strong. The charging time will usually be 5-15 hours depending on the various parameters already indicated. If this bugs you, the alternative is to use the standby generator and just insure that the thing is turned off after a while!

The remaining function in our homebrew control box is reading voltages; the circuit consists of voltmeter M2 and switch S2. One side of the meter is hooked to ground and the other to the common position on S2, which selects either the generator or battery voltage. The switch should be set to normally read generator voltage.

Wires in the control box for the power circuit -- generator, battery, and load -- should be large in size and short in length (where possible); the thicker lines in the schematic (Fig. 5-23) represent these large wires. Once you've obtained the components and installed them in the selected box, you'll need to make up a physical wiring diagram from the schematic. Neatness is a real asset in the control box, so the wires may be longer than straight connections between points. Indicate wire sizes and color on the wiring diagram, and it will make connections easier, correct, and save hours of checking after it's completed to find mistakes evidenced by an incorrectly operating control box.

Notes on Control Box Components

The values of components in the control box depend on what voltage and current your windplant will produce, the capacity of your storage system, and how fancy (and expensive) you want it to be. If you don't outright know how to proceed with the information I've provided thus far, then obtain a copy of some basic electronics text and, perhaps, a course in basic electronic construction (soldering techniques, wiring procedures, selecting and adjusting component values). Only a book-length treatment is going to arm you with all the information needed to build the finished box that you will want to install with your wind-electric system. So that you'll have some idea of where to start, I'll go thru a few of the parameters not included thus far. The terminology that I use may not be familiar, but once you find out what it does mean, it'll clue you to where to find any other info.

Relays

(1) The value of relay K1 will depend on the current rating of the windplant and not its voltage; in most cases, it will be a low voltage, low coil-current relay with a contact rating of 5 amps. Relays K2 and K3 should be rated at the windplant voltage or lower (never higher) and should also have a low coil current (high coil resistance). The contact rating of K2 need only be about 1 amp but relay K3 will have the same contact rating as K1 (5 amps).

Obtain sealed or enclosed relays, if possible; they will give better service if the contacts are not exposed to air or dust. I prefer the clear glass or plastic ones becuz you can see the contacts and this is helpful if you are trying to see the relay operate.

One way to avoid the cost of high contact (current) ratings for relays is to buy multi-contact relays (if you can find them less expensively) and to series the contacts. Do not confuse this with paralleling the contacts or you're going to crisp 'em right off. If you've got a relay of the correct rating for your control box and it has more than one set of making or breaking contacts (as required), you might as well connect them in series as well, to insure long contact life.

Be aware that relays K1 and K3 use "breaking contacts" (when energized they break a connection, not make one) and relay K2 uses "making contacts". When you buy the relays, the contacts will generally be discussed in terms of normally open or normally closed; this describes them not-energized. So . . . relays K1 and K3 will be listed as "normally closed" and relay K2 will be described as "normally open".

(2) The value (resistance) of all rheostats will depend very heavily on the field current rating and the windplant voltage. R1 is the only exception here; it's resistance will depend on the current rating of the windplant, the value of the relay K1, and the resistance of W1 (the current regulator shunt coil). Resistor R2 and R3 values depend on the windplant voltage, and the coil current and voltage of relays K2 and K3. Rheostats R4 and R5 values will depend on the amount of current required for the field coils of the windplant generator or alternator. An important point to remember here is that, if you halve the field current to the windplant, you will not receive one half the power it produces at full field current (but sumthin' quite a bit less); this is becuz field strength is not directly proportional to field current. In terms of control, this simply translates to resistance values, for R4 and R5, of something probably less than 100 ohms. (Look at the values for the field resistances of the Wincharger and Jacobs units.)

Rheostats are rated not only for resistance, but in the power (wattage) they will dissipate (in the form of heat). R1, R2, and R3 will be 2 watt rheostats (or potentimeters,as they're sometimes called) if the coil current of relays K1, K2, and K3 are around 100 milliamps. Rheostats R4 and R5 will probably be 5 watt or higher. To determine the required wattage of a rheostat, multiply its resistance by the square of the maximum amount of current that will flow through it; this is the I^2R value that we've occasionally mentioned. Always obtain a rheostat with a wattage rating twice that of the calculated value; this will give you a safety factor of two.

Non panel-mounting rheostats (called "variable resistors") are available and would make nice substitutes for the common rotary-types. These are large straight tubular resistors with a band of metal which is movable up and down the length of the resistor itself; a small screw is used to hold this band to a specific position. This is the type of resistor used in the Jacobs control box and it's practical, relatively easy to use, and is less susceptible to "derdialumtwistum". They're also less expensive than high-wattage rotary-types and easy to mount in the rear of the box.

(3) Coil W1 is a current shunt; it allows most of the current coming from the windplant to go straight through it rather than through the higher total resistance of rheostat R1 and the relay K1 coil. You must cut a length of copper wire (not too thick) or steel baling wire which will allow relay K1 to energize with rheostat R1 adjusted to minimum resistance while the current flowing through W1 is approaching the windplant's rated (maximum) current. When you've got this, increase the resistance of R1 so that the relay doesn't trip until the windplant reaches its full rated output. You don't want W1 any longer than necessary; it's wasting a bit of power to facilitate overcurrent protection and you want to keep that to a minimum.

(4) Switch S1 (if used) needs to have a large current rating. A large push-button switch is nice here, but if you can't find one that is large enuff (20 amps or more), use a less convenient knife switch. Switch S3 will need a current rating of 5 amps. Switch S2 will only require a current rating of 1 amp or less.

(5) A final note on control box wiring. If you want some real safe current capacity for internal wiring, consider flattening some small copper tubing and drilling holes in each end for bolt-together connections. By bolting all connections down to an insulated board, you can be fairly sure of a sound layout, even if you are not experienced with electronic soldering. These also make nice battery straps (between batteries in sets). They have very low resistance and good strenth and are less expensive than heavy wires with terminals.

Adjustments to the Owner-Built Control Box

If you're going to use the windplant to make adjustments in the control box, you're going to have to connect its leads and those from the batteries to the control box. Before you do this, set all five rheostats for maximum resistance. If the components have been correctly wired in, this will be at a zero setting, or one where the knob is at the maximum counter-clockwise position. When connecting windplant and battery leads, watch out for sparks and smoke; if you get either, disconnect immediately and check the wiring thoroughly. If nothing seems amiss, look for bad components. The number of things that can happen (that aren't supposed to) is truly unlistable. Assuming you have double-checked all wiring and all components are of the correct value and will function properly, let's proceed.

If you didn't barbeque your control box when connecting the windplant and battery leads, we're ready to begin adjustments. Make certain that the batteries are fully charged or these rough adjustments will be rougher than they should be. To adjust R2, move the knob clockwise (hereafter stated as "advance" the knob) and listen for relay K2 to energize (or visually watch this happen). When it does, note and mark the position where this happens. Move the knob counterclockwise (hereafter stated as "back off" the knob) until relay K2 de-energizes. Note and mark the position. Use pencil marks as these will only be rough adjustments. Advance R2 to the first mark. Relay K2 should energize. Back it off to the second mark. It should de-energize. Right?

Okay, R3's adjustment is next. Advance R2 until relay K2 energizes. Now advance R3 until relay K3 energizes. Note and mark this position for R3. Now back off R2 (not R3) to its second mark. When relay K2 de-energizes, relay K3 will de-energize. Now advance R2 until relay K2 energizes. Relay K3 should also energize. If it doesn't, advance R3 just a little bit more and it will cause relay K3 to energize. Erase the old pencil mark for R3 position and mark the new. Now back off R2 until both de-energize and advance R2 again. You want relay K3 to energize every time relay K2 energizes. That's it. Back off R2 to its original mark (so both relays are de-energized). Okay?

Let's adjust R1. This could be adjusted while the windplant was delivering its rated output but that's a bit dangerous (a bad time to find out you reversed a wire somewhere) so let's do it the safe way. Disconnect the windplant and battery leads from the control box (Battery + to G+ and Battery - to G-); in this way, the batteries will simulate the windplant. Connect a load to the battery terminals in the control box (at B+ and B-); this will simulate the batteries and allow current flowing into the load to pass thru M1. The load you connect should draw an amount of current equal (or very close) to the windplant's maximum (rated) durrent. Try using a good length of steel wire for the load. (For example, a 10-foot length of common baling wire will draw 50 amps at 12 volts; resistance will increase some as it heats up.) Or, connect enuff light bulbs, motors, etc. to pull the current.

When M1 indicates the amount of current at which you want relay K1 to energize, quickly adjust R1 until relay K1 energizes. You will be wasting a lot of power and heating a lot of stuff up in the control box. When you've got it right, mark the knob position (for R1) and reconnect the battery and windplant leads to their respective terminals. If, during the windplant's normal operation, you ever see the ammeter indicate more than what you thought you had adjusted R1 to prevent (by activating K1), you can make a fine adjustment on R1. Make a point of verifying its correct adjustment whenever the windplant is again delivering full power.

Rheostat R5 provides overcurrent protection for the batteries; if your batteries can't handle the windplant's current-producing capacity, you'll need to adjust R5, but this can only be done when the windplant is exposed to some pretty good wind and the batteries are near exhaustion (that is when the batteries will draw the most current). Additionally, R5 cannot be properly adjusted if relays K1, K2, or K3 are energized. With all of these conditions met, adjust R5 for minimum resistance (full advance clockwise) and then, observing M1, back off R5 anytime the current reading exceeds the recommended maximum charge current for your batteries. Take your time here and make only very small adjustments of R5. It's better to occasionally have the batteries receive a little more current than this value then to have them receive less than they could otherwise. Mark the final position of the knob becuz you'll probably end up moving this control frequently. When you're experiencing the low and infrequent winds of summer, you may want to move this control to minimum resistance (full advance) to take advantage of the relatively low amount of power available from the wind.

We've already gone thru a rough adjustment of rheostat R2 but a finer adjustment is required. This setting will depend on your batteries' recommended "finishing rate", maximum current rating, and "finishing voltage" and, even with this information, you will not have a precise indication of when the control box should activate the taper charge function. The value of voltage where you want relay K2 to energize will be that where a medium amount of current (say, twice the "taper charge" current) is causing the batteries to "gas" excessively.

Note: Normal gassing will cause a mist of fine bubbles in the battery and the electrolyte will appear milky. What I call 'excessive gassing' is when a hiss of bubbles (like in freshly-opened soda bottle) can be heard without putting your ear right up to the battery (and the battery feels warm to the touch). Really too much is indicated by what looks and sounds like a rolling boil (and the battery feels hot). Tiny bubbles will normally accumulate in pockets and suddenly rise to the top with a "blurk". If you're concerned with heavy gassing, give the battery a pound with your fist to release any more accumulated gas.

A rough adjustment to the voltage regulator will be made initially but progressively finer adjustments will be made as the battery conditions and experience dictate. Arm yourself with a lot of good battery information; the more you know, the longer you'll be able to stretch the life of the batteries. (See Wind and Windspinners, and Bibliography.)

A control identification sheet should be posted near the box or taped inside the lid. It lists the controls and briefly explains what they do. The importance of the sheet comes in explaining which way the control needs to move to accomplish the desired adjustment. An example: If you back off R1, you increase its resistance. The effect will be to decrease the sensitivity of K1 to windplant current; hence, it will take more windplant current (thru winding W1) to cause K1 to energize . If you advance R1, the reverse will happen. Got the message?

Meaningful terminology for control labels is highly recommended. Keep it brief, or the label won't fit in the space surrounding the switch position. The second rule is to use something that works for you. A few examples here: 'Current Regulator' might be a good name for rheostat R1, but 'Max. Windplant Current Adj.' might be a better description since R5 is, in effect, also a current regulator (for the batteries). So, maybe call R5 'Max. Battery Current Adj.' R2 is 'Voltage Reg. Adj.', R3 is 'Slave Relay Adjust' (or no label), and R4 is 'Taper Charge' or 'Finishing Current Adj.'. Switch S1 can be called 'Push to Motor' (not abbreviated) . Switch S2 can be called 'Voltmeter Sensing'. Label its positions: 'Gen.' for generator and 'Bat.' for batteries. Switch S3 has been labeled 'On/Off' (Jacobs) or 'Manual/Automatic' (Wincharger), but this is consumer oriented and not very explanatory. I'd label the switch positions 'Regulator In' and 'Regulator Out'.

CAT-Plans: CAT Machynlleth Powys Wales UK. 1976.

D.I.Y. PLAN 1

5W. WIND GENERATOR

5-WATT WIND GENERATOR

To trickle charge 6/12v battery, or to light lamp direct, up to 5 Watts approximately.

ADAPTATION

Cycle wheel & hub dynamo

COST (without tower) 1976

Cycle wheel & dynahub, new .... approx £10.80
Other materials, new .... approx £8.00

Scrapyard freaks will find almost all that is necessary for a fraction of this cost, except perhaps for diodes (see under) which cost 8p each.

MATERIALS (without tower)

Cycle wheel & dynahub
Sheet metal, 3' x 3', about 20 SWG - almost any material: aluminium, tin, zinc, galvanised iron
Scrap iron $\frac{1}{4}$" x 2" x 1'6"
Old cycle hub, front or rear, without 3 speed
Ex-T.V. aerial aluminium tube $\frac{1}{2}$" diameter x 2/2'0", or $\frac{1}{2}$" wood dowel,2/2'0"
Screws and nuts - 35 1" x 4 BA or 3/16" Whitworth, or odds and ends - or else pop rivets, 5/32" or 3/16"
Self-tapping screws - 6 No.8 x 1"
Diodes, 4/1.amp x 200 PIV

TOOLS

Basic D.I.Y., without power tools, plus:-

Tin snips (essential)
Pop rivetter (optional, but very desirable time saver)
Drill capable of $\frac{3}{8}$" holes in $\frac{1}{4}$" mild steel

METHOD

Basically, a cycle wheel is turned into a multi-blade windmill. Some of the theory of design of aero-generators may be found in the leaflet 'Wind Power Utilisation' from N.C.A.T. at 15p plus 8p postage and packing. Very briefly, the multi-blade (American) windmill is a slow turning machine with fairly high torque, and with a tip (or circumferential) speed roughly equal to that of the wind. The one we have made begins to charge at about 6 mph (6v) 8mph (12v) wind, and will withstand at least Force 8 gales.

CONSTRUCTION

The vanes of the windmill are carried by the spokes of the cycle wheel.

The wheel we used had 9 pairs of spokes each side of the hub. Nine vanes thus seemed called for.

To fasten the vanes conveniently we needed the spokes to be radial - which they were not - so we altered every other of the 18 spokes on the side away from the dynahub to carry the vanes.

At this point a jig to hold the wheel was needed. Any piece of large wood off-cut about 3" x 2" will do. We bored a $\frac{1}{2}$" hole at an angle in it, nailed it to the edge of the bench and put the hub spigot into the hole; this gave a convenient angle to work on.

We unscrewed every other spoke on the side of the hub away from the dynamo - one at a time, to avoid upsetting the balance of the wheel. Each spoke was clipped off about ½" from the knob end, rebent into a hook and reinserted into another hole in the hub, in such a way that the spoke was then a RADIUS of the wheel, and refastened (Fig.1). Go easy with the nuts - we had to undo them 3 times.

Now the shape of the vanes:

With a piece of cardboard as template, we marked out the area between 2 adjacent (radial) spokes, making an isosceles triangle truncated at the apex (hub end).(Fig.2)

Thus the 9 vanes, flat, would make a complete circle. As in fact the vanes would be angled, they should be increased in width so that they present as large an area as possible to the wind, without overlapping each other. The conflicting factors are: large area (for good starting torque) against overlapping of vanes (drag when running). Our compromise was to add ¾" to one side (Fig.3).

After trimming corners of cardboard template, we cut out 9 similar shapes in the sheet metal. This should be accurate for good balance. They were drilled to go over the spokes.

We slightly bent the vanes to approximate an aerofoil section. There may be some small advantage in this. It has to be done now or not at all.

The vanes were then journalled over the 9 radial spokes (having undone them once more, one at a time). We tightened each nut equally - you can tell by the squeak how equal they are.

At this point we had 9 vanes at all angles. There are two ways of finishing the rotor. Either you can strut the underside of each vane with a strip of metal to the neighbouring spoke, at a vane angle of about 30 - 35 to the rim of the wheel; or you can attach the vanes in such a way that you can (manually) alter the pitch of the 9 vanes simultaneously.

VARIABLE PITCH DEVICE

Our method was to wrap a 3" wide piece of the sheet metal around the rim of the wheel so that, by bolting the joint of the band, it was free to slide like a loose tyre round the rim. It was held by either pop rivets or bolts to stop it moving axially, in a position as far forward over the vanes as possible.

To this band the top edges of the vanes were attached.

We used a piece of found aluminium glazing bar, with a deep slot that went over the top edge of the vanes. By sawing and bending it, and drilling a pivot hole (Fig.4), it allowed the vane to feather as the strap was rotated a few inches around the rim.

Subsequently we found plastic 'SWISH SOLOGLYDE', the bracket-shaped bit being an ideal solution. It also had a screw with which to clamp the vane, once ideal pitch had been determined.

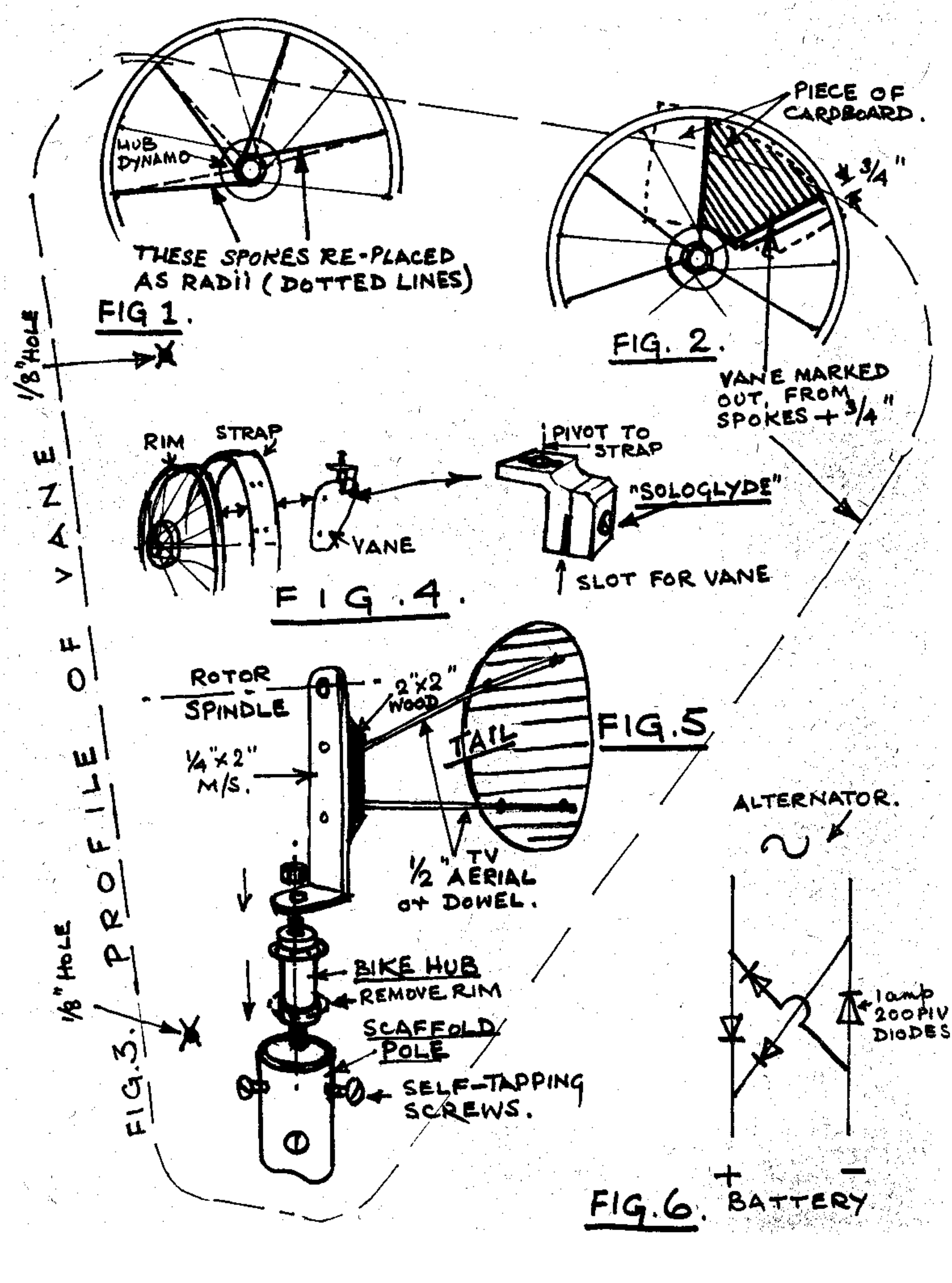
The pivot holes in the strap must be drilled exactly equally round the rim. Mark them off from the spoke ends at the rim, at a consistent depth from the edge of the rim - exactly. Assemble. Make sure everything moves freely.

MOUNTING

Ideally a m/s strap, about ¼" x 2" x 1'6", with drilled ⅜" holes, 1'3" apart, and bent (Fig.5).

We found a P.O. corner bracket on a house, of just about the right size,

5 WATT WIND GENERATOR.



with another hole which helped with the tail. Almost any found strap iron has holes in it, somewhere near each end, that will do if it's the right length.

A cycle hub served as mounting bearing. Perhaps a cycle front fork assembly would also do. We cut off one hub flange so that it would fit into the end of a scaffold pole, and fastened it with self-tapping screws through holes drilled in the pole (Fig.5). Attach strap to hub spigot, and rotor to strap.

TAIL

We made ours by boring ½" holes into a 6" piece of 2" x 2" wood, at such angles that, if the wood were bolted to the back of the mounting strap and ½" dowels driven into the holes, the dowels would spread to hold a tail about rotor size (24"). Tail design seems open to research. It would be interesting to find out what works best.

ELECTRICS

The dynohub is an alternator. O.K. for filament lamps of 6 - 12v, but, to recharge a battery, a rectifier is needed.

We made ours from a 4/1 amp 200 PIV diodes (Fig.6): IN 4003 or 4 or 5. Or you can use a bridge rectifier, where the bits are embedded in plastic, ready for connection, for about 75p.

FOOD FOR THOUGHT

A variable pitch machine or not? If wind can be excessive at times, it is a good idea. You can feather the blades and sleep in peace.

Contrary to current information that cables do not twist around the pole, ours took 3 turns in 24 hours! The tail too sensitive? Worth watching, and perhaps thinking about contact rings.

The rotor should be 10' above obstruction within 100 yards ideally. Find out all you can about the wind where you have to put the generator. It takes 6 - 8 mph to start generating - 10 or 15 mph is a good charging wind.

D.I.Y. is essentially the technology of improvisation. Don't slave away with a brace and bit drilling 3/8" holes through mild steel. Get round it some other way - it's always possible.

This information sheet has been prepared for the Centre by John Eyles ©. Other D.I.Y. plans, information sheets and books are available from the 'Quarry Bookshop' at the Centre. Please enclose a s.a.e. with all correspondence as we are a charity. Visitors are welcome.

The Centre for Alternative Technology, Machynlleth, Powys, Wales.
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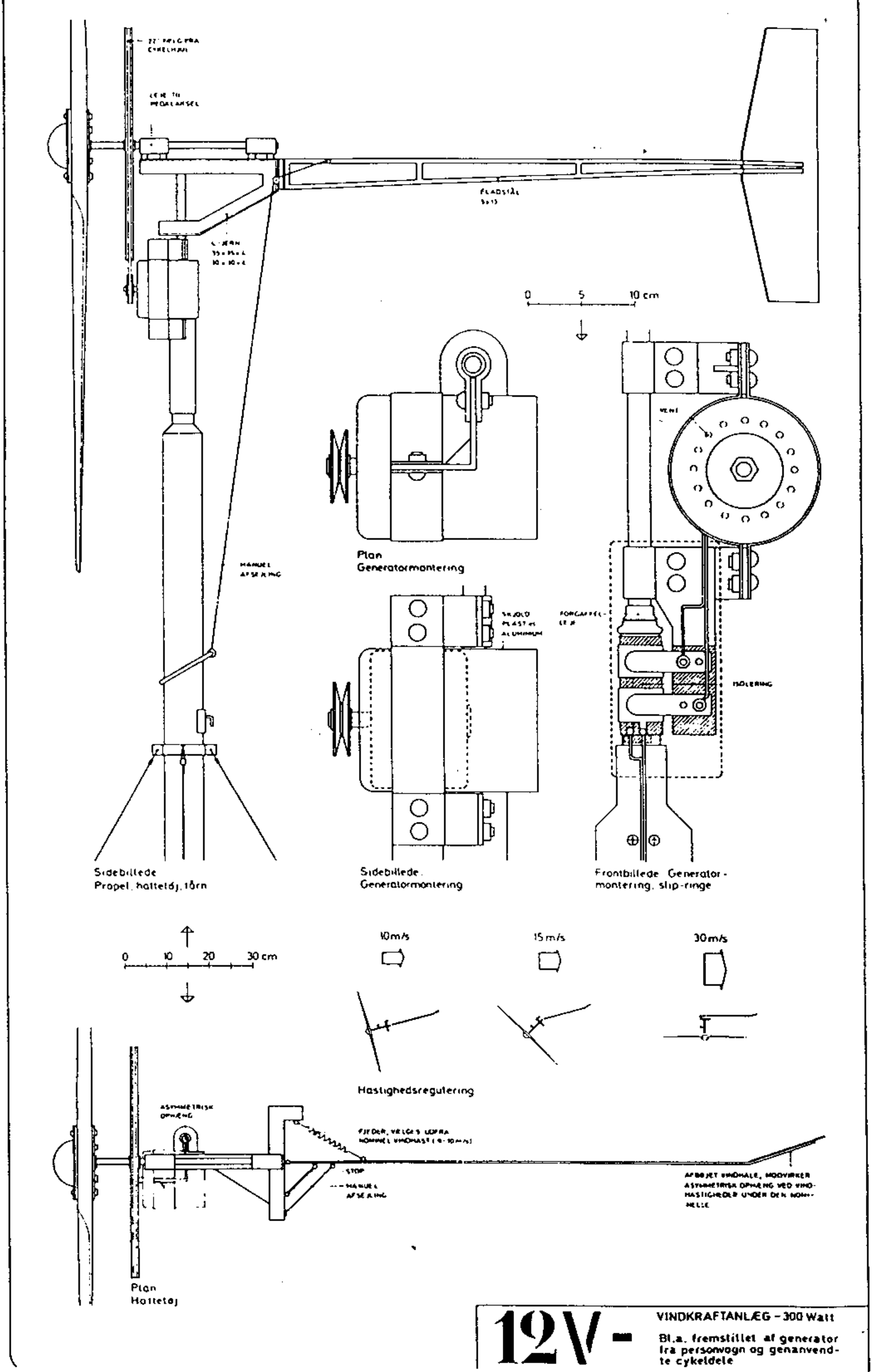
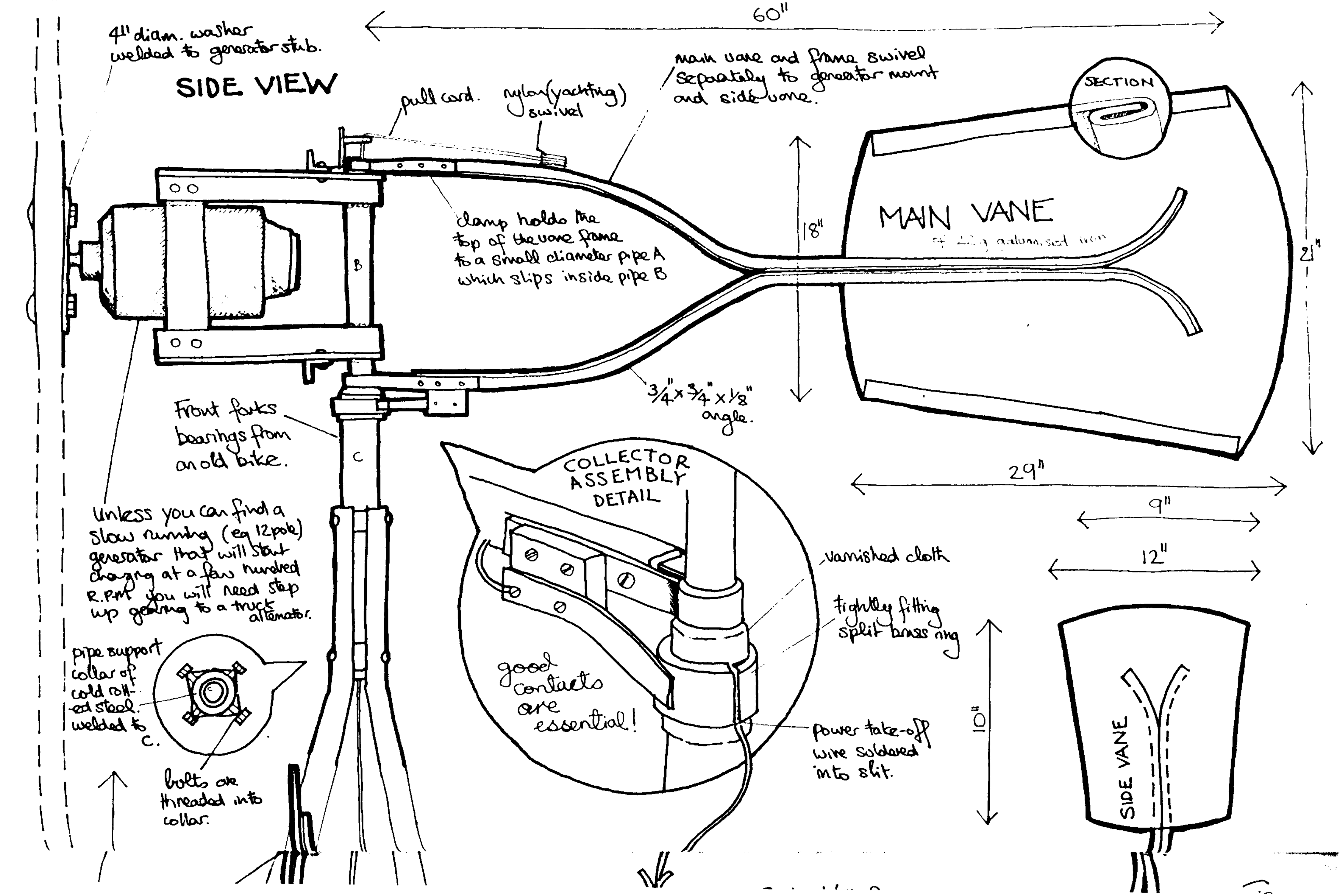
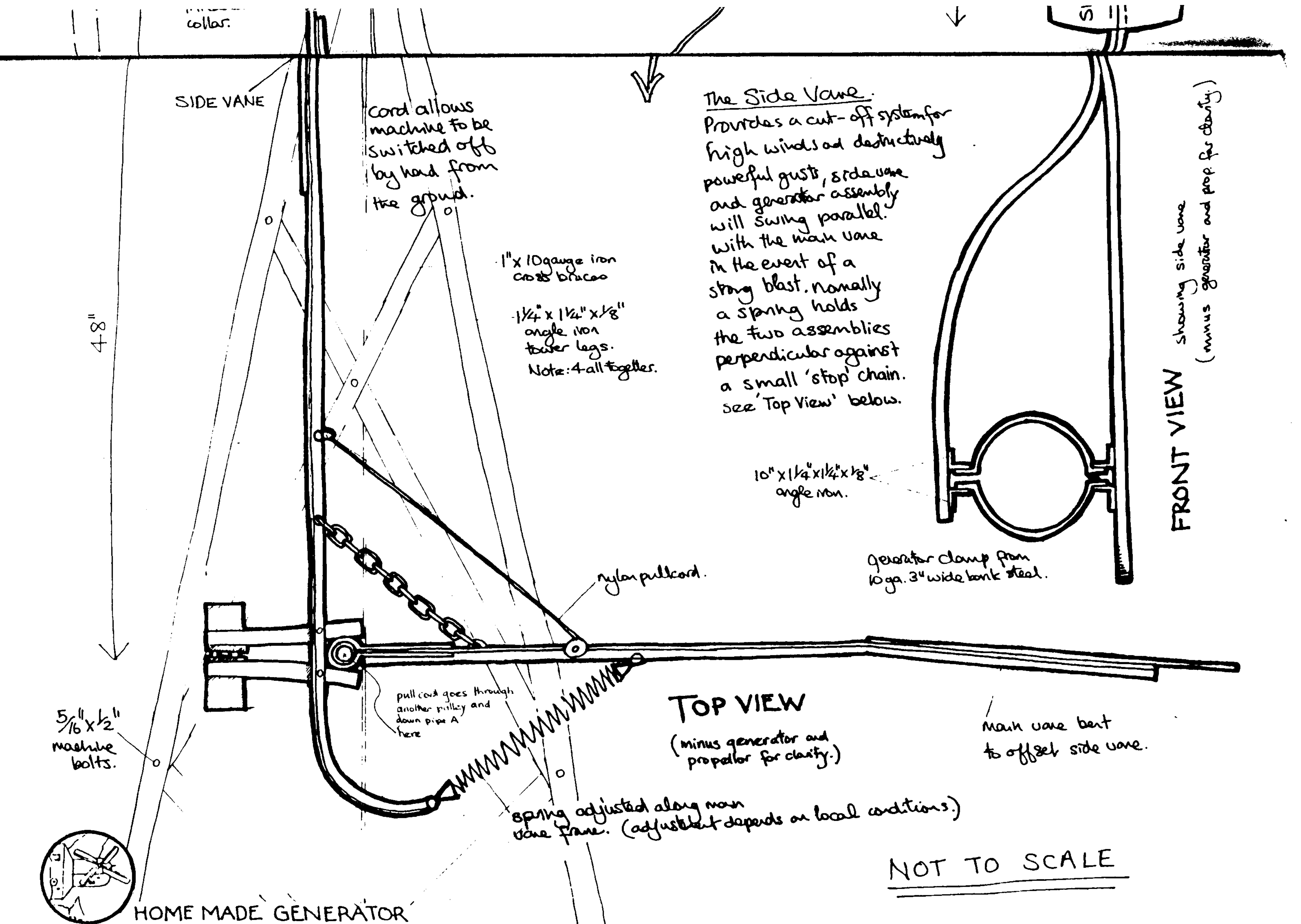

0 5 10 cm
Plan
Generatormontering
Sidebillede
Propel, halteløj, tårn
Sidebillede
Generatormontering
Frontbillede Generator-
montering, slip-ringe
0 10 20 30 cm
10 m/s
15 m/s
30 m/s
Hastighedsregulering
Plan
Haltetøj
12V-
VINDKRAFTANLÆG - 300 Watt
Bl.a. fremstillet af generator
fra personvogn og genanvend-
te cykeldele

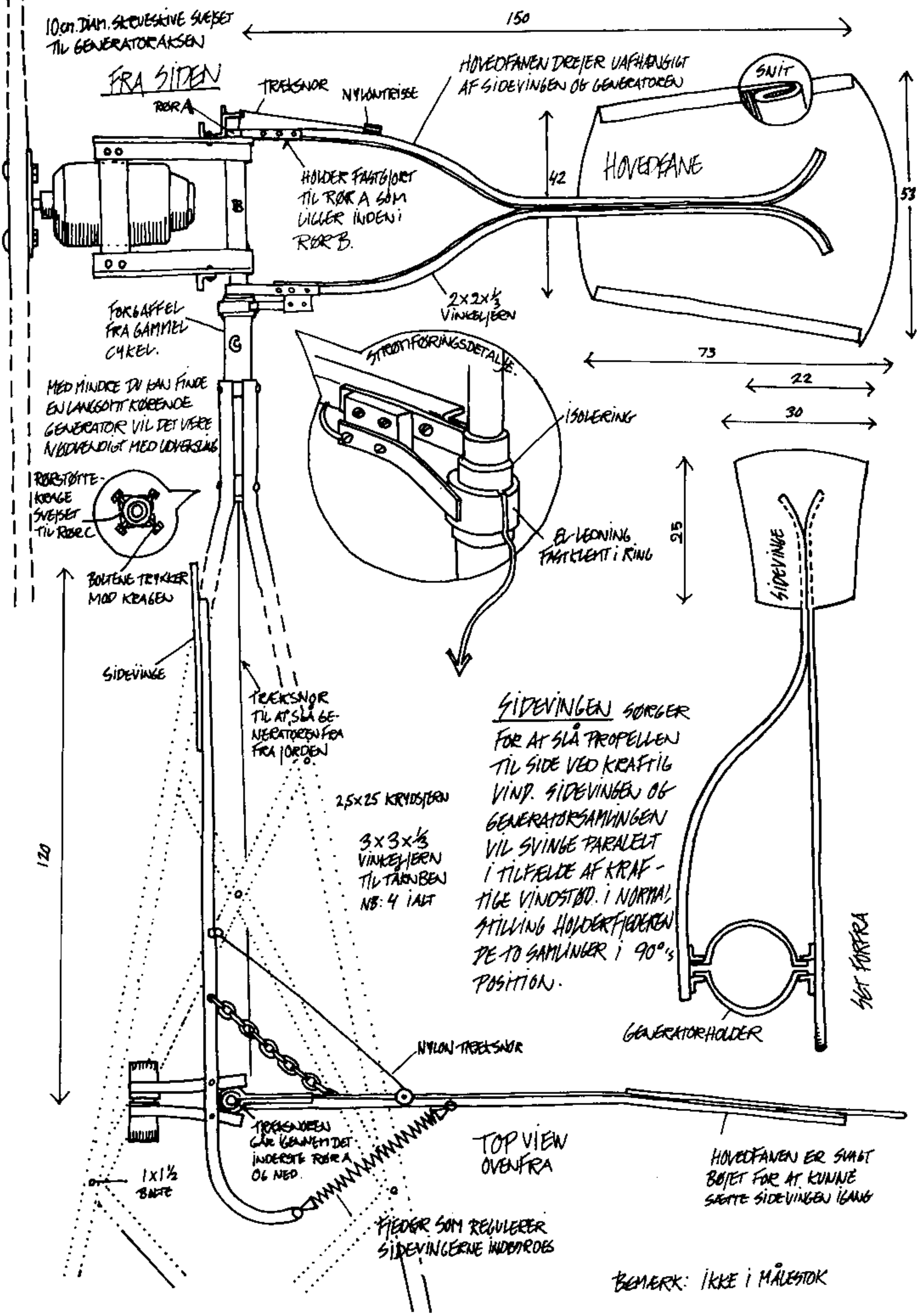
HOME-MADE SMALL ELECTRICAL GENERATOR





collar.
SIDE VANE
cord allows machine to be switched off by hand from the ground.
4'8"
The Side Vane.
Provides a cut-off system for high winds and destructively powerful gusts, side vane and generator assembly will swing parallel with the main vane in the event of a strong blast. normally a spring holds the two assemblies perpendicular against a small 'stop' chain. see 'Top View' below.
1"x 10 gauge iron cross braces
1¼" x 1¼" x 1/8" angle iron tower legs. Note: 4 all together.
10" x 1¼" x 1¼" x 1/8" angle iron.
FRONT VIEW
showing side vane (minus generator and prop for clarity.)
generator clamp from 10 ga. 3" wide bank steel.
nylon pullcord.
pull cord goes through another pulley and down pipe A here
TOP VIEW
(minus generator and propellor for clarity.)
main vane bent to offset side vane.
5/16" x 1/2" machine bolts.
spring adjusted along main vane frame. (adjustment depends on local conditions.)
NOT TO SCALE
HOME MADE GENERATOR

LILLE HJEMMELAVET VINDGENERATOR



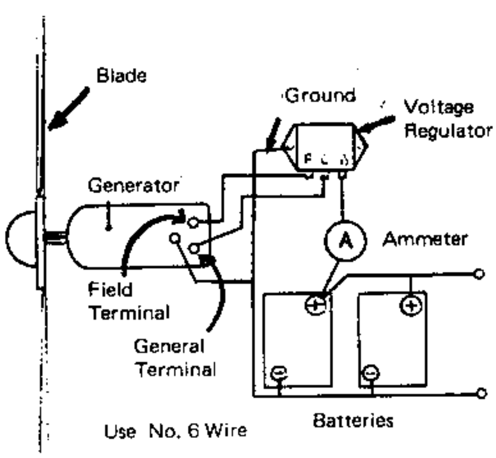
RECYCLED WIND GENERATOR

The basic design (below) shows the components necessary for building a small, working wind generator from purchased ("off the shelf") and/or recycled materials.

FEATHERING: The system is modified from a windplant built by Paris-Dunn Co. of Iowa in the 1930's and 40's. Its main advantage is that it eliminates most of the typical speed-governing problems (i.e. loading and vibration) using a simple feathering device. It uses a spring and hinge that allow the propeller and generator to feather when wind speeds become so high (see photos on next page).

WIND PLANT MATERIALS: The plant is constructed mostly with nuts and bolts, so only some drilling and cutting (but no welding) is required. A wide choice of materials is possible, depending on your imagination and what is available. There are many variations and "tradeoffs" possible in the design.

BLADES: The Clark "Y" airfoil is a blade which is easy to carve, and fairly efficient (a tip-speed ratio of 8). It could be carved from hardwood, and the leading edges covered with copper foil for longer life. Care should be taken not to carve the trailing edge so thin that it will split. Construction instructions can be found in ASE Newsletter No. 14, pp. 10-13. (Note that the LeJay Manual has a layout for a Clark "Y" with a tip-speed ratio of 3 or 4.) Cut the prop from 2"x6"x 8' hardwood stock. Other high tip-speed ratio airfoils may also be used.



SCHEMATIC WIRING DIAGRAM

GENERATOR: A good generator to convert to windplant use is a Delco unit that comes from International Harvester.

2900 Z Stock	Rewind
600 Watts	300 Watts
at 1925 rpm	at 962.5 rpm
18 slots in Armature	18 slots
36 bar commutator	36 bars
number 12 wire	number 15 wire
8 turns/slot in armature	16 turns/slot in armature

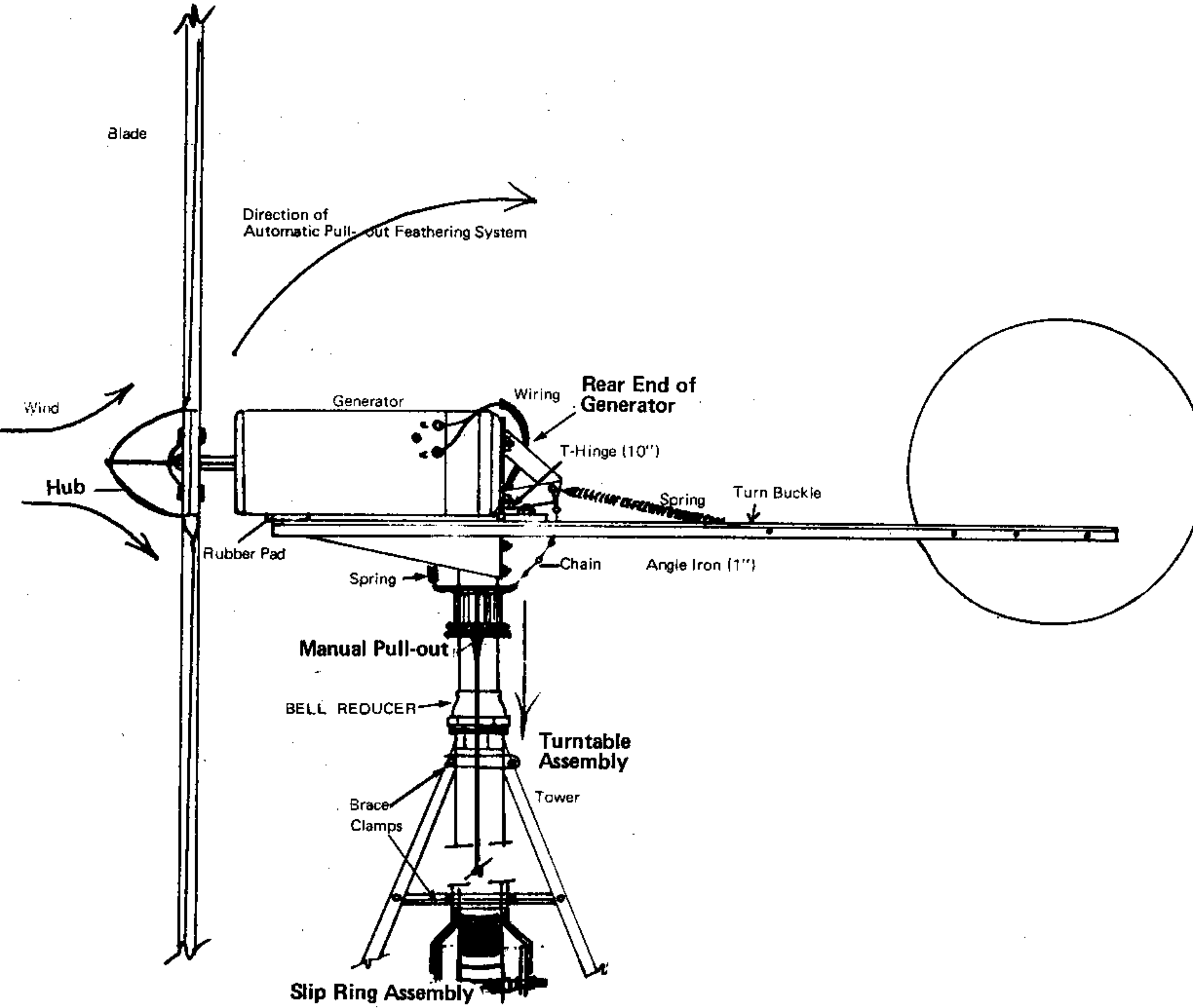
The way one rewinds or gears the generator determines the amperage and voltage output. If you rewind the armature with twice as many turns per slot (for example, from 8 turns of No. 12 wire per slot (stock) to 16 turns of No. 15 wire per slot), you achieve the necessary voltage to comply with battery and appliance requirements (12V). This output can then be attained at a slower speed (962 rpm), which the prop will reach in approximately a 25 mph wind. Note that the wire size has been reduced from 50 amps to 25 amps. 12 volts x 25 amps = 300 watts.

TOWER: The tower could be a standard windmill tower, or Hans Meyer's Octahedron Tower, which is very nice and is materials efficient

Consult the remaining pages in this section for additional information. Further information on small wind plants will be available from future Alternative Sources of Energy and New Alchemy Institute Newsletters.

—T.W.

Fig. 1 Hub Fig. 2 Frame
Fig. 3_A Slipring Assembly Fig. 3_B Sliprings
Fig. 4 Turntable Fig. 5 Rear View of Gen.
Fig. 6 Manual Pull-Out



WIND-DRIVEN GENERATOR (Side View)

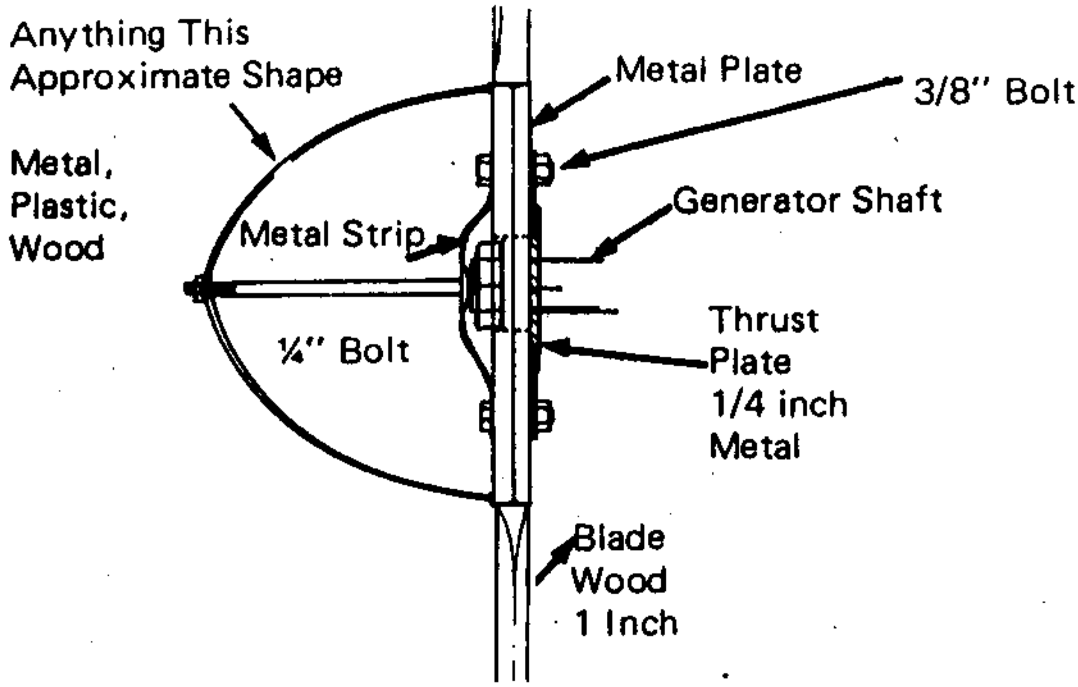


Fig. 1 HUB ASSEMBLY (Detail)

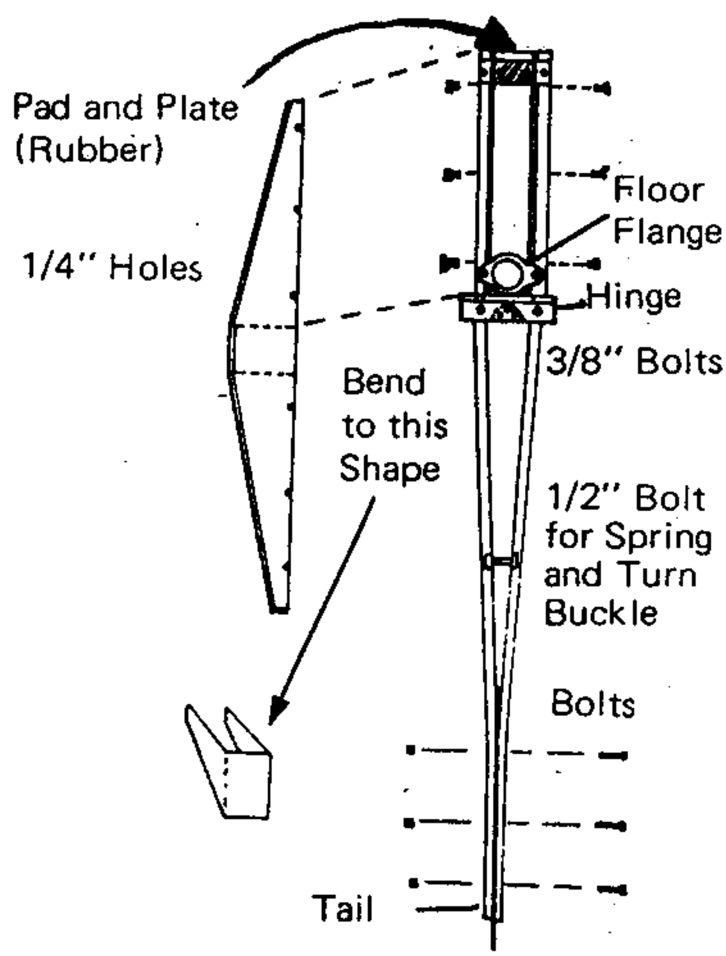
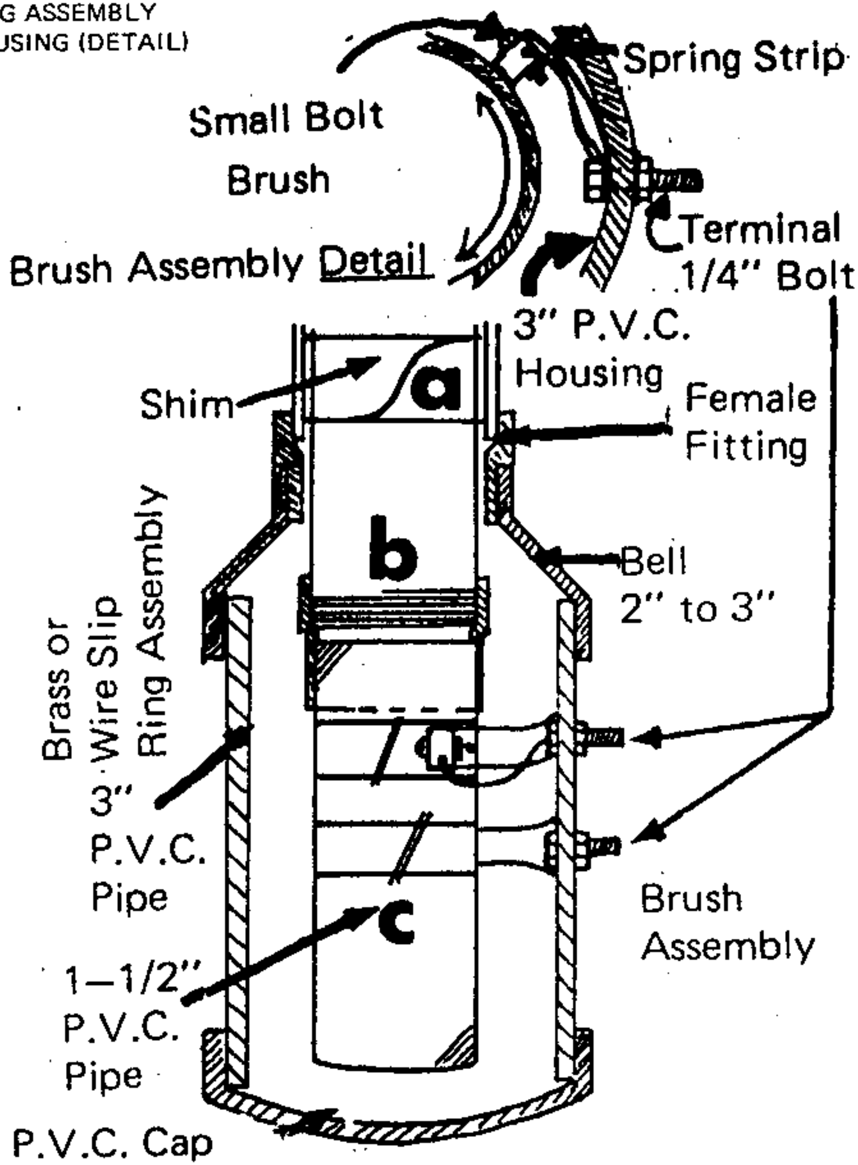
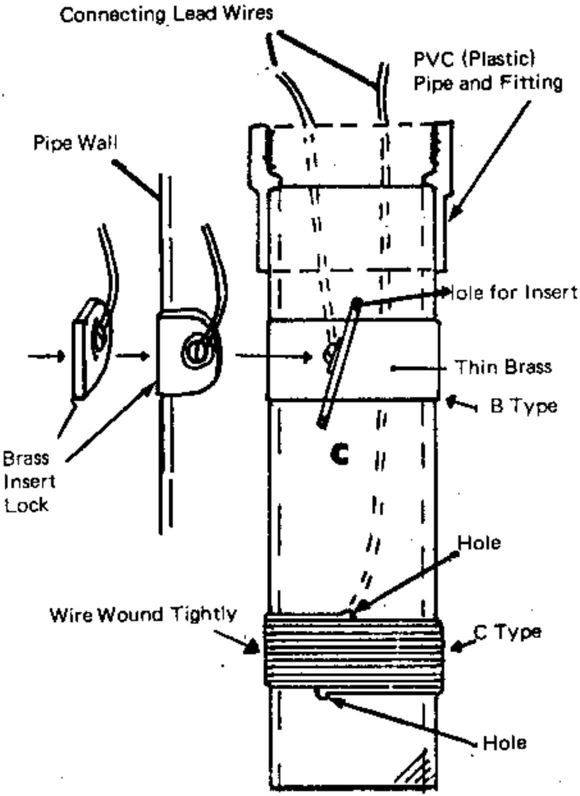


Fig. 2 FRAME WITH GENERATOR REMOVED (TOP VIEW)

Fig. 3_A SLIP RING ASSEMBLY AND HOUSING (DETAIL)





*Slip rings B or C type may be used.

Fig. 3_B SLIP RINGS *

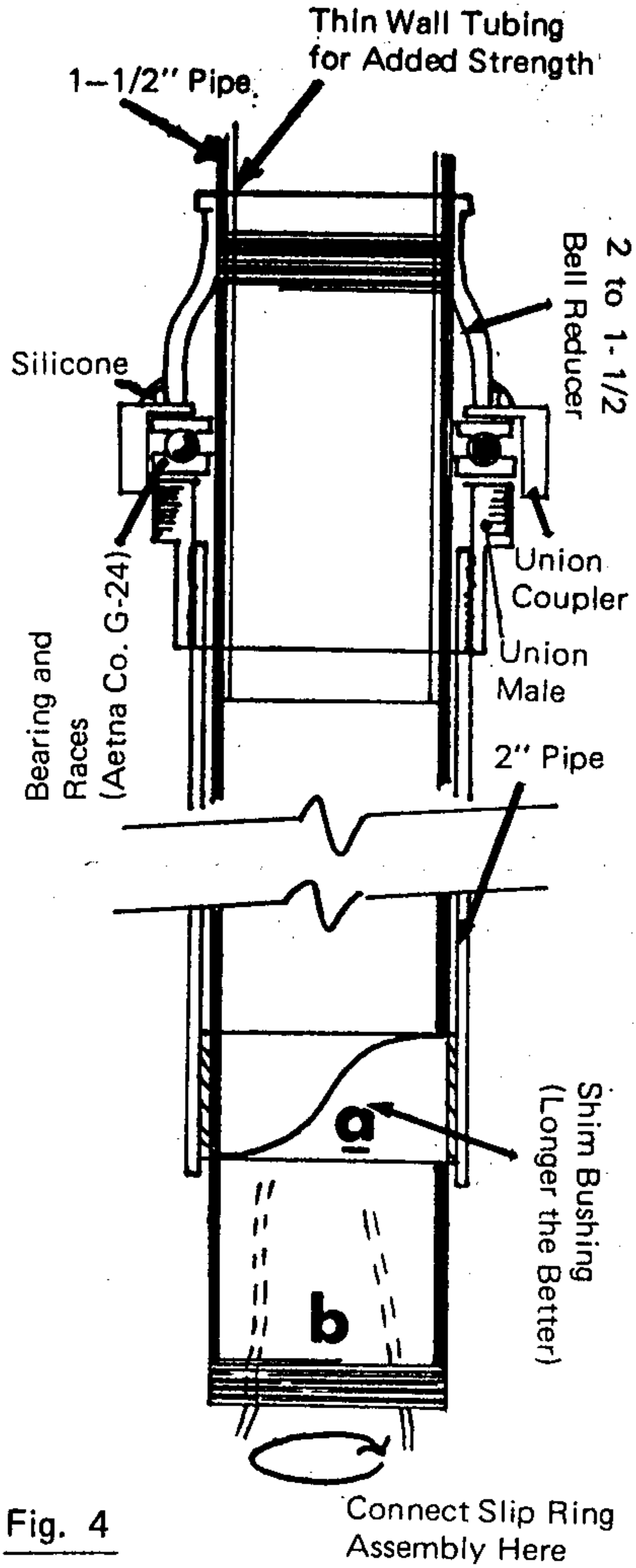


Fig. 4

TURNTABLE ASSEMBLY

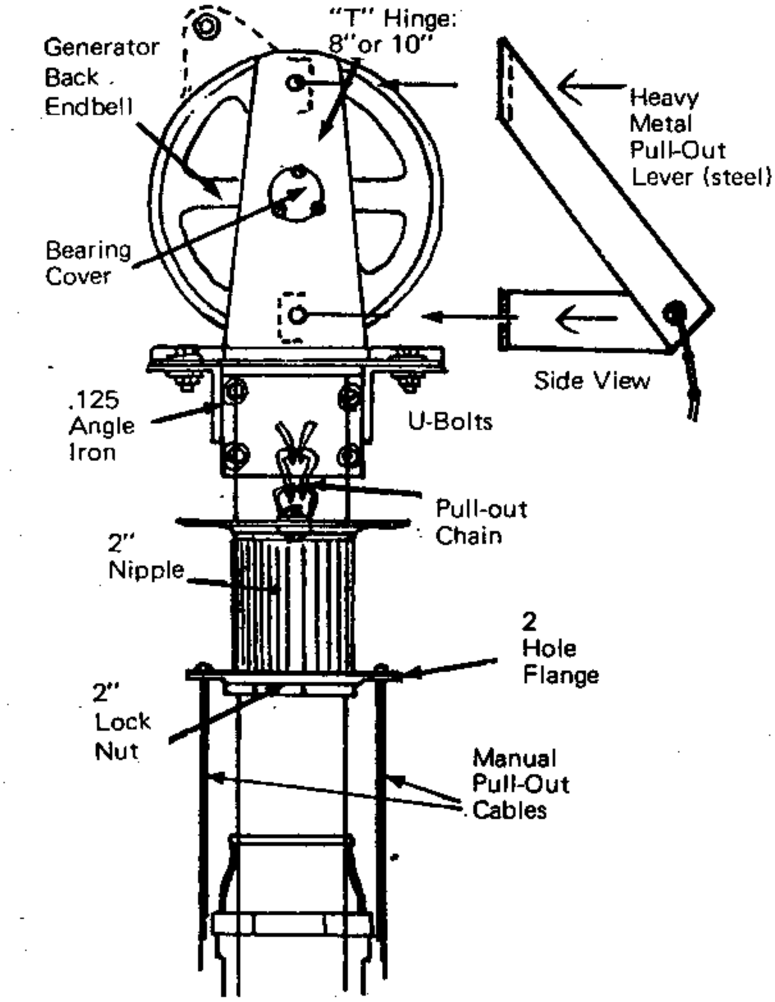


Fig. 5 REAR VIEW OF GENERATOR AND PULL-OUT SYSTEM

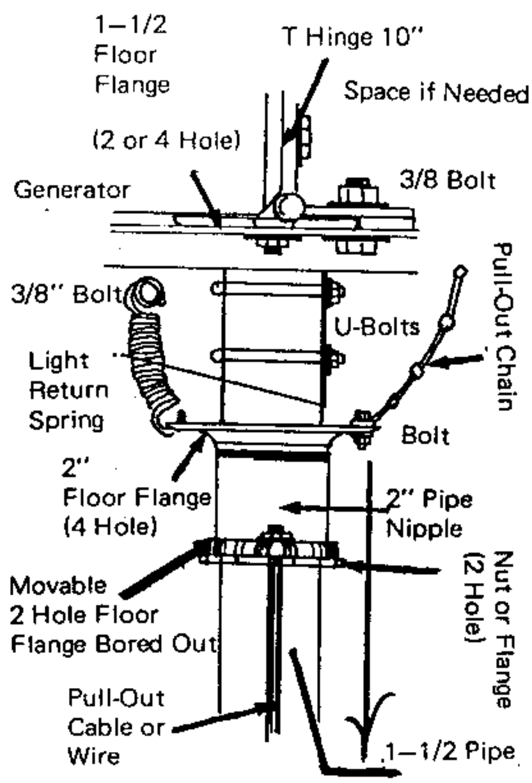
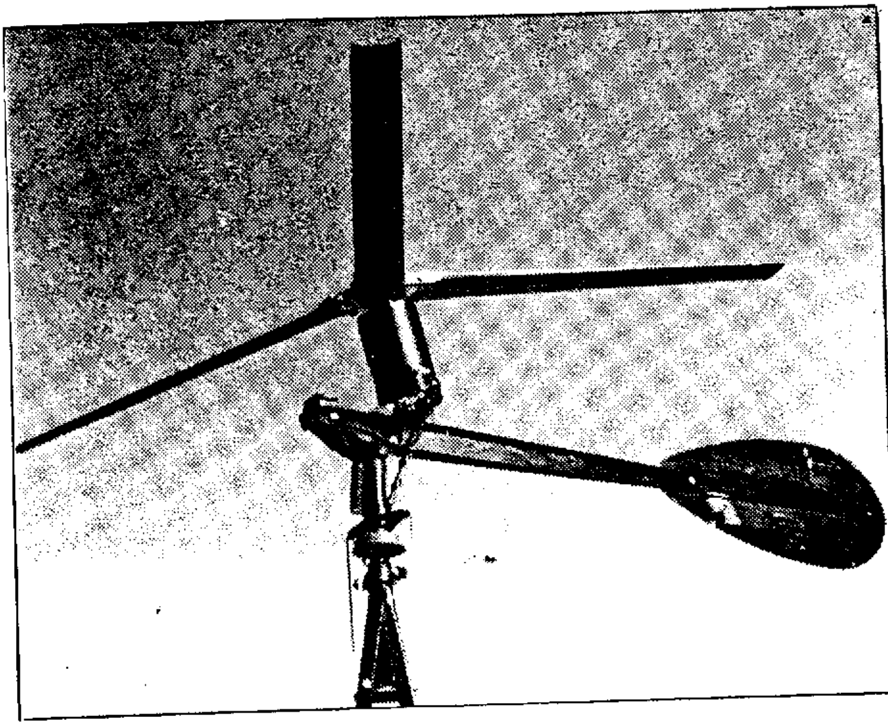
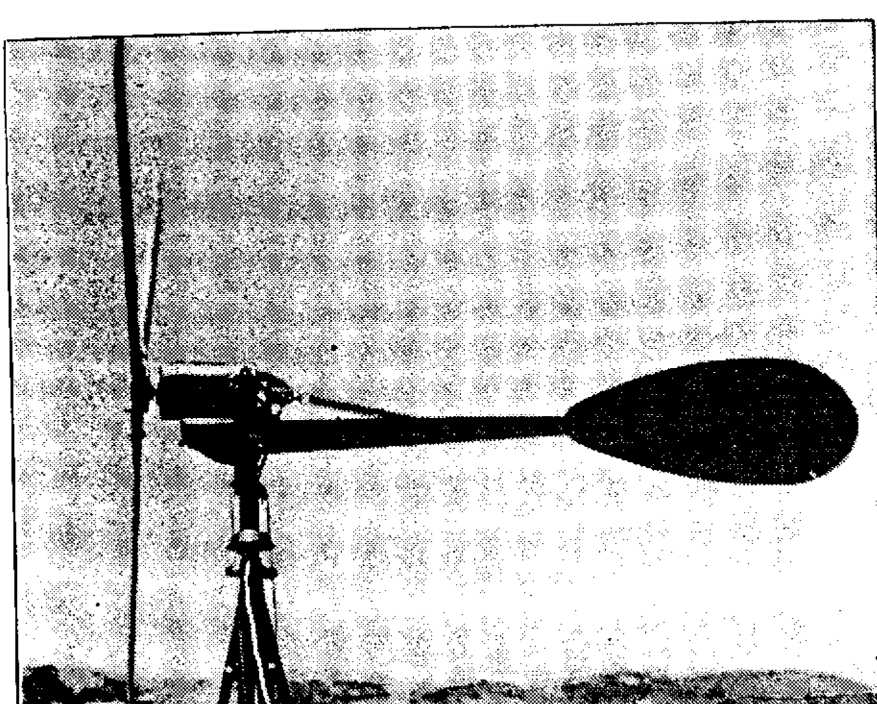


Fig. 6 MANUAL PULL-OUT ASSEMBLY (Side View)

PHOTOGRAPHS OF PARIS - DUNN WIND GENERATORS



FEATHERED



UNFEATHERED

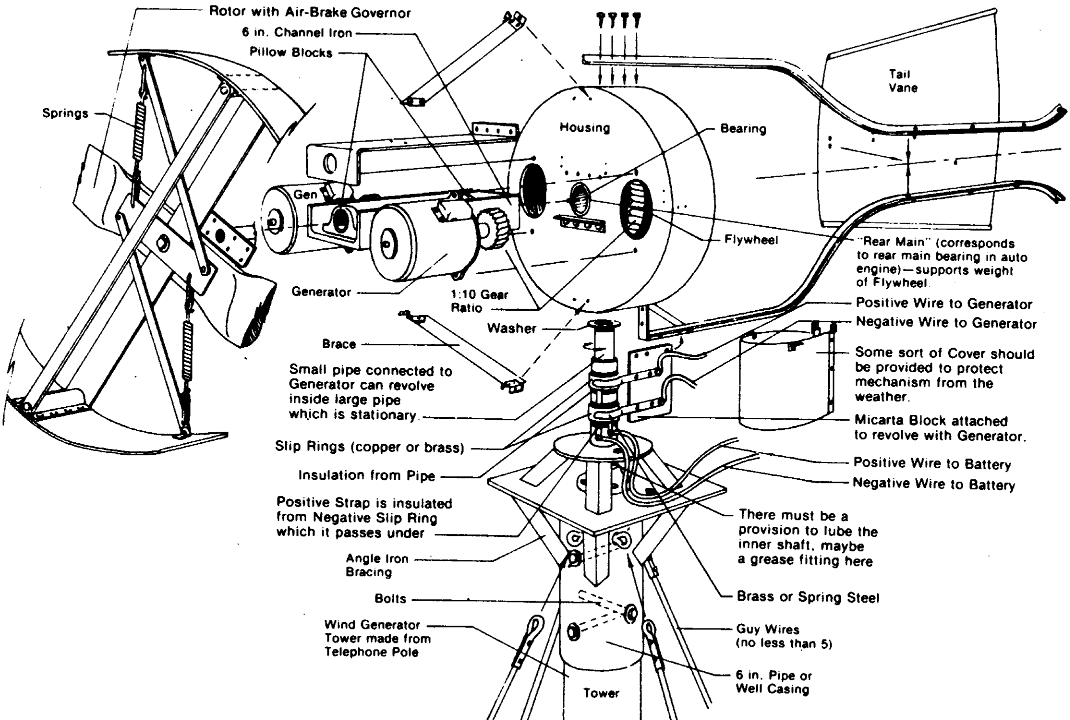
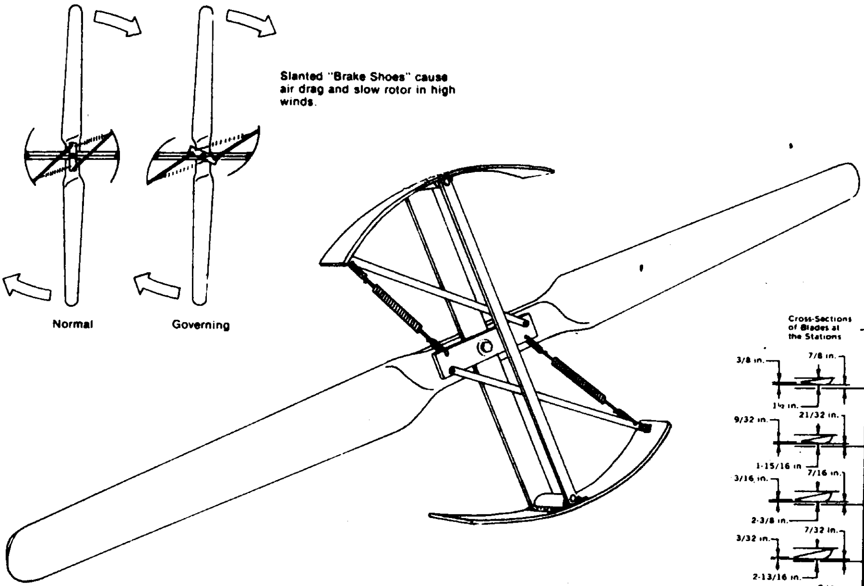
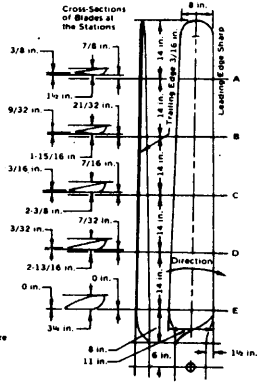
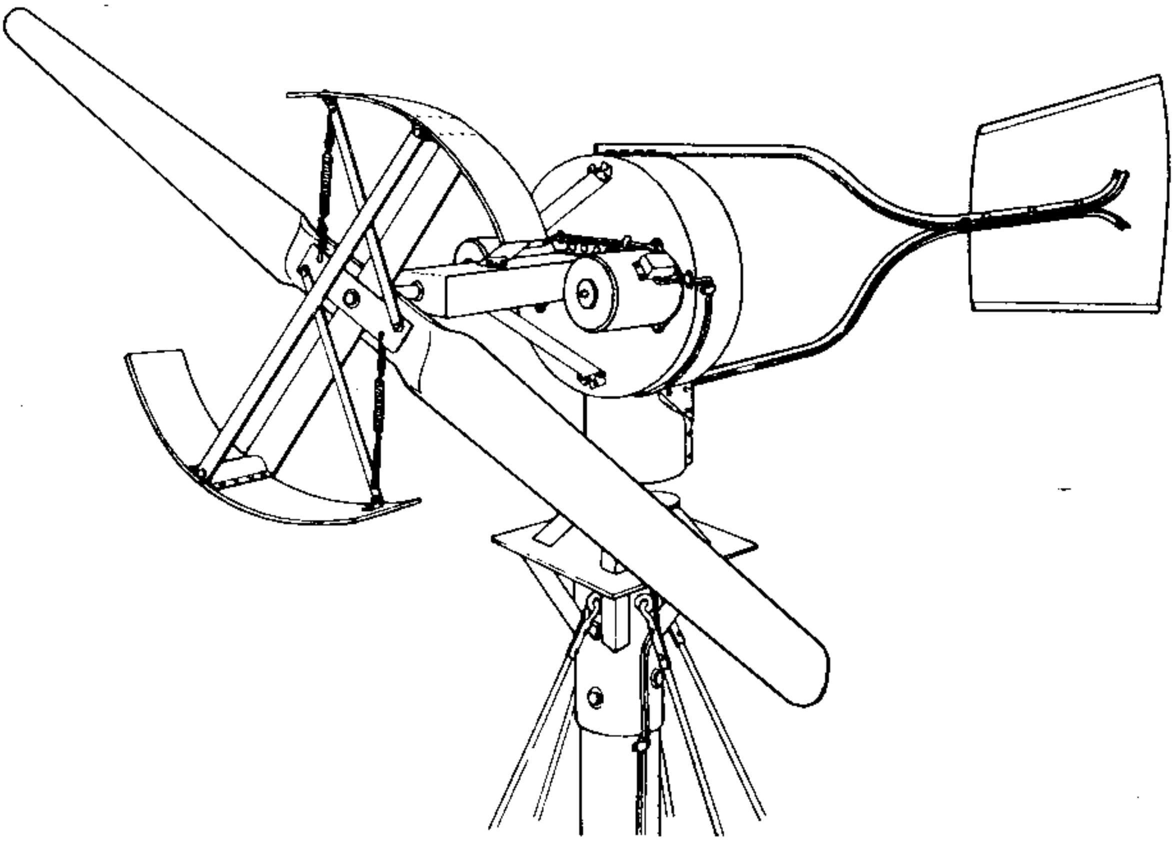


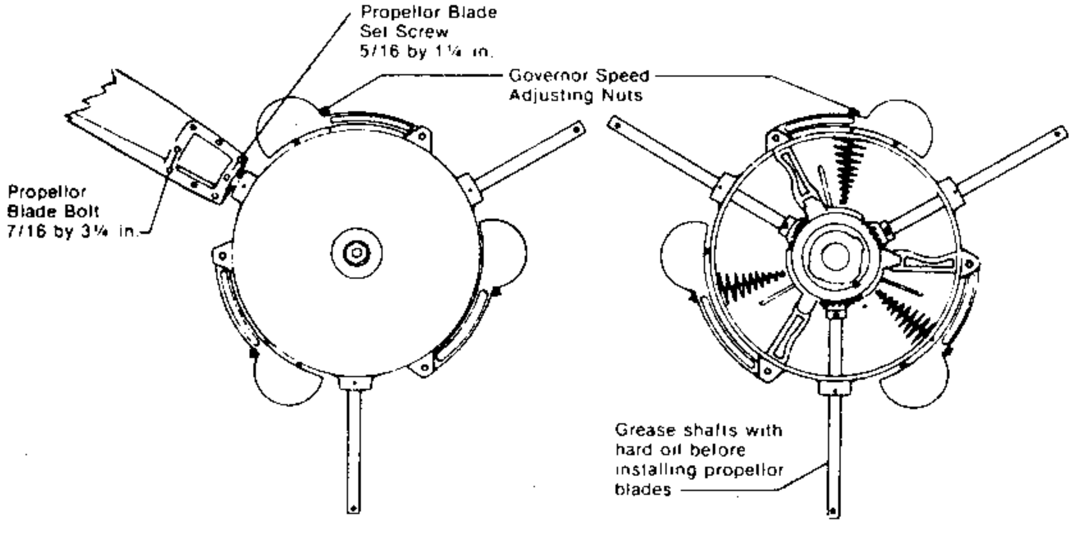
FIGURE 5. Home-built 4,800-watt generator, blown apart to show construction details.



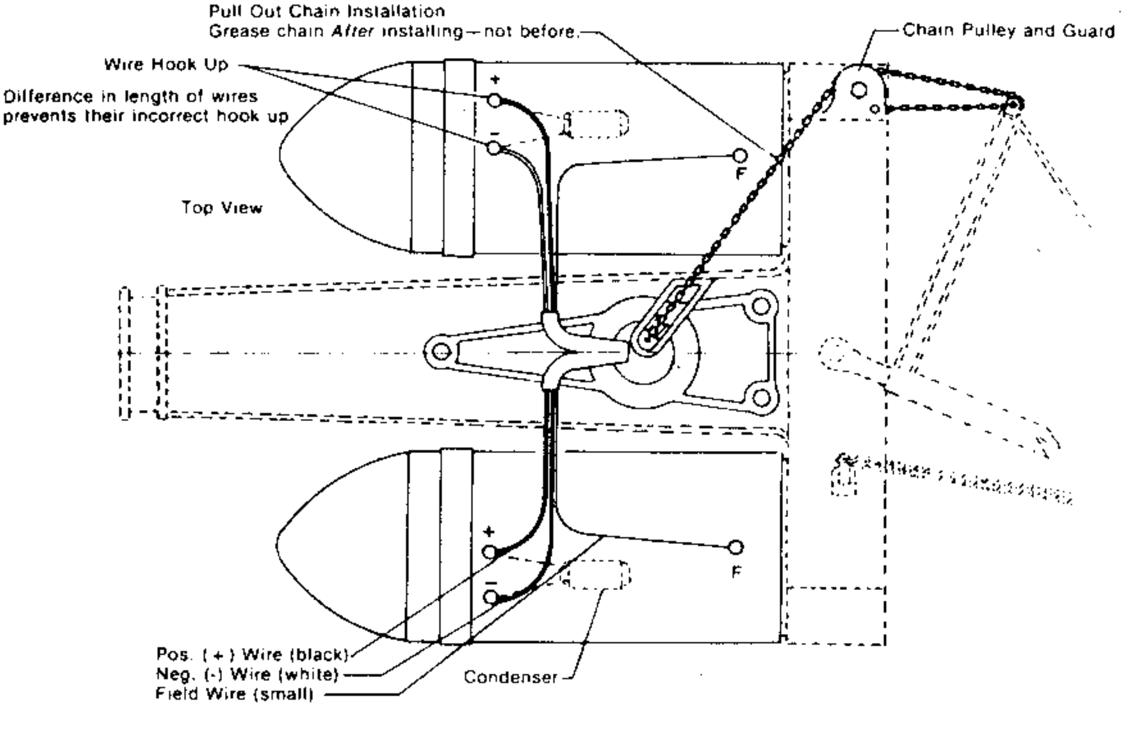


Two-bladed rotor with brake shoes.

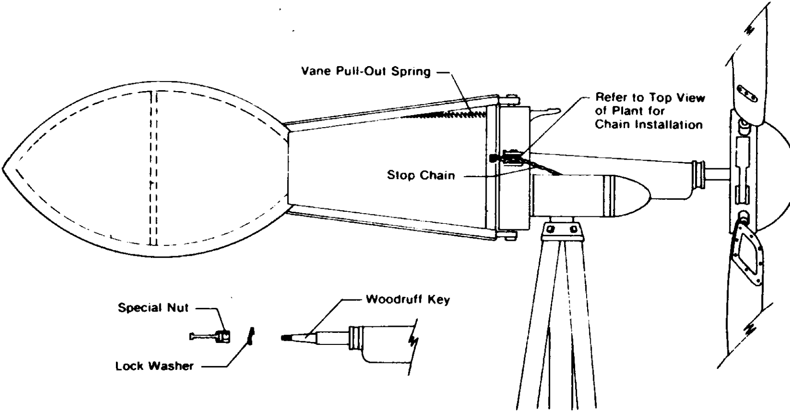


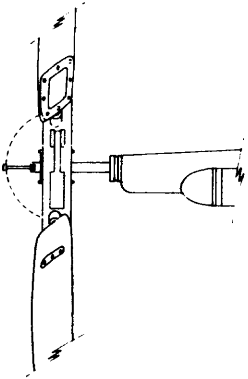


Propellor Blade
Set Screw
5/16 by 1¼ in.
Governor Speed
Adjusting Nuts
Propellor
Blade Bolt
7/16 by 3¼ in.
Grease shafts with
hard oil before
installing propellor
blades

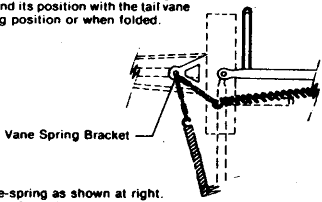


Pull Out Chain Installation
Grease chain *After* installing—not before.
Chain Pulley and Guard
Wire Hook Up
Difference in length of wires
prevents their incorrect hook up
+
−
F
Top View
+
−
F
Pos. (+) Wire (black)
Neg. (-) Wire (white)
Field Wire (small)
Condenser





View showing how vane pullout spring is attached, and its position with the tail vane in operating position or when folded.

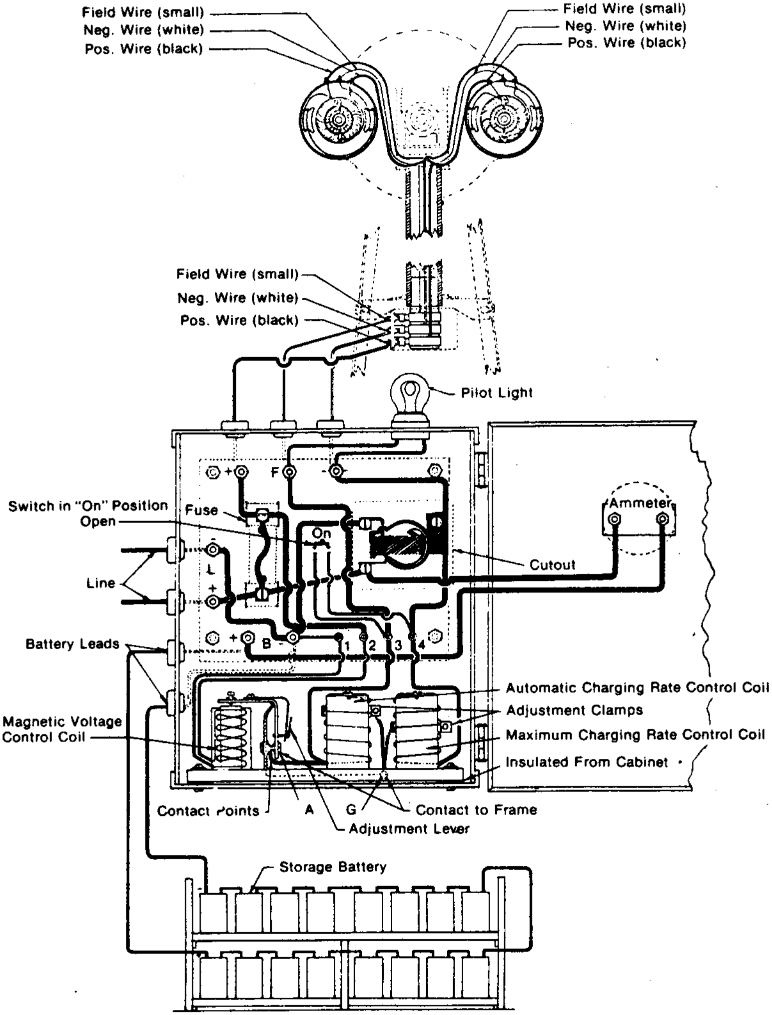


Attach release-spring as shown at right. (See other page for pullout chain installation instructions.)

In sliding governor head on generator shaft, line up keyway in hub properly with shaft key making sure latter is in place. Grease shaft before installing governor.

Wiring diagram of Jacobs Twin Motor Electric Plant. The field coils are shunt connected: one end of the field coil winding is attached to (+) positive generator brush, then attached to the insulated field terminal at rear end of generator, and from there to the upper collector ring. Then it goes through the third (field) wire to the center terminal "F" terminal, to lower terminal 3, to contact points "A", through frame to position "G", up the right hand wire. From there it runs to the adjustable band on the right–hand resistor coil (maximum charging rate control coil), then down through the resistance wire to the bottom and where wire is attached, returning the circuit to terminal 4 which is attached to the generator negative charging line. This completes the field circuit back to the (−) generator brush.

The "on" and "off" switch in the center of the control panel is open in "on" position. When thrown to the "off" position, it makes a direct circuit from the generator field (center binding post) terminal to the negative charging wire. The purpose of this switch is to give the battery an occasional over-charge by throwing to the "off" position and to make it easy to remove the automatic charging rate control unit from cabinet for replacement or repair. The generator will continue to charge as usual with the switch in the "off" position but, of course, there will be no control of the charging rate. It will be on constant full charging rate.



Field Wire (small)
Neg. Wire (white)
Pos. Wire (black)
Field Wire (small)
Neg. Wire (white)
Pos. Wire (black)
Field Wire (small)
Neg. Wire (white)
Pos. Wire (black)
Pilot Light
Switch in "On" Position
Open
Fuse
On
Ammeter
Cutout
Line
Battery Leads
F
B
1
2
3
4
Automatic Charging Rate Control Coil
Adjustment Clamps
Magnetic Voltage
Control Coil
Maximum Charging Rate Control Coil
Insulated From Cabinet
Contact Points
A
G
Contact to Frame
Adjustment Lever
Storage Battery

Mechanical brakes are rare in small windmills. A brake which is large enough to stop the mill in a good breeze needs to be well built. Half measures are not of much use. A good brake:

- is expensive;
- takes up space in the 'nacelle' or clutters the shape of the windmill;
- requires maintenance and testing if it is to be relied upon, and so it is generally best avoided.

Brake switches and heaters

Permanent magnet alternators keep working right down to very low speeds because the flux is always present. If you short circuit the output, by connecting all a.c. wires together (using a 'brake switch'), the alternator will pump large currents around its windings and the cables. Even at 'no volts' the copper loss will waste enough power to stall the rotor blades very effectively.

The brake switch is a good way to prevent unwanted start-up, but not always a good way to actually stop a windmill. There are two potential problems.

Firstly, some alternators, once they are in full power production, will generate very little more torque with the brake switch on than off. They limit their own current (by internal inductive reactance). Windmills with this sort of alternator cannot be stopped unless the speed drops below a certain rpm. (Hint: switching on the right size of heater on the a.c. wires will ensure that it stalls during the next lull in the wind.)

Secondly, other alternators deliver such high currents when short circuited that the shock puts an unacceptable load on the rotor blades, causing cracks at the roots.

Brake switches cannot be relied on in the case of an electrical failure, such as when the cables become disconnected from a windmill. It will run away, because the load has been removed. The same fault is likely to have disconnected the brake switch too, so that will not help.

Despite these drawbacks, the brake switch is a very useful parking brake, and since it costs nothing (except a decent, big switch), it is well worth having, if only for use during erection of the tower. Alternatively, a heater, which is tripped on in the event of overspeed, makes a good automatic shut-down.

How to carve a set of rotor blades

Here is a detailed, step-by-step description of the process for carving a set of blades for a three bladed rotor with diameter of 2.3 metres, and tip speed ratio of around 5.5. You can adapt the technique for any other tip speed ratio by adjusting the dimensions.

Tools

You will need the following: a hand saw (and optionally jigsaw or bandsaw), wood chisel (and mallet), plane, spokeshave, draw knife (recommended, if you can find one), callipers, compasses, square, tape measure, ruler, pencil, spirit level, drill.

Keep your tools very sharp, using an oilstone. The angle of the edge of the tool is quite critical. Always start by honing the tool, and then work up to the edge. Go easy on the edge itself, or you will actually make it blunter. Finish by removing any rag from the edge, using swift, light longitudinal strokes, or stropping the edge on leather or wood.

Always work with the grain of the wood, to prevent it splintering. Grip the workpiece firmly to a bench with a G clamp. If a tool judders or sticks, try sliding it sideways as you cut. A slicing motion like this gives more control.

Materials

3 pieces of wood, 150 mm by 50 mm, by 1150 mm long.

2 plywood discs, 12 mm thick, 300 mm in diameter, exterior or marine grade.

Table 4.1 Summary of Finished Dimensions

Station	Width	'Drop' (step 3)	Thickness
1	145	50	25
2	131	33	20
3	117	17	18
4	104	10	15
5	90	5	11

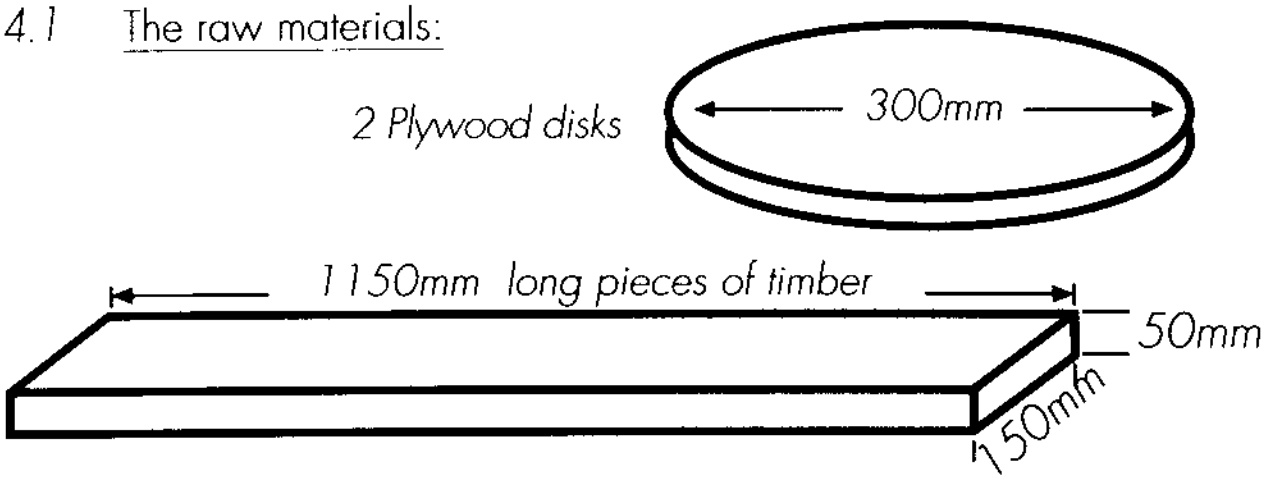
Mounting bolts to suit your hub.

48 galvanised woodscrews, size 40x4 mm countersunk.

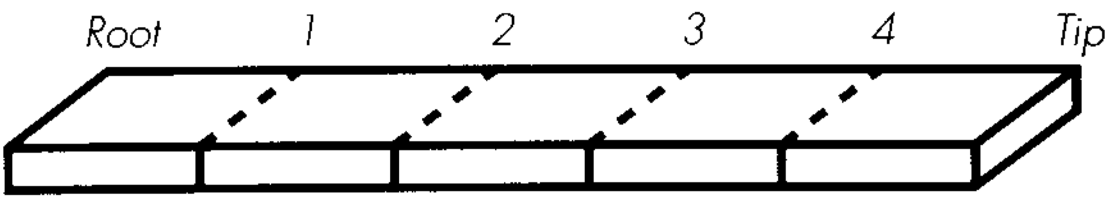
If you have access to a thicknesser machine, you should start by passing the three pieces of wood through, to remove any warp and give a smooth straight finish. Do not worry if you lose a few millimeters off the overall dimensions, provided that all three are identical.

Carving the Blades

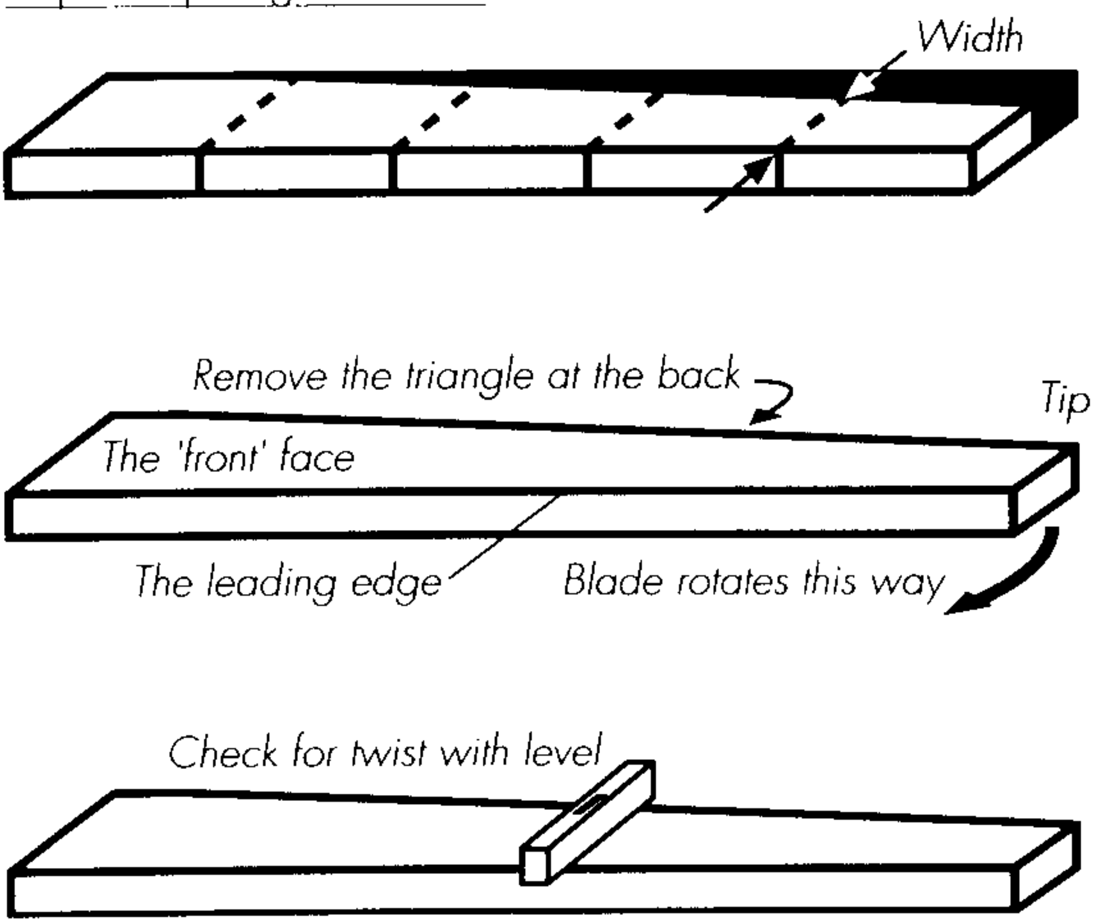
Fig. 4.1 The raw materials:



Step 1. Marking out the stations:



Step 2. Tapering the blade:



Step 1. The stations

Mark out the stations on the pieces of wood (Fig. 4.1), equally spaced at intervals of 230 mm. Draw a line right around the piece, using a square. The left hand end is the root of the blade, which will be at the centre of the rotor. The fifth station is the tip.

Step 2. Taper the blade

Measure the widths in millimetres (Table 4.1) from the edge which is nearest to you, and mark dots. Join the dots with a line. If there are any knots in the piece, turn the wood over so that they are in the triangular piece at the back which you will remove. You can use a bandsaw, or cross-cut the waste and split it out in sections using a chisel. Plane the newly cut surface smooth, straight and square.

Try to visualise the shape of the finished blade (Fig. 4.1). The tip moves clockwise, viewed from upwind, so the leading edge is the one nearest to you. The front (or windward) face is uppermost now. It should be perfectly flat (untwisted) at this stage. If not, then plane it flat. Check for twist with a spirit level, laid across the piece at each station in turn.

Step 3. Carving the twist

The next view (Fig. 4.2) shows the piece turned around, so that the leading edge is at the back, and the tip is on the left. At each station, draw a vertical line on the newly cut face, square to the front face.

Mark a point on each line, a certain distance down from the front face. We call this distance the 'drop' (Table 4.1). It determines the setting angle at that station. Join the dots to draw the line of the trailing edge of the blade. Carve away all the wood above the trailing edge (pencil line). The windward face should end up so flat that when you lay a ruler edge across the blade between the leading and trailing edges, it will not rock.

At the root, the pencil line must rise again to the uncut face in a steep ramp 100 mm long. The root is to be left uncut, for assembly between the hub disks. (Note: with larger blades, it is easiest to use a bandsaw to remove much of this deep 'scoop' near the root — see the above photograph).

Step 4. Carving the thickness

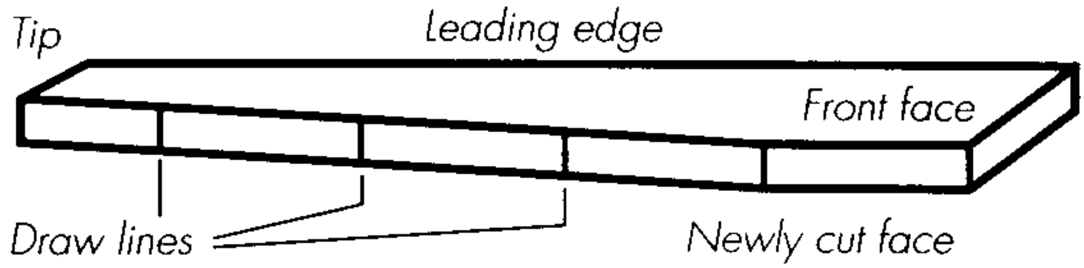
You now have a slightly tapered piece of wood, with a twisted face hollowed out of the 'front'. The next step is to remove wood from the back of the piece, so that it is the correct thickness at each station (see Table 4.1).

Lay the piece of wood with leading edge uppermost. At each station, make a mark at the correct (thickness) distance from the leading edge. Join the dots with a line. Turn it over and do the same relative to the trailing edge. Now you have two lines (Fig. 4.3) to guide you as you cut off the waste wood. Support the piece so that the front face is underneath, and cut away the waste until you get close to the lines you have drawn. When you get close, it is

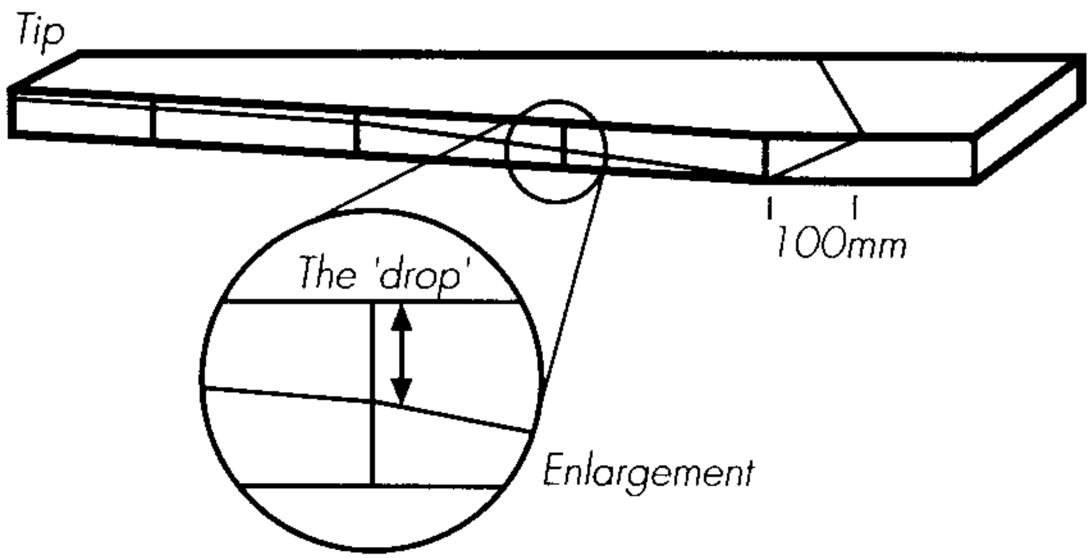
Carving the Twist

Fig. 4.2

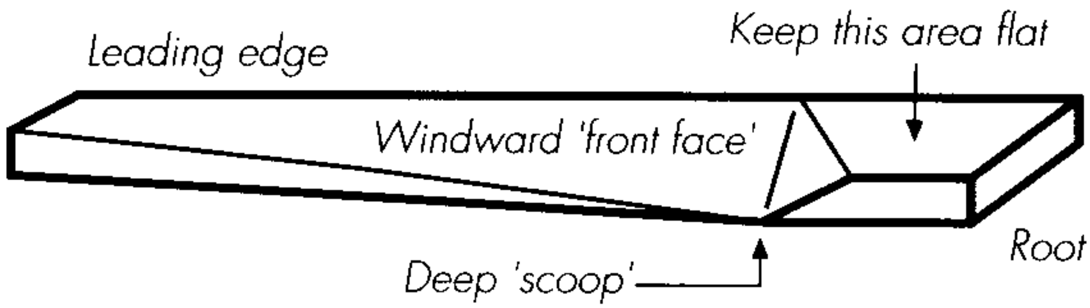
A



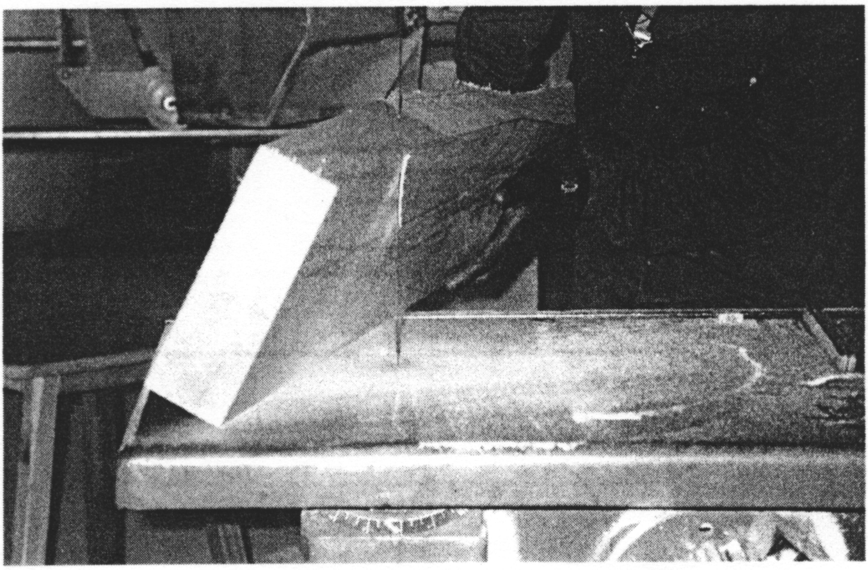
B



C The end result of this step looks like this:



Cutting out a Rotor Blade



necessary to use callipers (Fig. 4.4) to check the actual thickness at each station. Measure how many more millimetres need to be removed, write it in pencil on the workpiece at each station, and resume shaving the piece down until the thickness is correct to within 0.5 mm.

(Note: If you do not have callipers, it is easy to make a good pair [Fig. 4.4] using two pieces of sheet aluminium, or even plywood, bolted together.)

At the root, be sure to leave an area untouched (just as you did with the front face) for sandwiching between the hub disks.

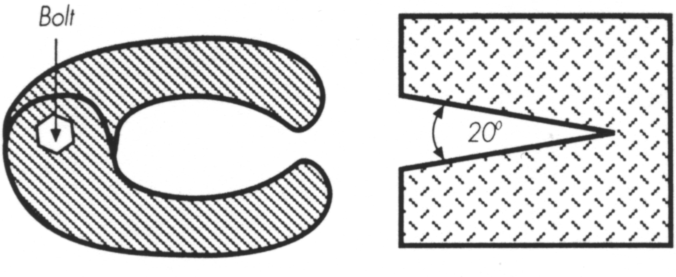
Step 5. Smoothing out the section

You should now have a tapered, twisted blade, of the correct thickness. The cross section is just a crude parallelogram shape (shown bold in Fig. 4.5), which is not very aerodynamic. The final stage of carving your blade is to give it a streamlined airfoil 'section'.

Start by feathering off the trailing edge. Plane off wood from the

Two Tools You Can Make Yourself

Fig. 4.4

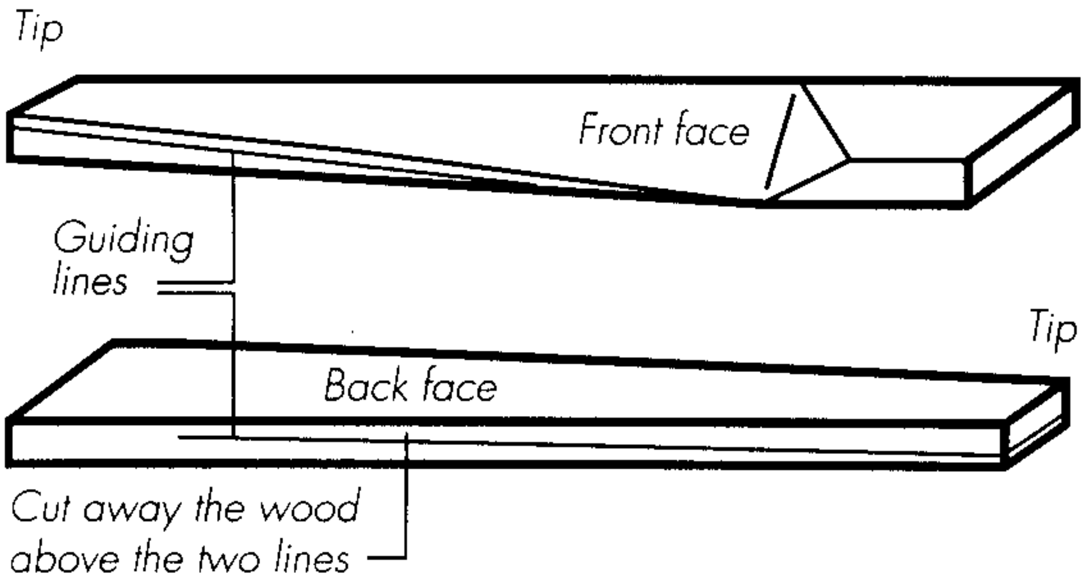


Callipers

Trailing edge template

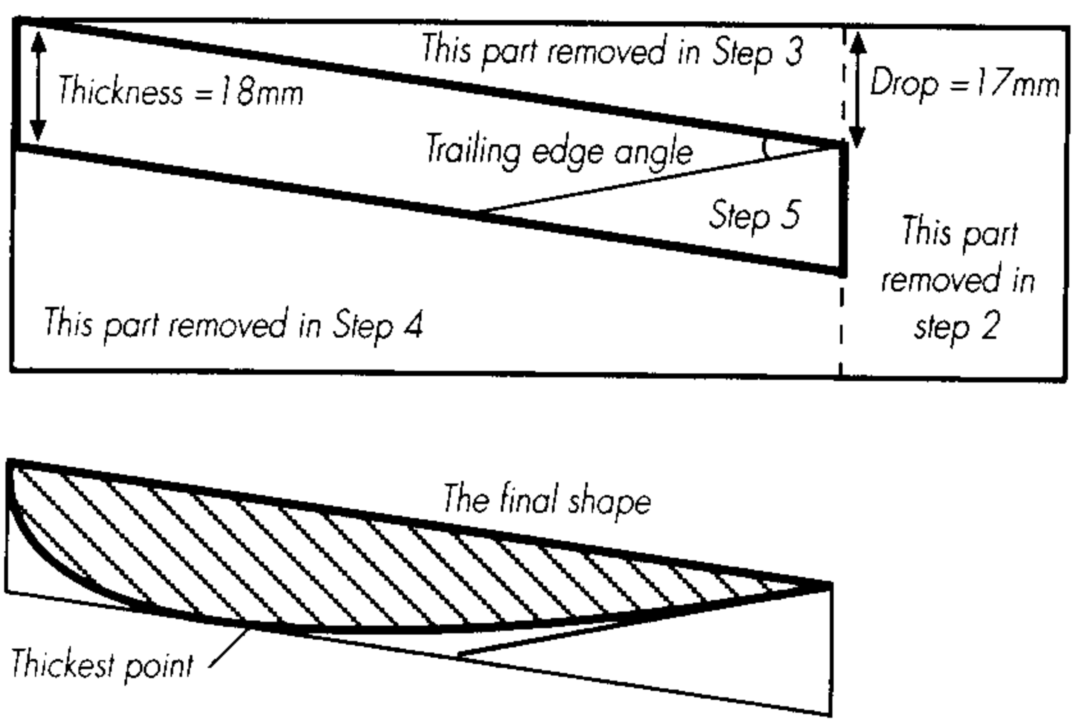
Carving the Thickness

Fig. 4.3



A Cross Section of the Blade

Fig. 4.5



back (not the windward face) until you have a sharp edge, less than a millimetre wide, bevelled at the 20° angle shown. Set the work up with light shining onto the trailing edge, so you can easily see how wide it is. The finished edge should be under 1 mm wide.

Note: It may be helpful to make an angle template (Fig. 4.4), which you can fit over the trailing edge, to check that you have got it right, and adjust it accordingly. Again, this can be made from plywood or aluminium sheet material.

Finally, the section needs rounding off into a smooth 'wing shape'. Take care not to reduce the overall thickness. The thickest part should be at about 35% of the width back from the leading edge. Draw a line along the back of the blade at this thickest point, and avoid cutting the line.

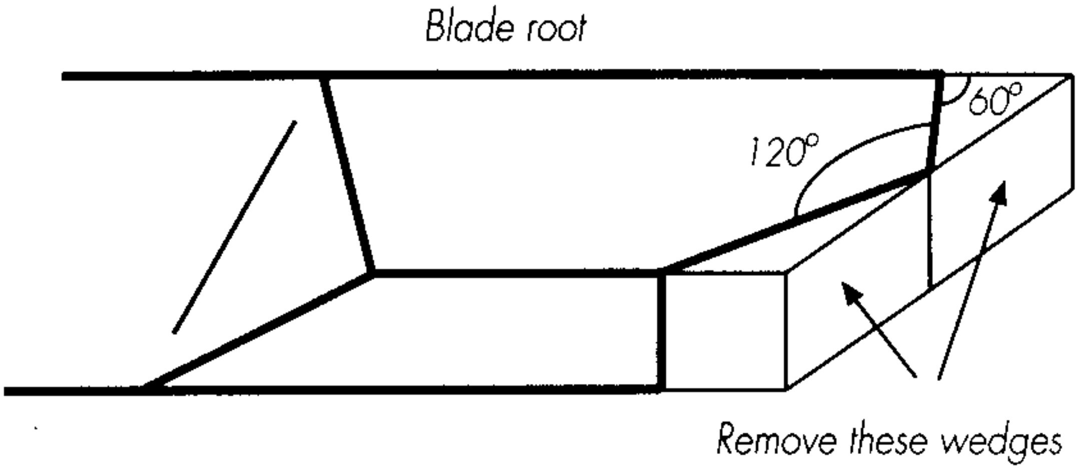
Round the back of the blade off by continually removing the corners, running your fingers over the surface of the back of the blade or watching the way the light casts shadows as it rakes across the wood. Use sandpaper if you must, but a really sharp spokeshave, set very fine, is lovely to use.

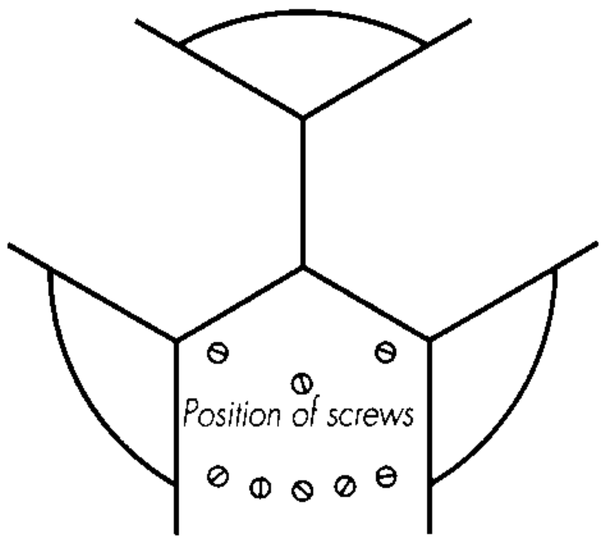
Step 6. Assembling the rotor blades

Ensure that the thickness is the same all over each blade root. Reduce the large ones if necessary. The exact thickness does not matter as long as they are all the same.

Assembling the Hub

Fig. 4.6





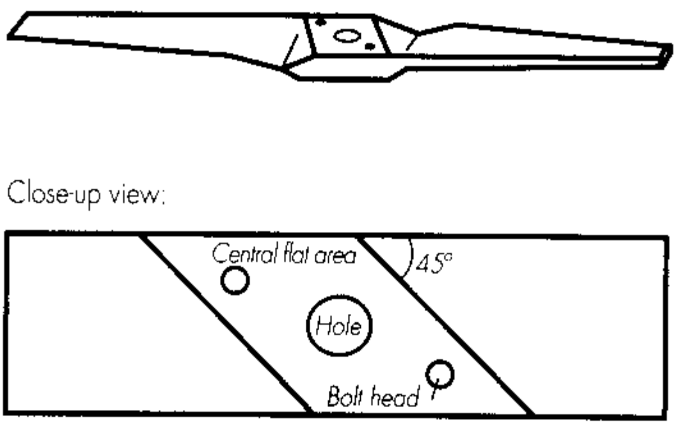
Each blade root must be cut to a point (Fig. 4.6) to fit snugly at the hub. Measure the exact centre of each blade root, and draw lines out to the edges, at an angle of 60° to each edge. Mark them front and back, then cut along the lines.

The blades can now be laid out with all three roots fitting together. They will be supported in this position by the two plywood disks, one on each side. Make a pencil mark on each blade, 152 mm from the root (front and back), to help you to centre the plywood disks.

Drill and countersink holes in each disk for the screws (Fig. 4.6). I suggest 8 screws on each side of each blade. They must not obstruct the holes which you will need to drill, for bolting the rotor to the windmill. Check that the blades are equally spaced. Measuring the distance from tip to tip and adjusting them until equal is the easiest way to ensure a 120° angle between the blades. Check also that the tips are all the same height above the bench on which the plywood sits. This will ensure that they 'track' properly

Two Bladed Rotor

Fig. 4.7



(follow each other through space). If the blades do not track within 5 mm, there will be some 'dynamic' imbalance.

Drilling the bolt holes is best done with a drill press if possible. In any case take care to drill the holes square to the rotor.

While dismantling the hub for painting, take care to mark each blade for re-assembly. Use a drill to make a number of shallow dimples in each blade (one, two or none), and mark the disks to match.

More hints on wooden blade construction

The above procedure does not cover all shapes and sizes of blade. Here are some more hints:

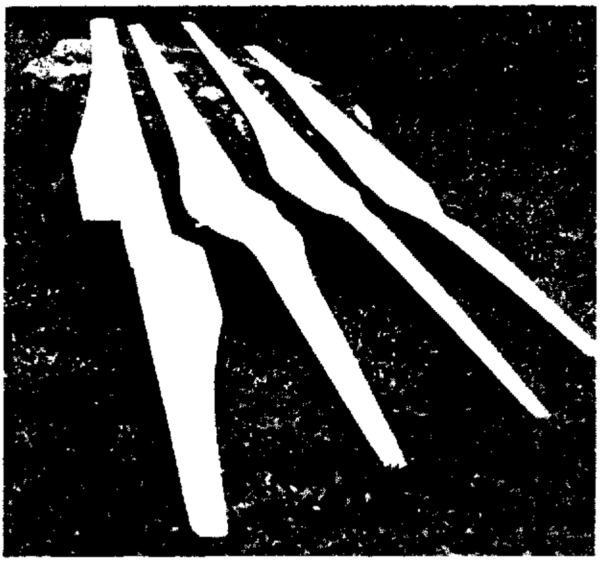
Two bladed rotors can be built from a single piece of wood (Fig. 4.7). This saves work in constructing a hub. It is simple and strong.

The central portion of the piece of timber can be left full-size. Bolt the rotor to the generator pulley, then drill a large hole through the centre of the rotor, to accommodate a socket spanner when fitting the pulley to the shaft. The shaft nut must be locked with thread sealant to prevent it from working loose.

Fins at the root

A glance at the blade designs in chapter four shows that it is desirable to have a wide section and a coarse setting angle at the root of the blade. If you cut such a blade from a single piece of

Two Bladed Rotors



Some two bladed rotors carved from wood.

timber, it would be very wide and thick, and there would be a lot of waste. A simple solution is to use offcuts from the outer parts of the blade, glued on as supplements to the inner part. Build up the trailing edge with a fin to increase the chord width. Build up the windward face with another fin to increase the setting angle.

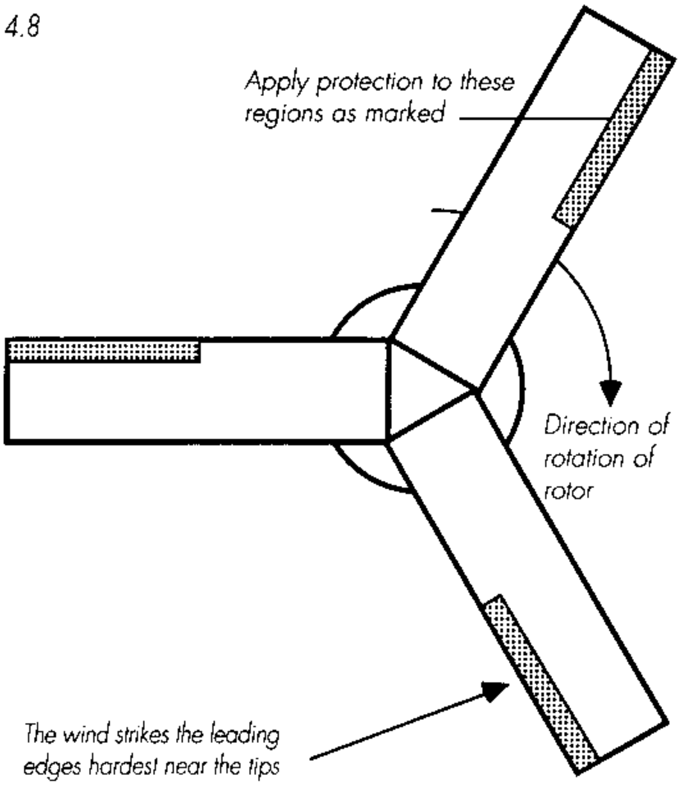
Painting and balancing the blades

High tip speeds cause rapid erosion of the blade material. The leading edges of the blades need special treatment (Fig. 4.8), either with epoxy resin or 'leading edge tape'. Leading edge tape is sold for the propellers of microlight aircraft (see the Resource Guide for suppliers). It is easy to apply and to replace, and it offers very effective protection for a period of time. Apply the tape after painting.

If you are using epoxy resin, you should first plane off about 3 mm from the leading edges and rebuild them with a paste, mixed from epoxy resin and aluminium powder (or a similar filler). Polyester resin pastes such as 'Plastic Padding' are not so durable as epoxy. Apply the resin before painting.

The ideal protective surface would be a resilient (rubbery) finish. Good adhesive strength is also required. Silicone rubber can make a good on-site repair, but it is hard to produce a smooth finish.

Fig. 4.8



Painting

Prime the wood carefully, and apply plenty of coats of gloss paint. Sand it well before the final coat. Household gloss paint may seem crude, but it has advantages over epoxy paints and varnishes.

Epoxy paint is completely watertight, which is not always an advantage. Water within an epoxy coating cannot escape, whereas other paints will breathe. If the blade is damaged, for example by fastenings biting into the wood near the root, then water will enter, and be centrifuged out to the tip, where it will collect, and swell the wood, until it bursts. Varnish degrades much faster than paint in ultra-violet light. (Varnished wood does look lovely though, for a while.)

Balancing

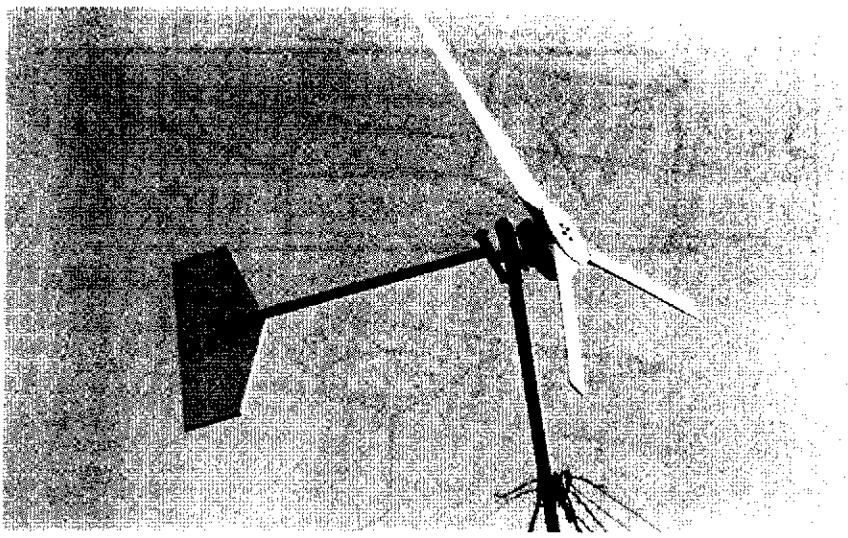
It is essential to balance the blades carefully. The aim is to ensure that the centre of gravity of the assembled rotor is exactly at the centre of rotation, i.e. the centre of the shaft. This is known as 'static balancing'. Dynamic balancing is not necessary, provided that you ensure that the tips of the blades 'track' each other. Rotor blades are axially thin, so static balancing is quite sufficient.

Balancing should be done indoors, in a large open space, free of draughts.

Pieces of lead flashing (from the scrapyard) make ideal balance weights. If very heavy weights are required, they can be shaped (from steel or lead), and tucked into the recesses between the three blades.

Here is one method of checking the static balance. The blade is poised on a sharp spike (Fig. 4.9), perhaps made from a 100 mm

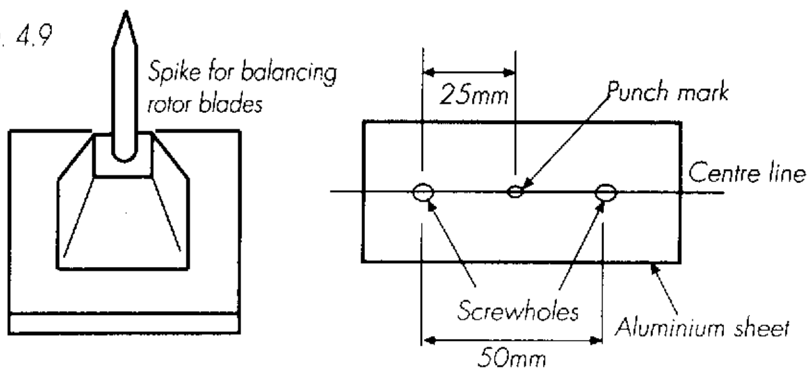
The Finished Rotor



A 2.3m diameter rotor as described in the instructions.

A Jig for Balancing the Rotor

Fig. 4.9



nail or similar, driven into a wooden support, and sharpened with a grinder. The spike engages with a punch mark at the exact centre of the rotor.

Make a jig from a small piece of aluminium sheet (Fig. 4.9) with a punch mark at the centre, between two screw holes. Position the holes precisely, at (say) a 25 mm radius from the mark. Make two corresponding holes in the back of the rotor hub, on an exact line through the centre of rotation. Screw on the jig, with the punch mark at the exact centre of the rotor.

Engage the spike with the punch mark and sit the whole thing on its stand. It will be unstable. Set the rotor level, using a spirit level. Lift off the spirit level gently, and observe in which direction the rotor falls. Add weights to the opposite side, until the rotor is capable of balancing momentarily on the spike, with no preferred direction to fall in. You need to place the spirit level both 'north-south' and 'east-west'.

Making the rotor is perhaps the most satisfying part of building a windmill, and it is a feasible task for anyone with simple tools, patience and enthusiasm.

MAKING THE PROPELLER

Whilst I am aware that many people are apprehensive about carving their own propeller out of wood, I still strongly advocate that you try this method, as it yields much better results than bent bits of metal. Making moulded fibreglass blades is a tricky operation and very laborious for a one off job.

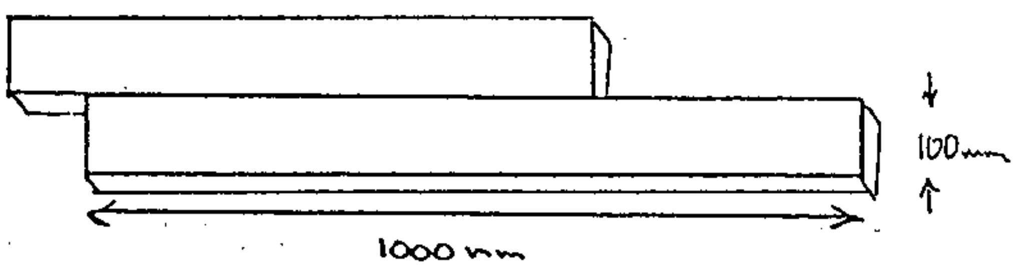
You will need some sharp tools: a plane, spokeshave, chisel, saw, and ideally, a drawknife, which is great fun for ripping out great hunks of wood. Sharpen the edges with an oilstone, at the correct angle (work up towards the edge rather than back from it), and remove any rag which may result, by stropping the edge to and fro until it breaks off.

I usually clamp the wood onto a bench with a G-clamp, or clamp it to a waste piece of wood, which in turn is firmly gripped in a vice. This allows me to turn it around to the best working angle with ease, and hold it rock steady. If it vibrates, and the tools judders, try cutting slightly crabwise, angling the blade diagonally to the direction of motion. Obviously you will need to cut with the grain for best results. Power tools may be useful but they create a lot of dust, and it is difficult not to cut too much off at once.

Reasonably knot free ("clear" is the technical term), straight grained wood is necessary for a satisfactory job: if you buy it new, then Oregon Pine is a good choice but very expensive. Old bedframes can be a good source of propeller wood, or even old building timber or church pews. In what follows I assume that you are using 4"x2" timber 100mm by 50mm, but you can piece the same shapes together with any starting size once you understand the principle.

You need a total of over 5 metres of 100x50 timber, cut into six pieces, 3 at 1000mm, 3 at 750mm. Each blade is then built up by gluing two pieces together, overlapping as shown in fig1:

FIG 1

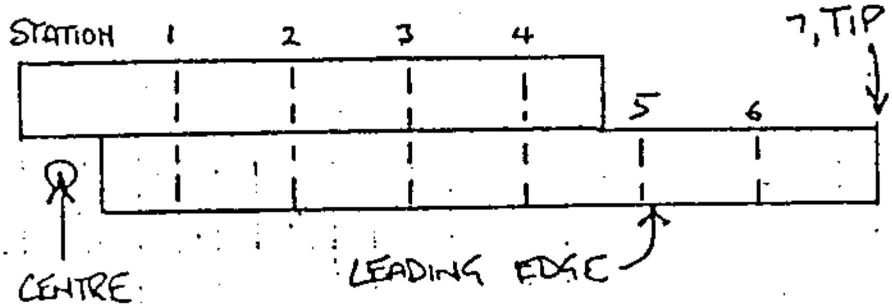


If you do not have enough wood, you may be able to work out a way of producing the final shape by cutting what you have into triangles. Use the same epoxy as for the alternator job. Other glues may be ok, but epoxy is definitely very suitable. Clamp the pieces together very firmly while the glue sets.

Each of the operations which follow will start by marking the correct measurements onto the work piece at each of a series of "stations". There are 7 stations including the tip, spaced equally at 150mm intervals from the centre of the propeller. Mark the stations on the work piece now, using a square to draw a line right around the piece, as shown in figure 2:

FIG

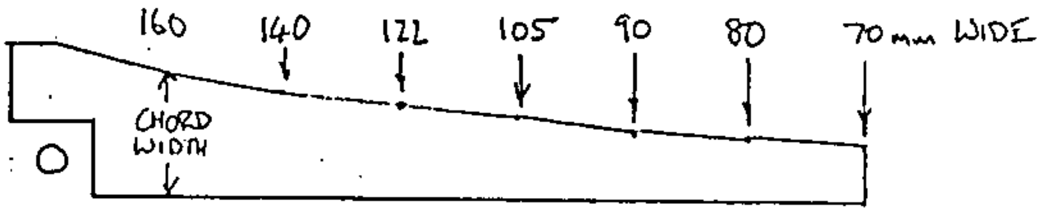
2



Next you need to produce the correct taper : ie get the blade "chord width" right at each station. In all that follows, the leading edge remains untouched, as a sort of reference line. Measure the width from the leading edge at each station, join the dots with a line, and cut away the surplus wood, as shown in fig 3:

FIG

3



Turn the blade on edge, and work down to the line to an accuracy of plus/minus 1mm, and keep the cut face square to the "top" of the wood (see fig 4). Where there is more than 10mm of wood to remove, it may be easiest to cut through the waste across the grain with a saw and then chop out chunks with a chisel, along the grain. Or you can use a bandsaw if you have access.

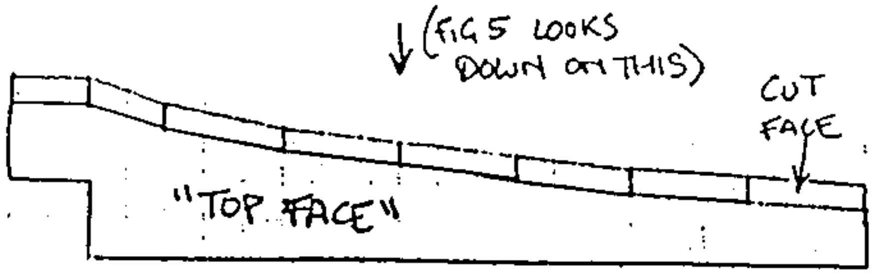
The next job is to put the correct angle on the blade, so it will catch the wind and run at the right speed. This is variously known as the weather angle, setting angle or pitch of the blade. The angle is measured relative to the "top face" of the piece of wood: the one shown facing you in the above figures.

Before going any further, check for warp on this face, as this will affect the angle produced. You can check for warp by laying the work piece on a level surface, with the top face horizontal. Place a spirit level ACROSS this top face at each station in turn. At each station the bubble should sit at the middle of the glass. If there is a tilt at some of the stations then you will need to compensate, either by planing the top surface carefully level, or by measuring the error and compensating for it in what follows.

Turn the wood up on edge again. Draw your square lines at each station on the newly cut face, as shown in Fig 4.

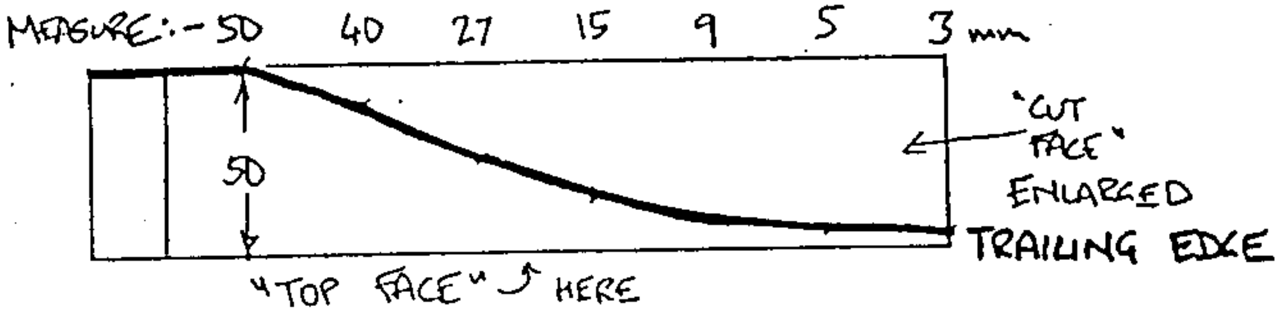
FIG

4



Now we need to draw a line to mark the position of the trailing edge of the blade on the newly cut face. At each station, measure the prescribed amount (figure 5) from the "top face" along the newly drawn lines on the cut face. Mark a dot on each line at the correct distance from the top face. Join the dots, to produce the trailing edge line of the blade, as shown in figure 5. The thickness of the wood is exagerrated to make it easier to see what is happening:

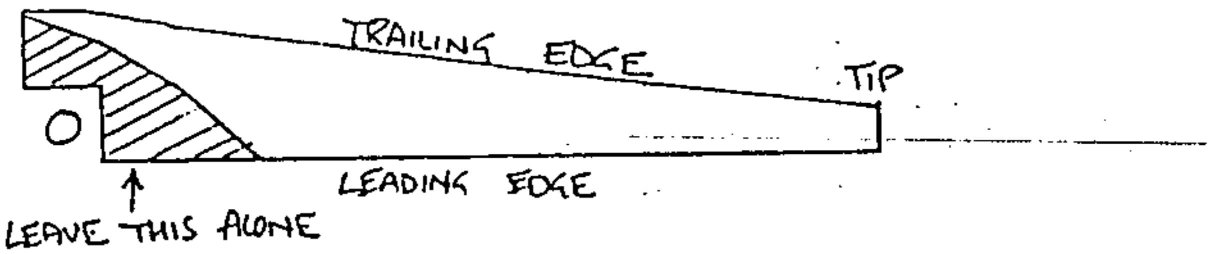
FIG 5 edge of wood



The trailing edge line is shown in bold in figure 5. This line is all that will remain of this face of the wood when you have finished the job. Now it is time to tackle the windward face (front) of the propeller blade. For simplicity, I recommend a flat front face, although some people cut them concave. When I say flat, I mean that the line between leading and trailing edges is straight. The face itself is not flat, but twisted, due to the strange curve of the trailing edge.

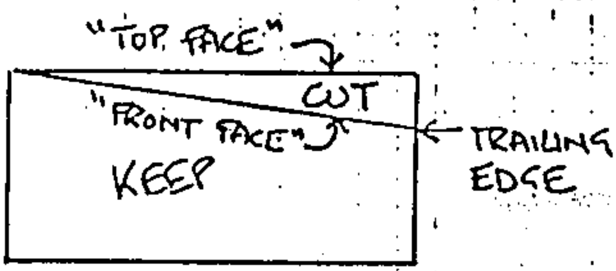
First mark the top face as shown in figure 6, which shows (hatched) the part of the top face which should be left alone:

FIG 6



Now you have to cut away all the wood above a line between the leading and trailing edges, to produce the flat, twisted, front face referred to above. Figure 7 is a CROSS-SECTIONAL view of the fourth station, to show the part of the wood which must be removed (marked"CUT"):

FIG 7 CROSS SECTION AT STATION 4.



Having cut the front face, the next step is to make the blade the correct THICKNESS. Near the root, the thickness should be about 15% of the chord width. It drop to about 12% of the chord width at the tip. The actual thicknesses I recommand are shown in figure 8.

You must measure these thicknesses from the front face, in a way similar to marking out the trailing edge in figure 5. Do it at both, the leading and trailing edges, and make two lines running the length of the blade, on opposing faces as shown:

FIG 8

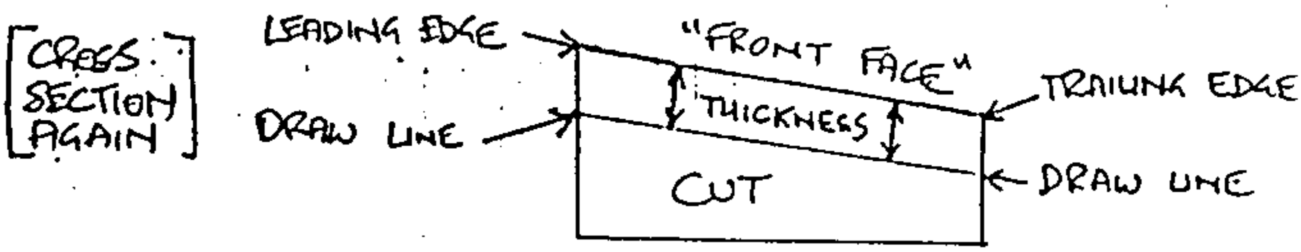


TABLE OF THICKNESSES:

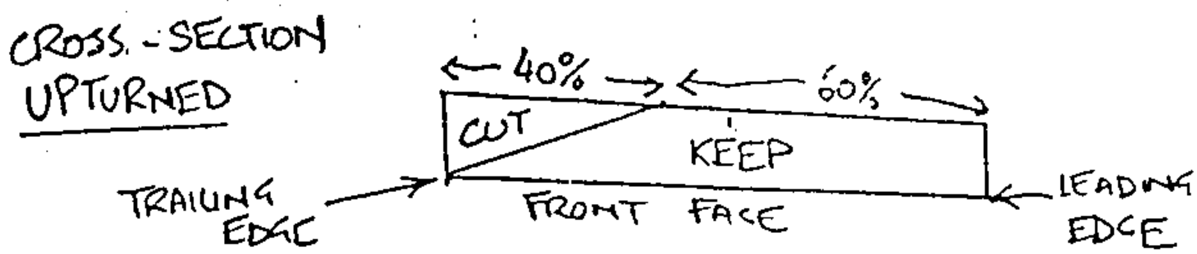
Station :	1	2	3	4	5	6	7
Thickness:	(50)	20	18	16	14	12	9 mm

Turn the work piece upside down, with the front face downward. Now cut away the portion marked "CUT", working down to the two lines you have just drawn. It may be helpful to use callipers for accurate measurement of the remaining thickness, especially near the tip where precision is required.

You will be left with a blade which is the correct width and thickness, but has a crude rectangular/parallelogram cross-section. This now needs to be made into an aerodynamic shape. I normally leave the front face flat, but the back face (away from the wind) has to be convex (bulbous), and the trailing edge needs to be sharp, for minimum drag.

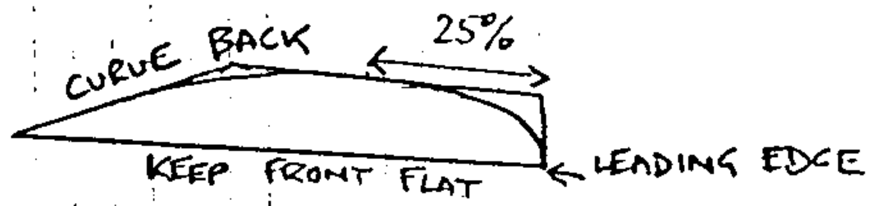
Shave wood away from one side of the most recently cut face to sharpen the trailing edge. The correct angle for the trailing edge is obtained by cutting away about 40% of the back face into a bevel down to the trailing edge as in figure 9:

FIG 9



Finally you need to round off the sharp corners on the back of the blade, to produce a smoothly curved airfoil shape. I do this by eye really. Draw a line on the back face about 25% of the width back from the leading edge, and leave this line untouched, or you will lose your thickness. Figure 10 shows the general idea:

FIG 10 SAME SECTION



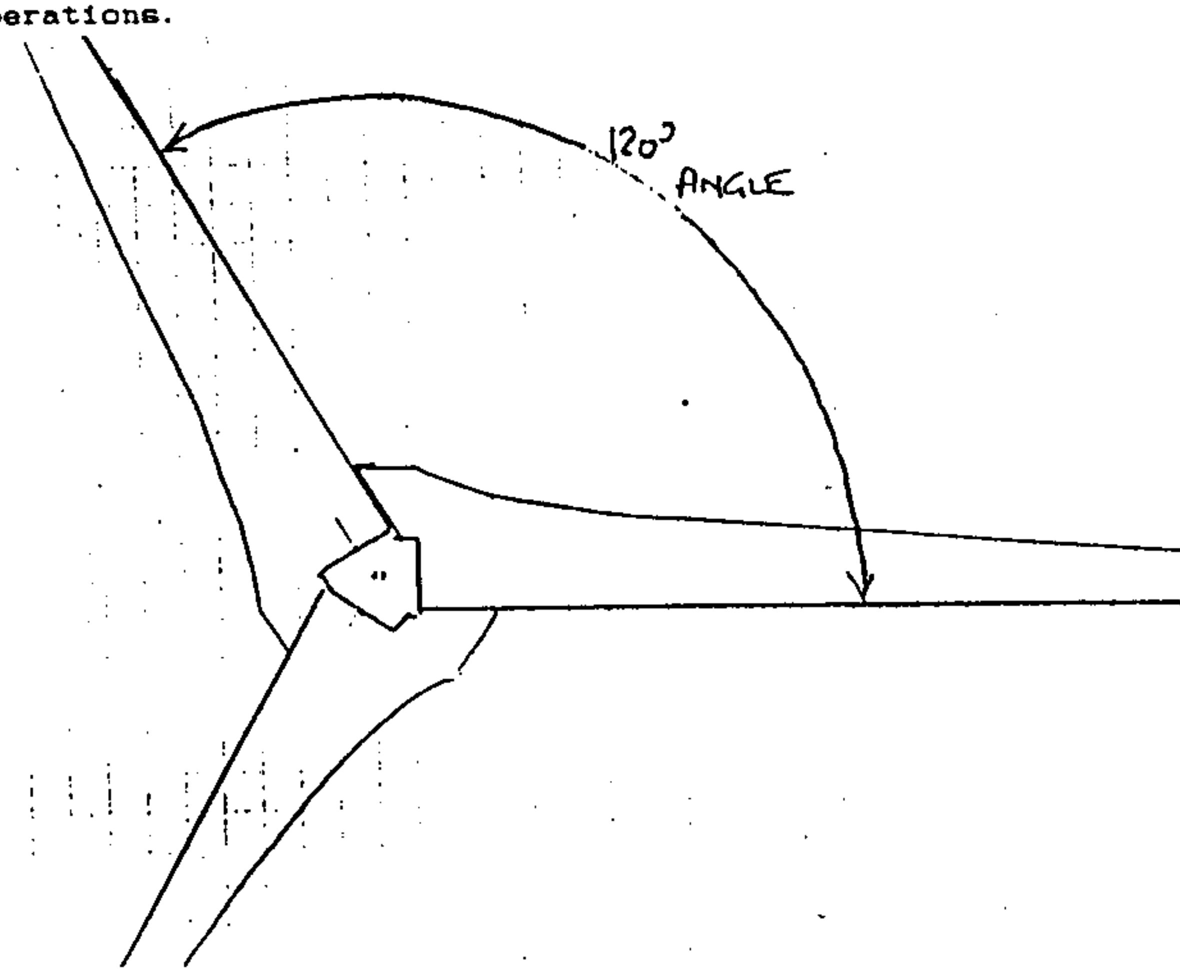
There is usually some debate about the best shape of the leading edge. I tend to keep it rather too sharp for some people's taste, maybe it should be more bulbous. In any case the wind generally wears this bit out of all recognition after a couple of years.

You should now have three lovely propeller blades. Normally I remove the leading edge with a plane to a depth of about 3mm and rebuild it with a mixture of epoxy and powder, to provide a tough setting paste. This has to be applied with a butter knife, and filed off when hard to make the original shape again. With this windmill, which turns much more slowly than my old dynamo ones, erosion is not such a problem, and even a bare wooden blade lasts a few months without serious damage. It's up to you.

However, I do recommend painting the blades thoroughly. I use Woolworths non drip gloss on primer, and coat them thickly, sanding smooth with waterproof abrasive paper after the fourth coat. Painting should follow the next bit: assembling the whole rotor at the hub.

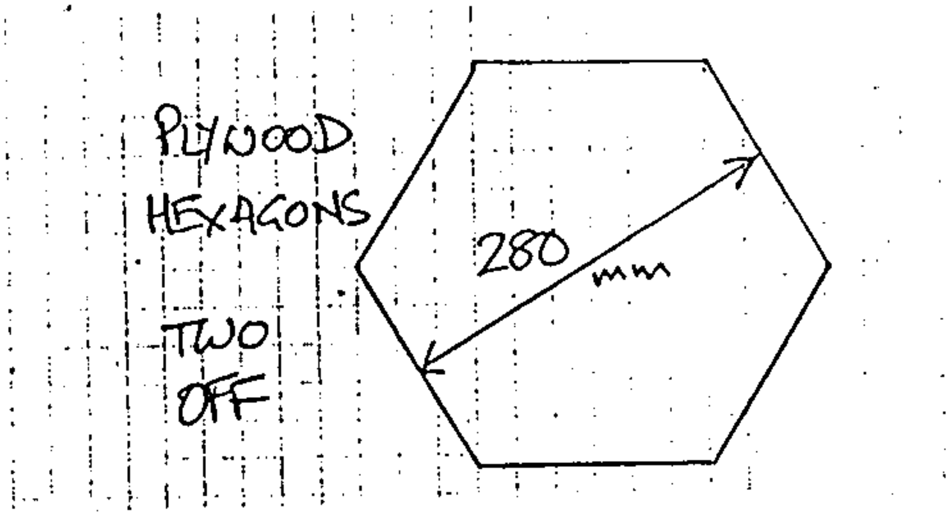
The way the blades fit together is shown in fig 11. The centre of the prop is 50mm back from the line of each leading edge, and 50mm from the end of the longer piece of wood, in the original construction (see fig 2). Position the blades so that these centre points coincide, and the angle between any two leading edges is 120 degrees. Fitting them together will require the removal of some wood (a triangle at the root) from the pieces you glued on the sides (see fig1). I leave this until last, because these pieces are useful for clamping up during the carving phase of operations.

FIG 11



When you have the blades all fitting snugly as described, cut two hexagons out of sturdy plywood (minimum 9mm better 12mm) as shown in figure 12:

FIG 12



Sandwich the centre of the propeller between these two hexagons and fasten the whole together with a pattern of 2" woodscrews. I used 36 screws in all. Obviously you need to position the blades carefully before you start driving in screws.

If you will never need to take the propeller to bits again (for easy transport or painting for instance) then it may be an idea to use epoxy as well as screws in the assembly of the hub.

The propeller is now complete, but it still needs to be balanced and fitted to the brakedrum alternator. Balancing is just a matter of making sure that the centre of gravity of the propeller assembly lies exactly on the centre of the shaft of the alternator. First find the centre fo gravity of the propeller as follows:

Mount a sharp "knife edge" about 300mm long, horizontally in the jaws of a vice or similar. Balance the back of the propeller hub on this knife edge. Sit the propeller dead level, and release it gently. If it tips, move it in the opposite direction a fraction and try again. Finally you should reach the point where it can hardly decide which way to tip. Press down firmly and slide it to and fro on the knife edge to mark this position. Rotate through 60 degrees or so and repeat the process. Rotate a second time and cut a third line on the underside of the hub. When you have three lines, all passing below the centre of gravity of the propeller, turn it over and check that all three scratches meet at one point. This is the centre you need to use. It may not be the exact geometrical centre of the prop, due to differences in density or whatever, but it is the centre you must use. If you do not like it, you can move the centre by attaching weights (eg bits of lead screwed on), and repeating the process. The back of the hub will get a bit messy and you will find the lines hard to interpret after a while.

Having found the centre, you can interface this with the mounting to the alternator. I mounted the prototype propeller by drilling and tapping two M10 holes in the front of the hub. One was in a hole previously used by a small screw which holds the brakedrum to the hub. The other hole I put exactly opposite. Precision is necessary for correct balance of the propeller. The holes are not flush with the surface of the alternator but I filled the gap with nuts and washers. See figure 13

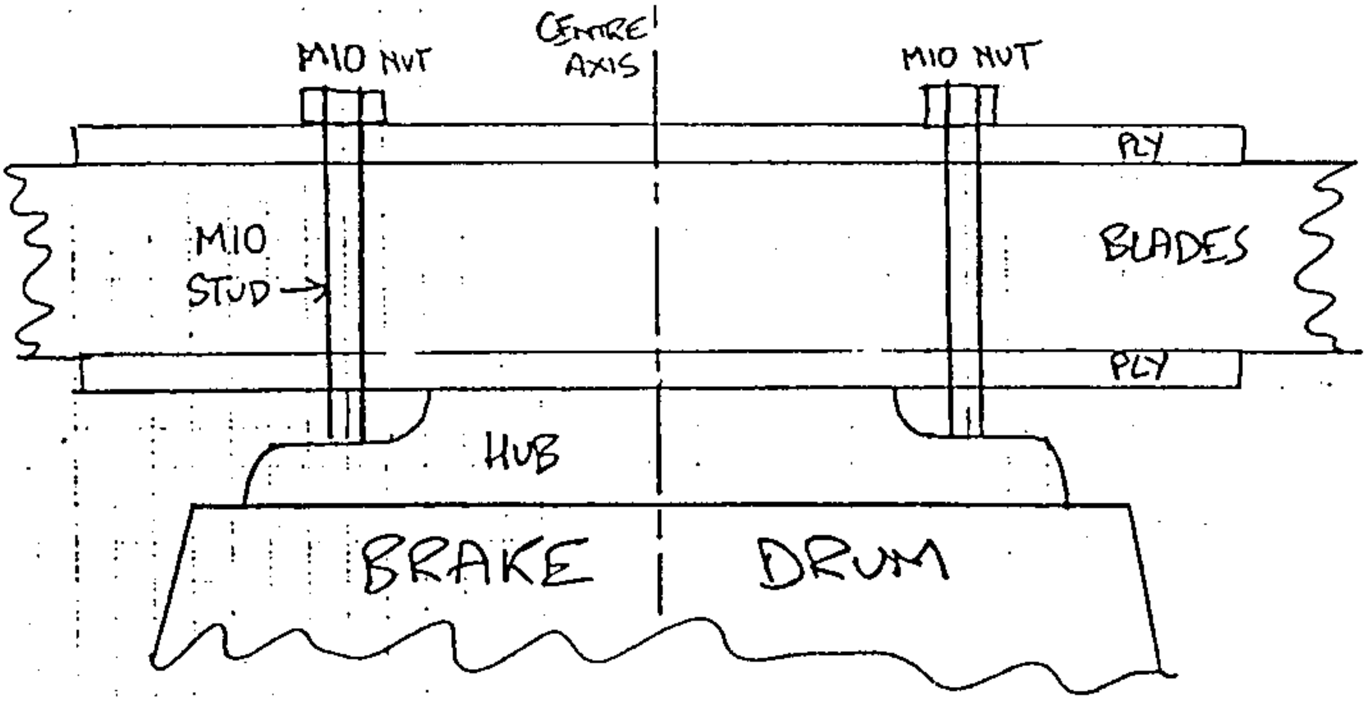


FIG 13

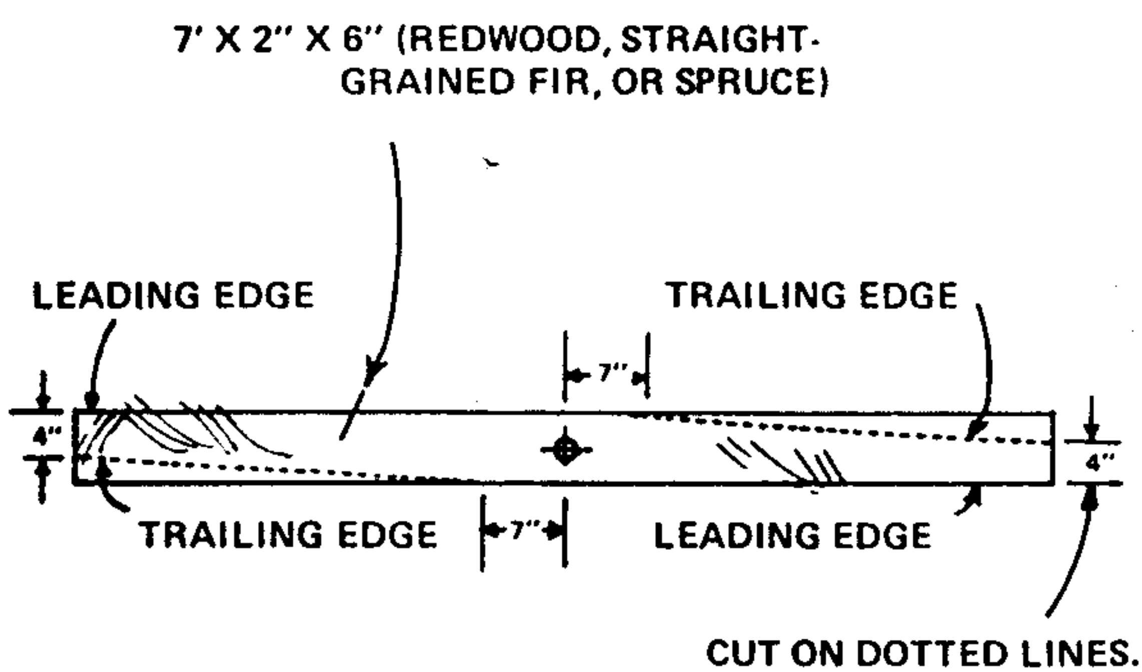
When drilling the two 10mm holes in the propeller hub assembly, use the centre of gravity as the mid point between holes. This will ensure correct balance.

The studs for securing the half-shaft need to be removed or ground off. I tried drilling them out at one point, but found them very hard indeed. You can seal the front end bearing against entry of moisture, using silicone sealant or mastic. Put a bead of sealant around the hexagonal face where the propeller sits on the alternator before applying the propeller.

When the propeller is correctly attached, the tips should follow each other exactly through space, as the blades rotate. If you find that the tips are more than 3mm in front of or behind each other, then it will be worth shimming the propeller slightly to correct the tracking.

I decided to use an alternator because I thought it would put out at lower rpm's than a generator and because it was modern and had diodes in it. But I'm beginning to think that there is no problem using a regular DC car generator. In fact, there are some definite advantages: they are cheaper, they *don't* have diodes in them, and you can use a cutout relay to take the battery out of the circuit when the wind stops. With an alternator, you have to rig up some kind of wind- or centrifugal-force-activated switch to accomplish this.

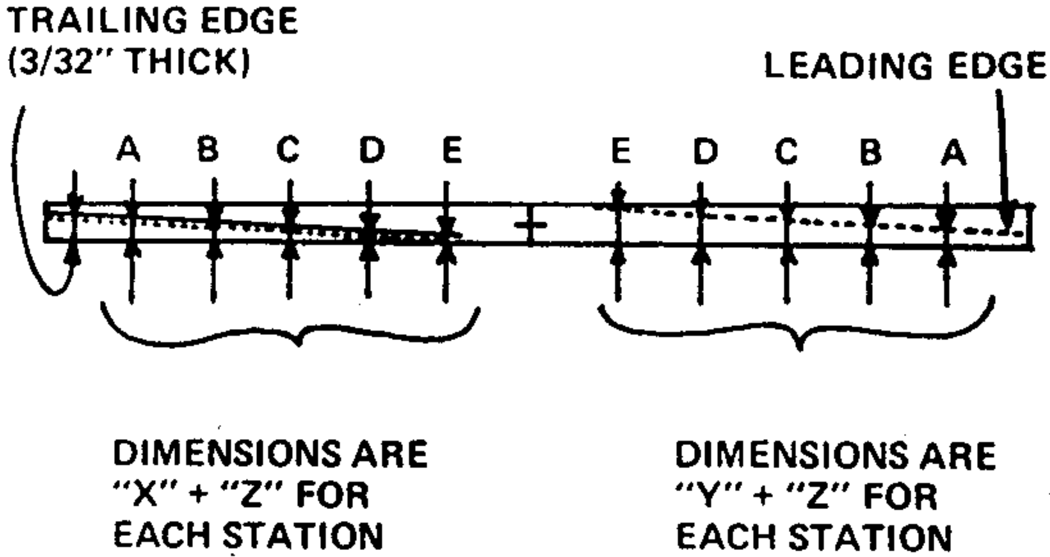
Now, about the propeller. This is really the heart of the thing . . . and if nothing else, the main point of this article is that a wooden propeller of this type is *easy* to build with almost no woodworking skill and very little money. The plan I used is from the LeJay Manual and I've included step-by-step instructions which I hope anyone can follow to make a prop, using a good piece of wood, a drawknife, a rasp and some sandpaper. If you've never seen a high-speed prop going in the wind, by all means try building this one. Mount it on an old generator or something and set it up in the wind. Don't hold it in your hands! I almost lost my head that way. It'll blow your mind when you get a feeling of the power that this thing produces!



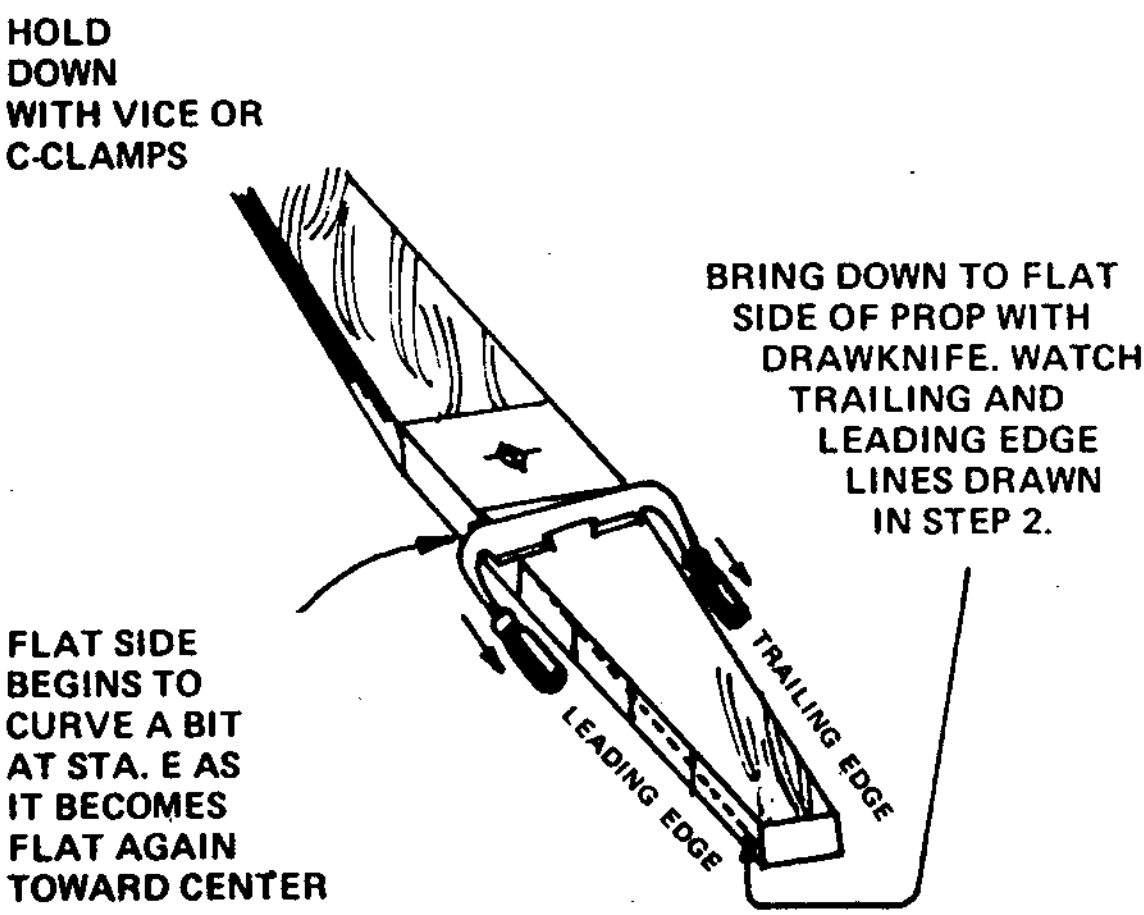
STEP 1

Handbook of Homemade Power. Shuttleworth Mother Earth News/Bantam Books USA 1974 0 553143107.

DRAW DOTTED LINES ON EDGES (FIGURE FOR STEP 2 SHOWS RIGHT-HAND EDGE OF FIGURE IN STEP 1).

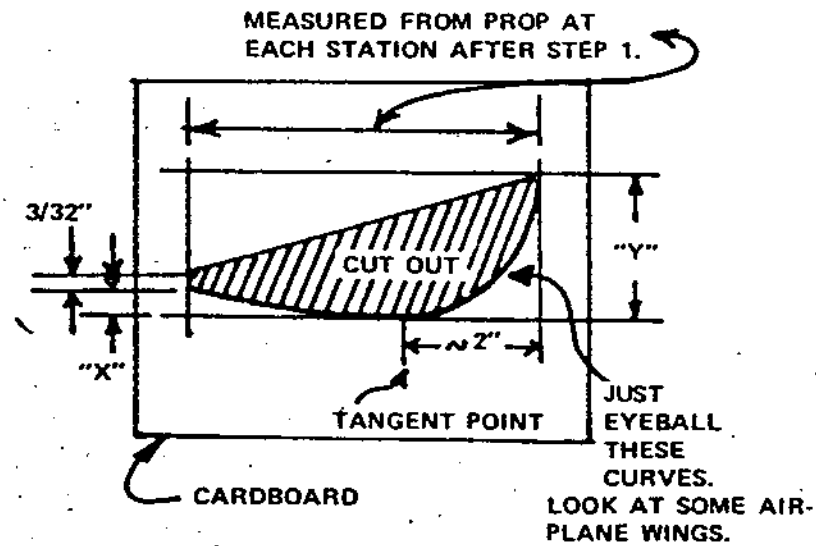


STEP 2



STEP 3

DRAW CROSS SECTIONS FOR EACH STATION
FULL SIZE ON CARDBOARD AND CUT OUT
WITH RAZOR TO MAKE TEMPLATE



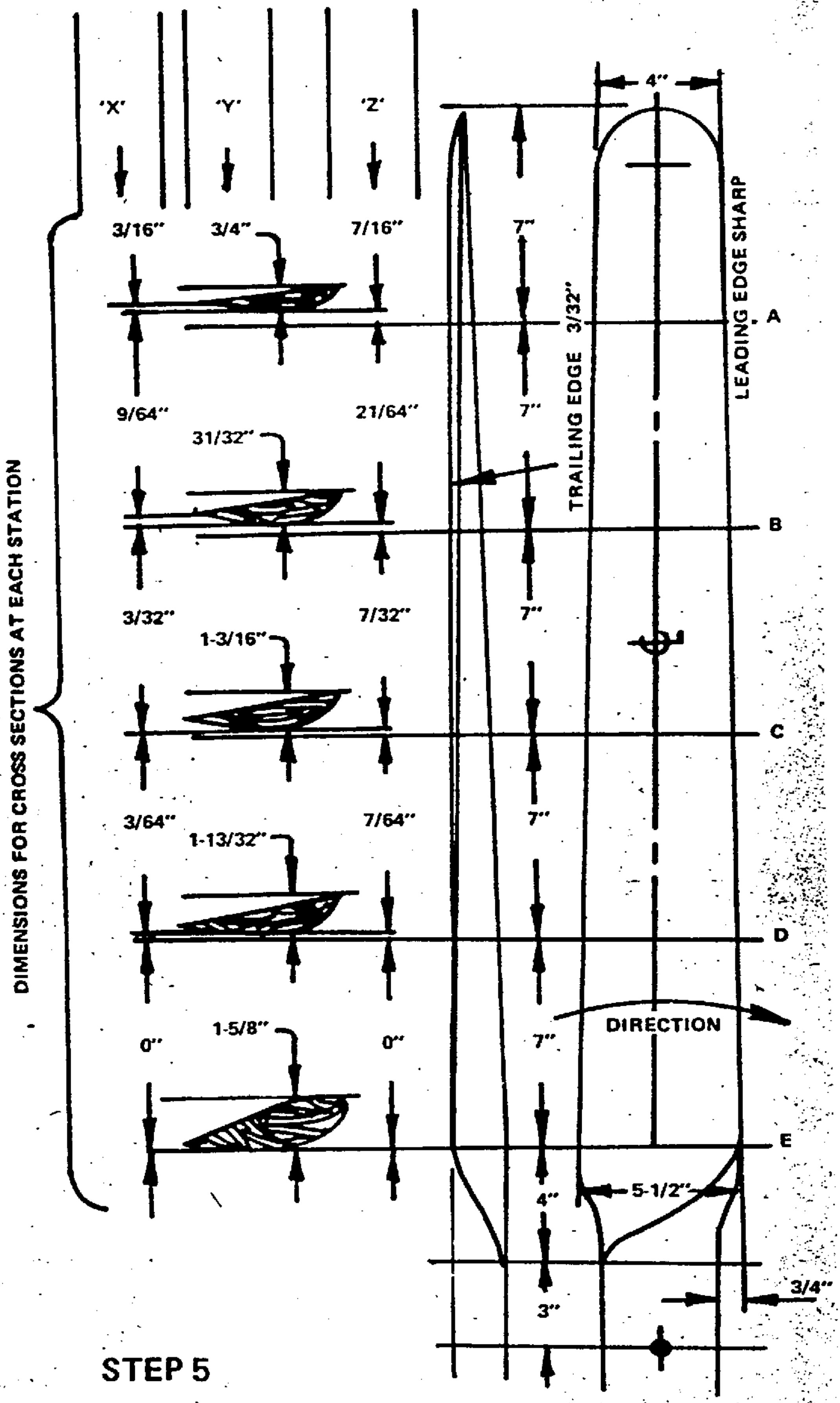
STEP 4

GENERAL CONSTRUCTION TIPS

Start at tips bringing wood down on airfoil side of prop with drawknife (or rasp when it starts getting close) until template for station A will fit on prop in the right place (7" from tip)—then go to template B until it fits (7" from A)—and so on toward the center. The flat side made in Step 3 is your reference for positioning the templates.

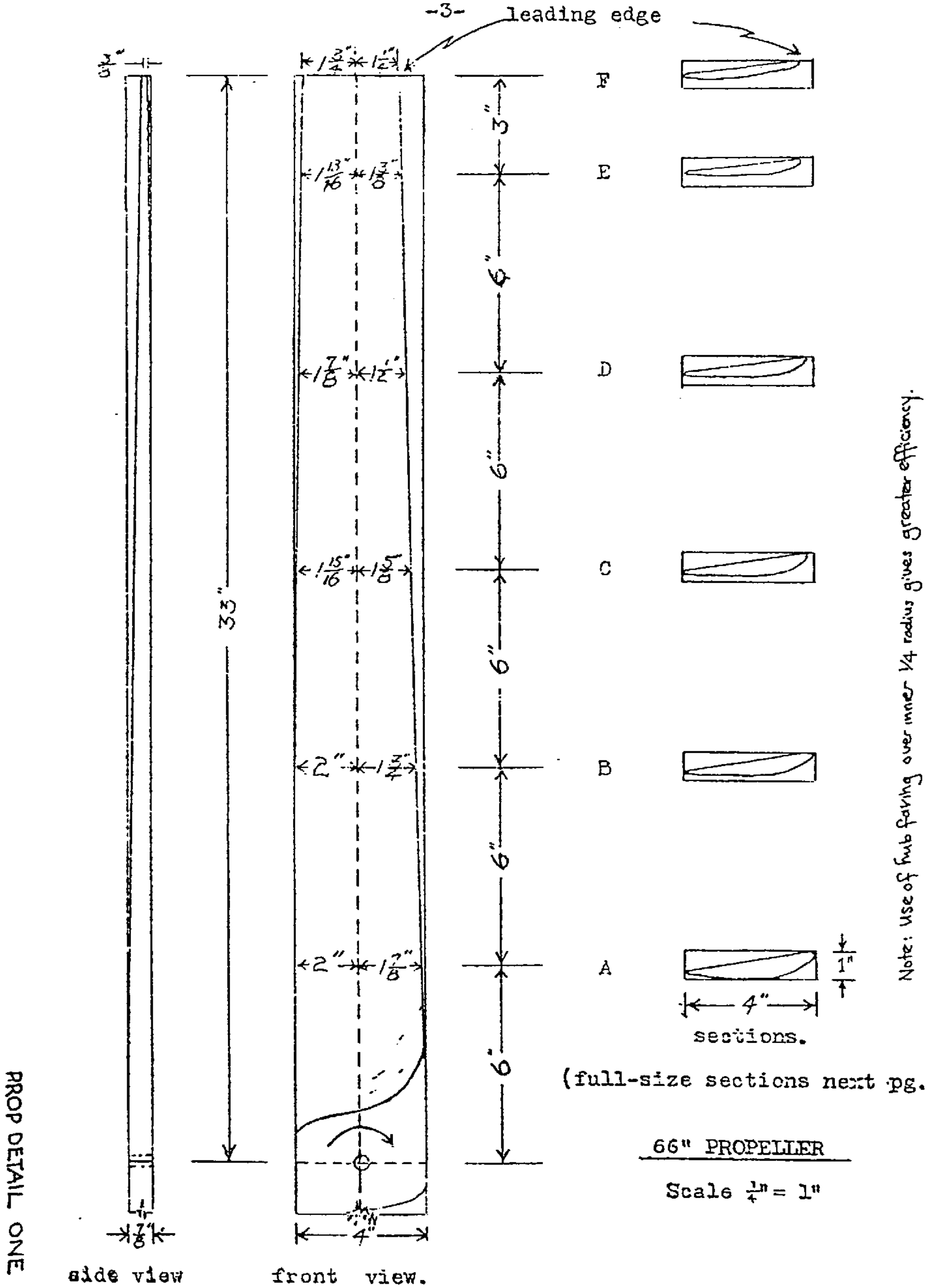
Sand well, varnish (several coats), and balance both horizontally and vertically. Balancing can easily be accomplished by adding small weights to the edge (vert. balance) and front (horiz. balance).

NOTE: This prop can be made 10 feet long by extending the distance between stations from 7" to 10", making the 3" x 4" sections both 5". All other dimensions, the same.



'X'
'Y'
'Z'
DIMENSIONS FOR CROSS SECTIONS AT EACH STATION
3/16"
3/4"
7/16"
9/64"
31/32"
21/64"
3/32"
1-3/16"
7/32"
3/64"
1-13/32"
7/64"
0"
1-5/8"
0"
4"
7"
7"
7"
7"
7"
4"
3"
TRAILING EDGE 3/32"
LEADING EDGE SHARP
A
B
C
D
E
DIRECTION
5-1/2"
3/4"

STEP 5



(full-size sections next pg.)

66" PROPELLER

Scale $\frac{1}{4}" = 1"$

FIG. 1.

Energy. Szczelkun USA 1973 Library of Congress book number 73-82211.

HOW TO SHAPE THE PROPELLER

WITH THE USE OF PATTERNS

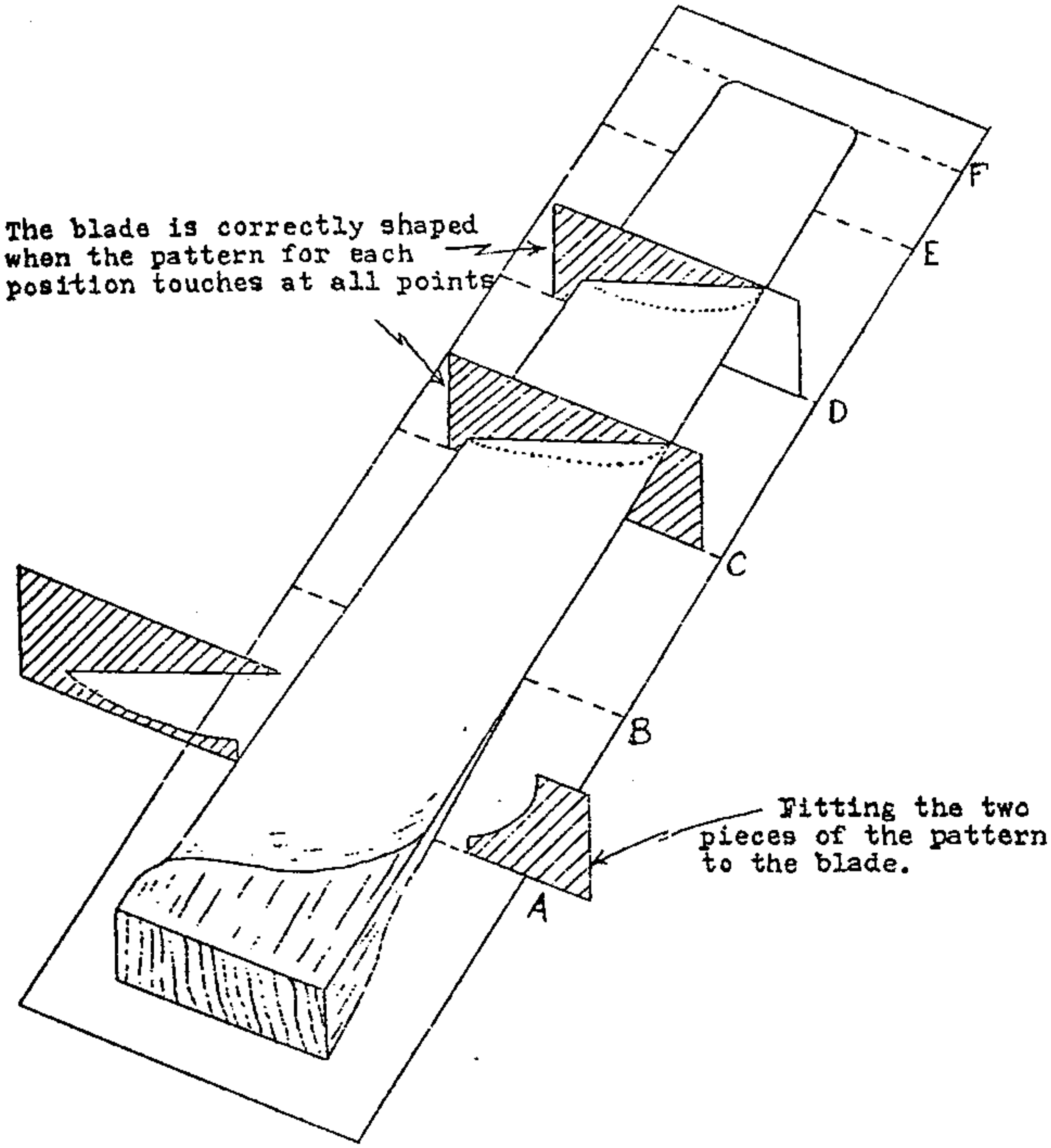


FIG. 2

Shape it with a spoke shave or a rasp or a surform.....Best wood? Redwood or straight-grained fir. Willow? Sitka spruce.

PROP DETAIL TWO

FULL SIZE PATTERNS FOR EACH POSITION 1:1

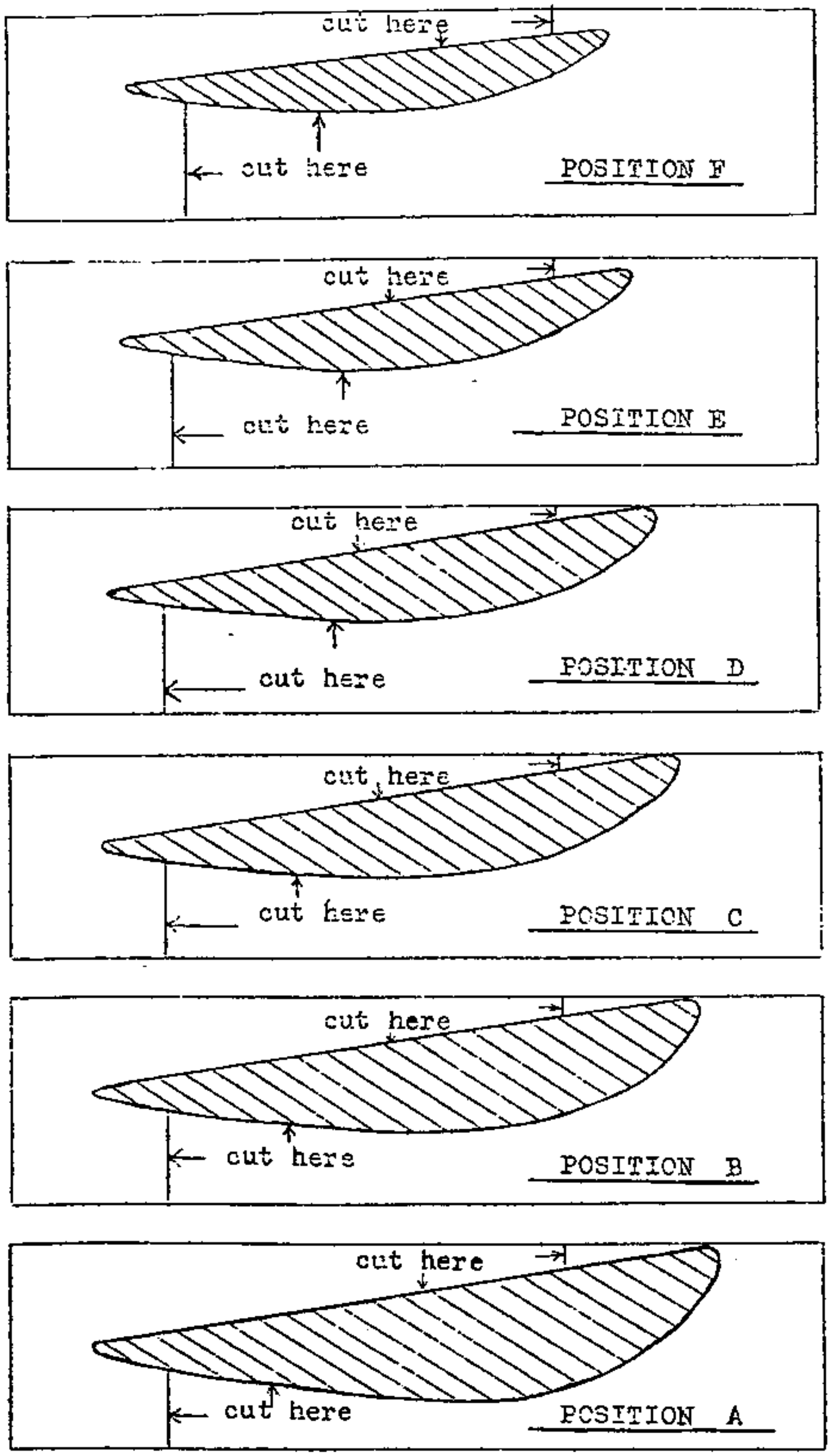
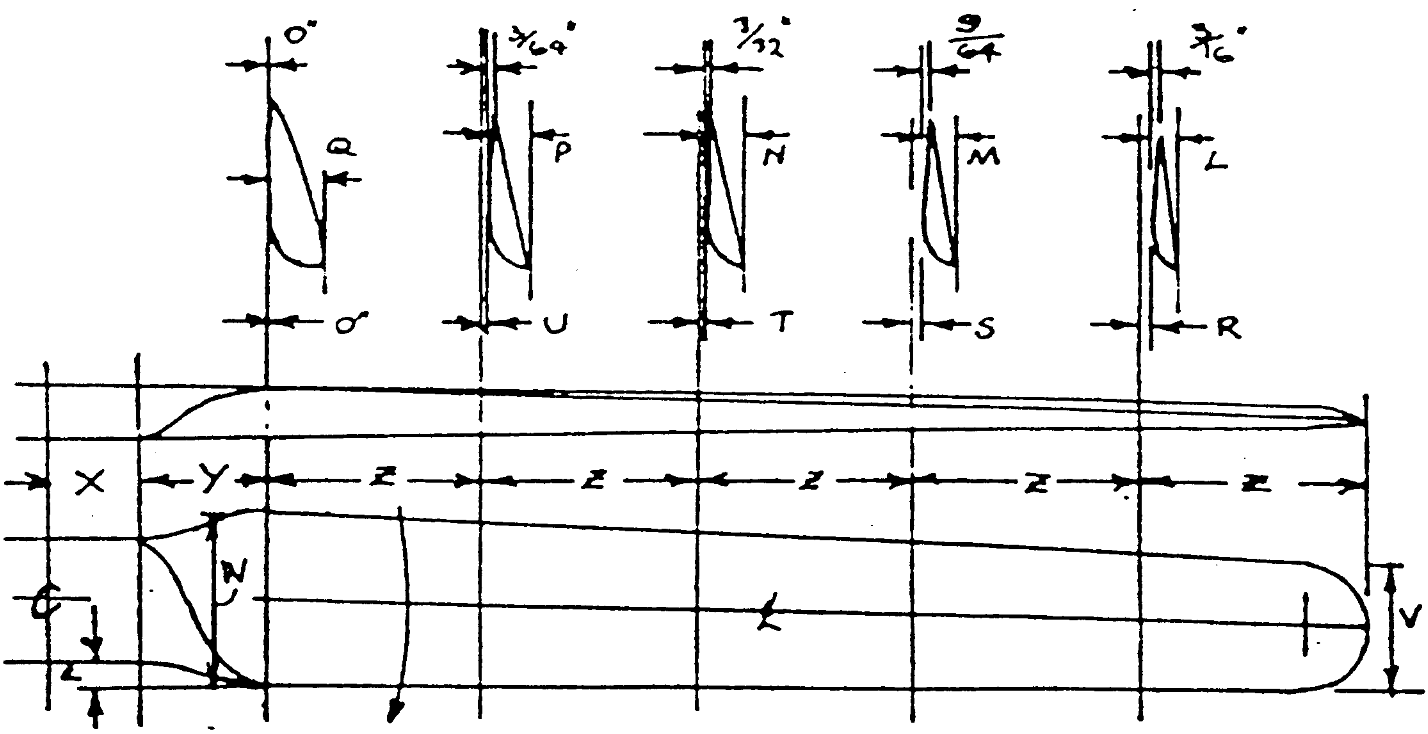


FIG. 3

PROP DETAIL 3.

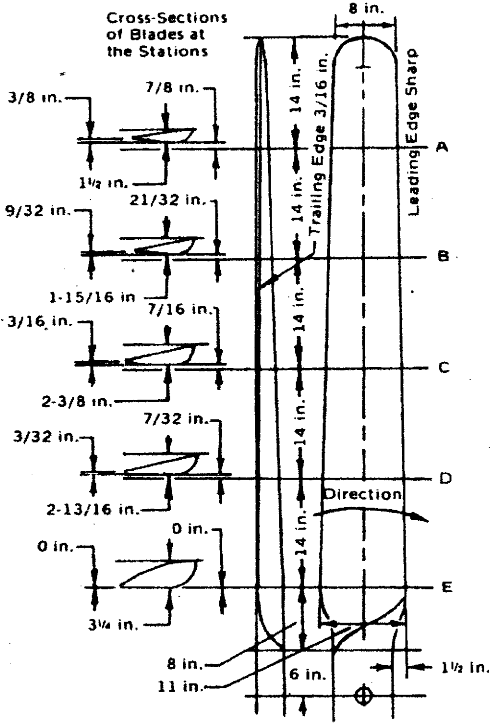
Blades are carved out of the plank by means of plane, saw, spokeshave and sand paper. The blades should be protected by sealing against moisture with about five coats of enamel or varnish, and rubbing with wet and dry emery paper between each coat. The tips also have to be protected by means of metal foil or a standard metal tip designed for aircraft propellers.

Leejay design wooden propeller blades for diameters from 6ft to 10ft.



	Z	Y	X	W	V	U	T	S	R	Q	P	N	M	L
6ft. dia. prop	6"	3½"	2½"	4½"	2¾"	1/16"	1/8"	3/16"	1/4"	3/4"	21/32"	9/16"	15/32"	3/8"
7ft. " "	7"	4"	3"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"
8ft. " "	8"	4"	4"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"
10ft. " "	10"	5"	5"	5½"	4"	7/64"	7/32"	21/64"	7/16"	1 5/8"	1 13/32"	1 3/16"	31/32"	3/4"

Radical Technology: G.Boyle, P.Harper. UK. 1976



Cross-Sections
of Blades at
the Stations
8 in.
3/8 in.
7/8 in.
1½ in.
9/32 in.
21/32 in.
1-15/16 in
3/16 in.
7/16 in.
2-3/8 in.
3/32 in.
7/32 in.
2-13/16 in.
0 in.
0 in.
3¼ in.
14 in.
14 in.
14 in.
14 in.
14 in.
Trailing Edge 3/16 in.
Leading Edge Sharp
A
B
C
D
E
Direction
8 in.
11 in.
6 in.
1½ in.

Fiberglassing a Prop

If a wood prop is basically sound and airworthy, it can be made stiffer, stronger and more resistant to erosion by sheathing the blades in fiberglass. It is NOT a means of salvaging a split, damaged or otherwise unsafe prop.

The resin used can be either polyester or epoxy, but it must be laminating resin, not casting resin. To get fresh resin and hardener, it is a good idea to go an aircraft supply house that sells a lot of it, such as Aircraft Spruce and Specialty Company in Fullerton, CA. Resin from a local marine or paint store may have been sitting on the shelf for a long time.

The glass cloth should be bidirectional and about .011 inch thick (about 8 oz. cloth). The selvage edge should be trimmed off.

Mask off the center of the prop and sand the prop down to bare wood. Do it by hand or with an oscillating sander. Don't use a belt or disc sander, as they will leave an uneven surface that will increase drag.

Mount the prop in a vise, with the jaws covered with wood blocks. Lay the cloth over the leading edge with the weave at a 45 degree angle and trim it to within about an inch. (Fig. 11-18) Set the cloth aside and brush a layer of resin on one blade. (Fig. 11-19) Give the resin a few minutes to set up and then lay the cloth over the leading edge. Smooth the cloth with the palms, working out all of the wrinkles and bubbles (Fig. 11-20).

Trim the cloth within about 1/4 inch all around the edge. (Fig. 11-21) Brush on a light layer of resin and work it into the cloth with the brush. Don't use a squeegee, as this will keep moving the cloth around. Brush on enough resin to fill the weave of the cloth. (Fig. 11-22) When the resin is no longer tacky, trim off the excess cloth with a razor blade (Fig. 11-23).

Let the resin cure overnight at room temperature. Don't attempt to speed the cure by using heat, as this can weaken the fiberglass. Grind or sand off any bumps or threads. Then brush on a layer of Featherfill (available at some auto stores or Aircraft Spruce). This will fill the weave of the cloth and is ready for sanding in about an hour or so. Sand it lightly, taking care not to sand into the glass cloth. (Fig. 11-24) Use another layer if necessary. Let the Featherfill cure overnight. Spray on a coat of automotive Hot Rod gray primer. This is necessary to allow the paint to adhere to the fiberglass. For a finish coat, use a urethane paint.

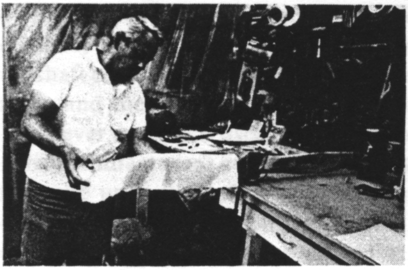


Fig. 11-18.

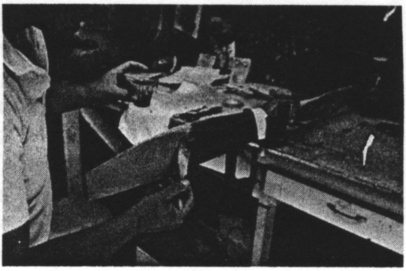


Fig. 11-19.

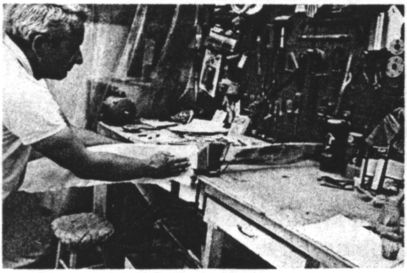


Fig. 11-20.

Fig. 11-21.

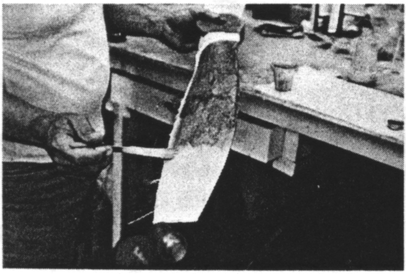


Fig. 11-22.

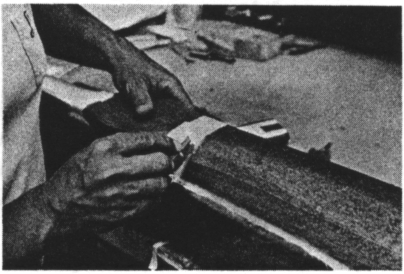


Fig. 11-23.

Fig. 11-24.

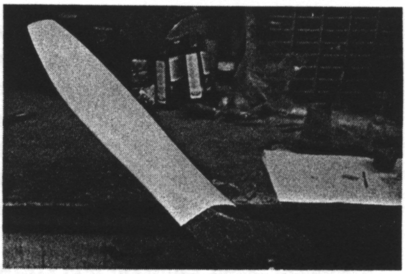
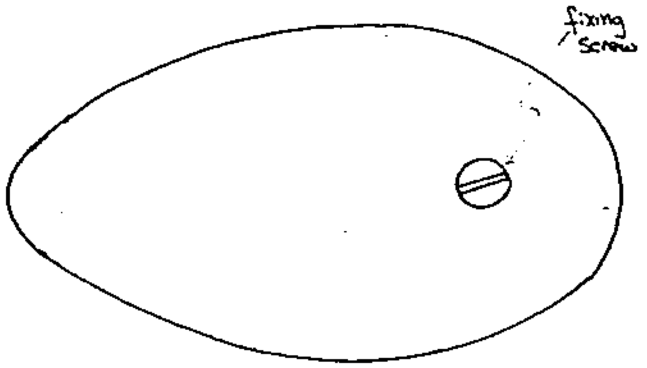


Fig. 11-25. The completed fiberglass covered prop, ready for use.

PROPELLOR FINISHING.

Choice of Wood: Close grain is best to give the prop. rigidity and stiffness. The wood used should be well seasoned and dried out for at least 2 weeks before using. This is important as the blades may lose their balance by uneven drying out.

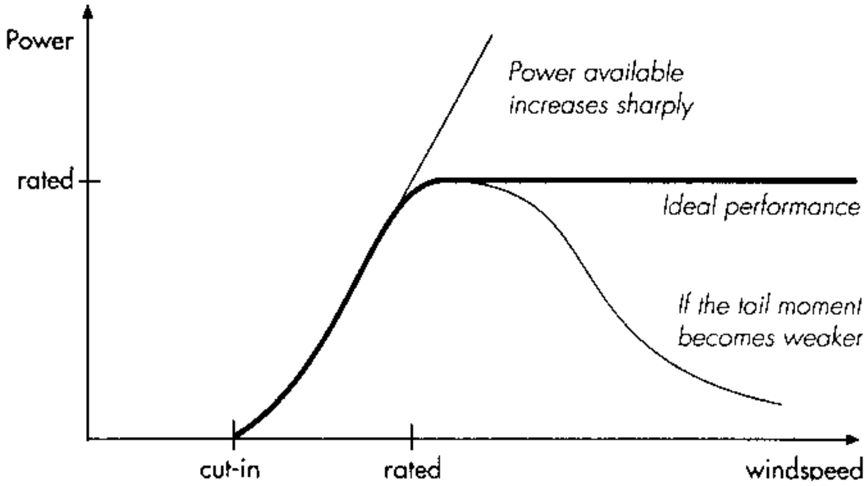
Balancing the Propellor. A unbalanced propellor will soon destroy itself. Method: Place the prop. on a free turning shaft indoors where there are no air currents. The prop. is rotated and allowed to come to rest. The heavier blade will determine the point of rest. A properly balanced prop will come to rest at varying points on repeated testing.



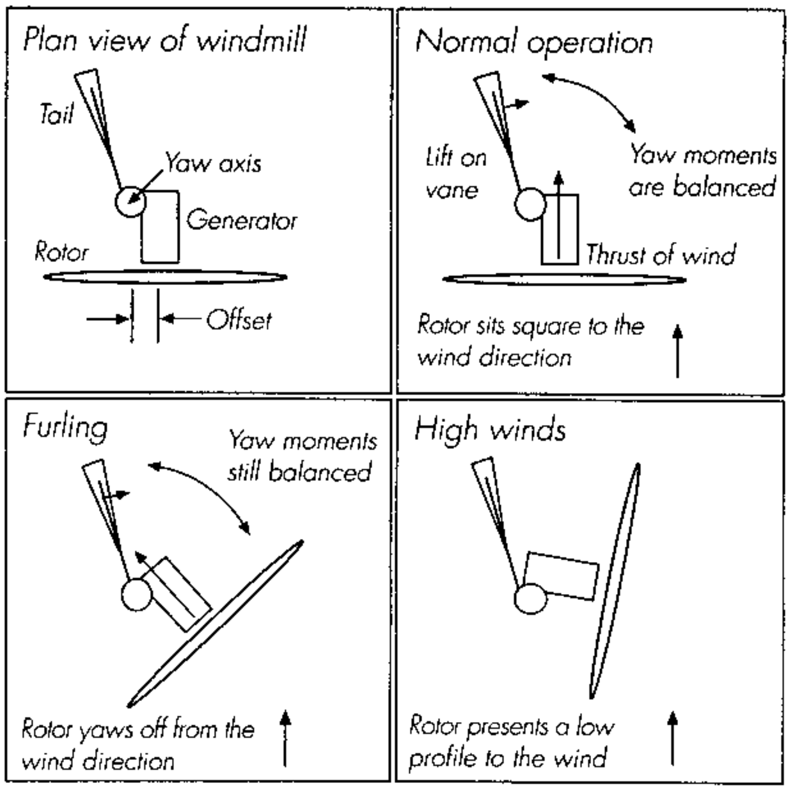
Choose a piece of sheet metal of a weight that would logically balance your propellor. Shape it elliptically and drill an 1/8" hole at the larger end. Now take a 1/2" wood screw and the balancer and hang them from a piece of light thread on the lightest end of the prop. move the weight along the blade until the prop. is fairly well balanced. Then screw the weight to the blade in that position. Fine adjustement is then made by rotating the shape about the fixing screw. Great care and patience should be taken to thorough balance any propellor. The balance should be rechecked at least once a year.

Note: Sealing against moisture must be well done. Five coats of enamel or varnish rubbing down well with wet and dry emery paper between coats is what is needed.

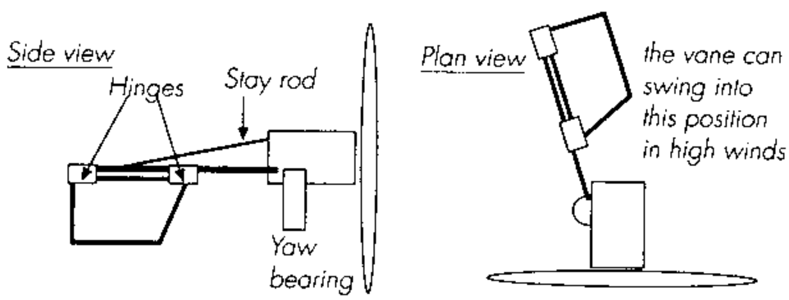
Graph of Power versus Windspeed



Yaw Governing System

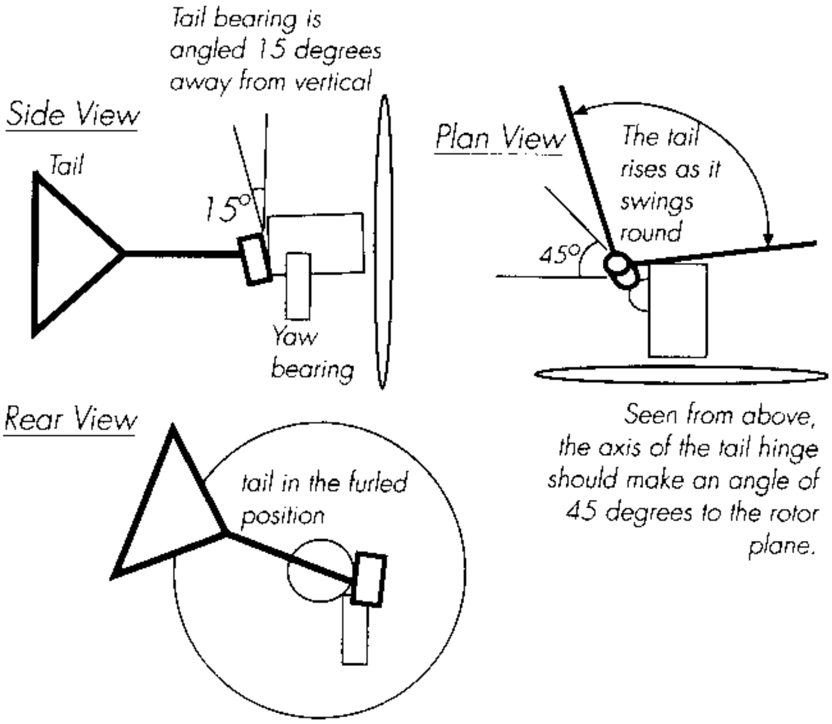


Hinged Vane System

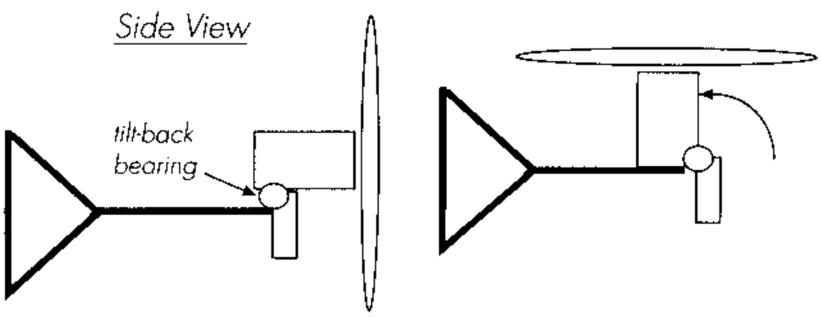


Windpower Workshop: H.Piggott. UK. 1997.

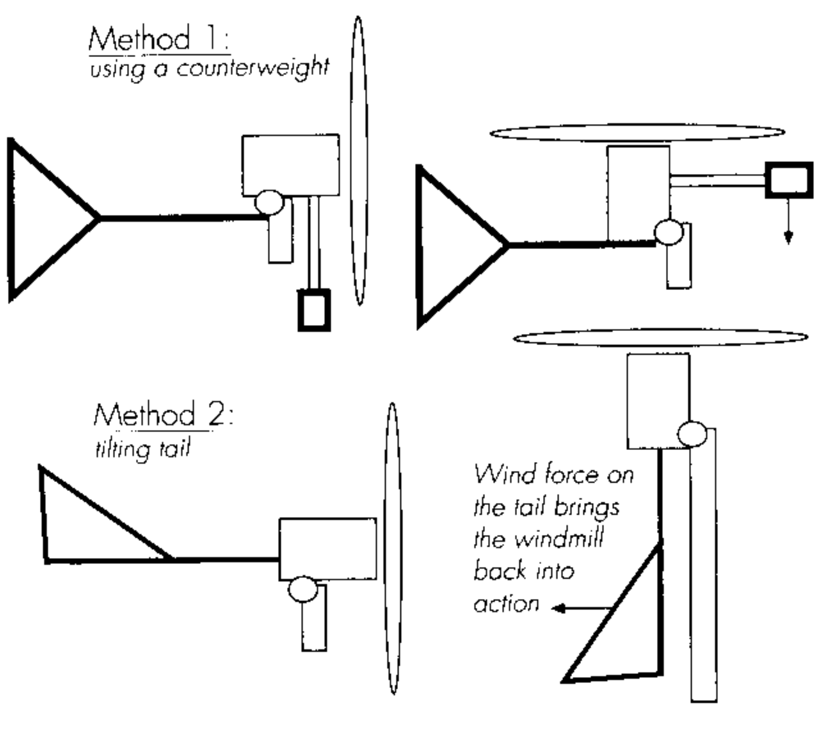
Gravity Operated Furling Tail



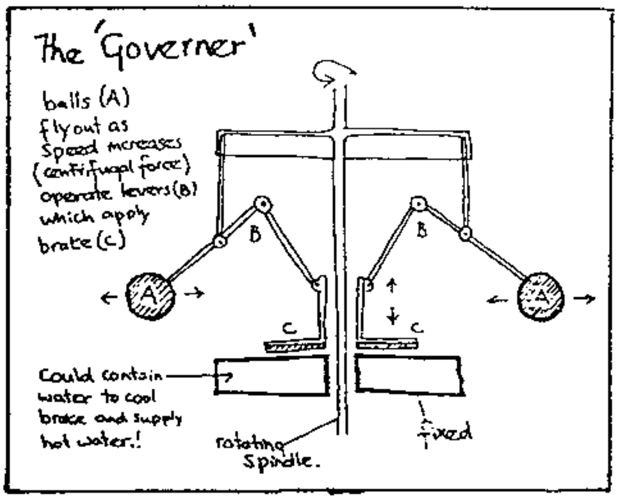
Tilt-Back Governing System

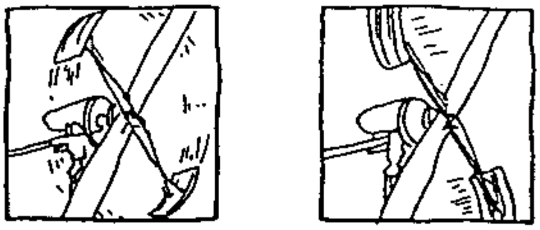


Tilt-Back Governors without Springs

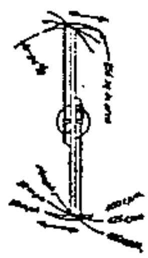


AUTO-CONTROLS for high wind gusts that might otherwise endanger the structure.





PATENTED AIR-BRAKE GOVENOR



Operates by centrifugal force. When wind velocity exceeds 23 miles per hour, govenor flaps automatically open and spread wind away from propeller (See illustration). Govenor also acts as a fly wheel to maintain even propeller speed and eliminate vibration in gusty wind.

(DYNA TECH. USA.)

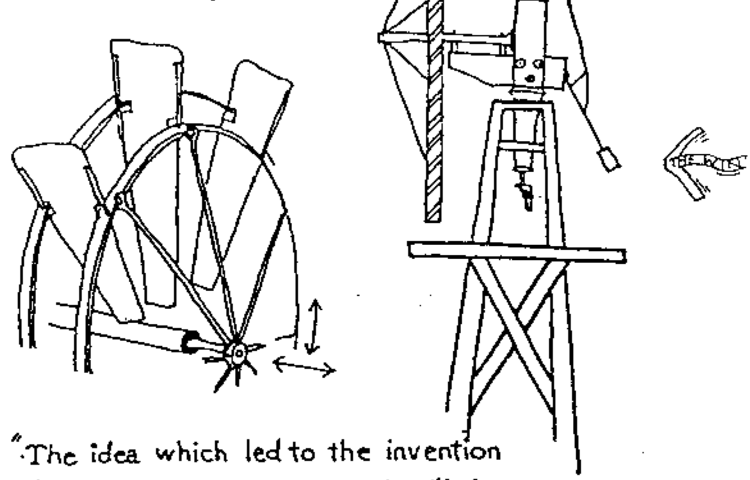
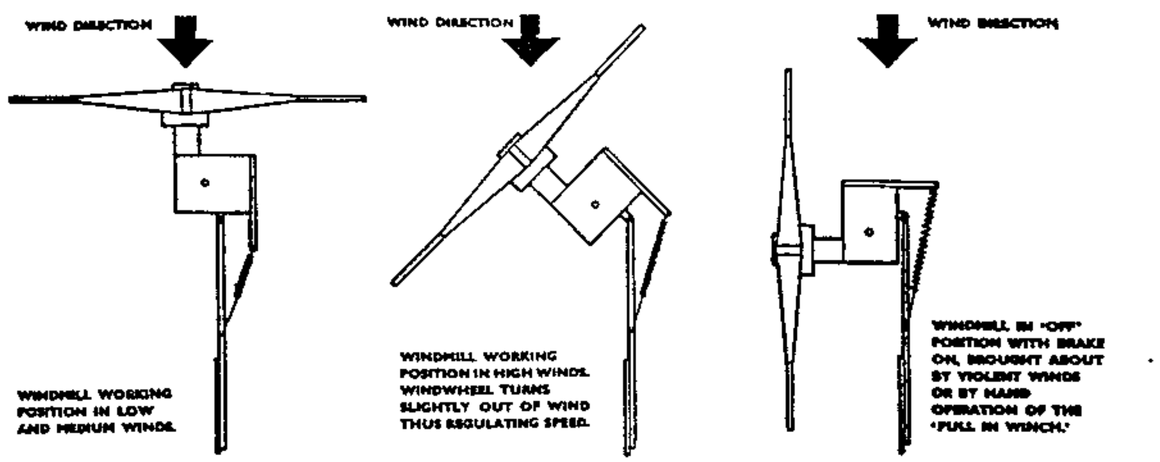


FIG. 65. A homemade Turbine windmill made by attaching rough board fans to the driving wheel and crank of an old reaping machine. The swivel is the thimble of an old wagon.

"The idea which led to the invention is this; in the ordinary steel mill the fan is struck by the full force of a sudden gust before its mechanism begins to turn it out of the wind and so to adjust it. In the meantime it sustains the shock of the full wind. This led Mr. Baldwin to devise a method whereby the regulating lever should be struck by the blast first, and so throw the fans as to escape the full fury of the wind. He has attained this end in a very clever way. In Fig. 65 may be seen a regulator or rudder-like lever, in front of the fans. The slightest motion of the lever is instantly conveyed to the fans, which are turned edgewise more or less, according to the velocity of the wind, thus adjusting it with nicety."

fm. *The Homemade Windmills of Nebraska*

AUTOMATIC GOVERNING DEVICE



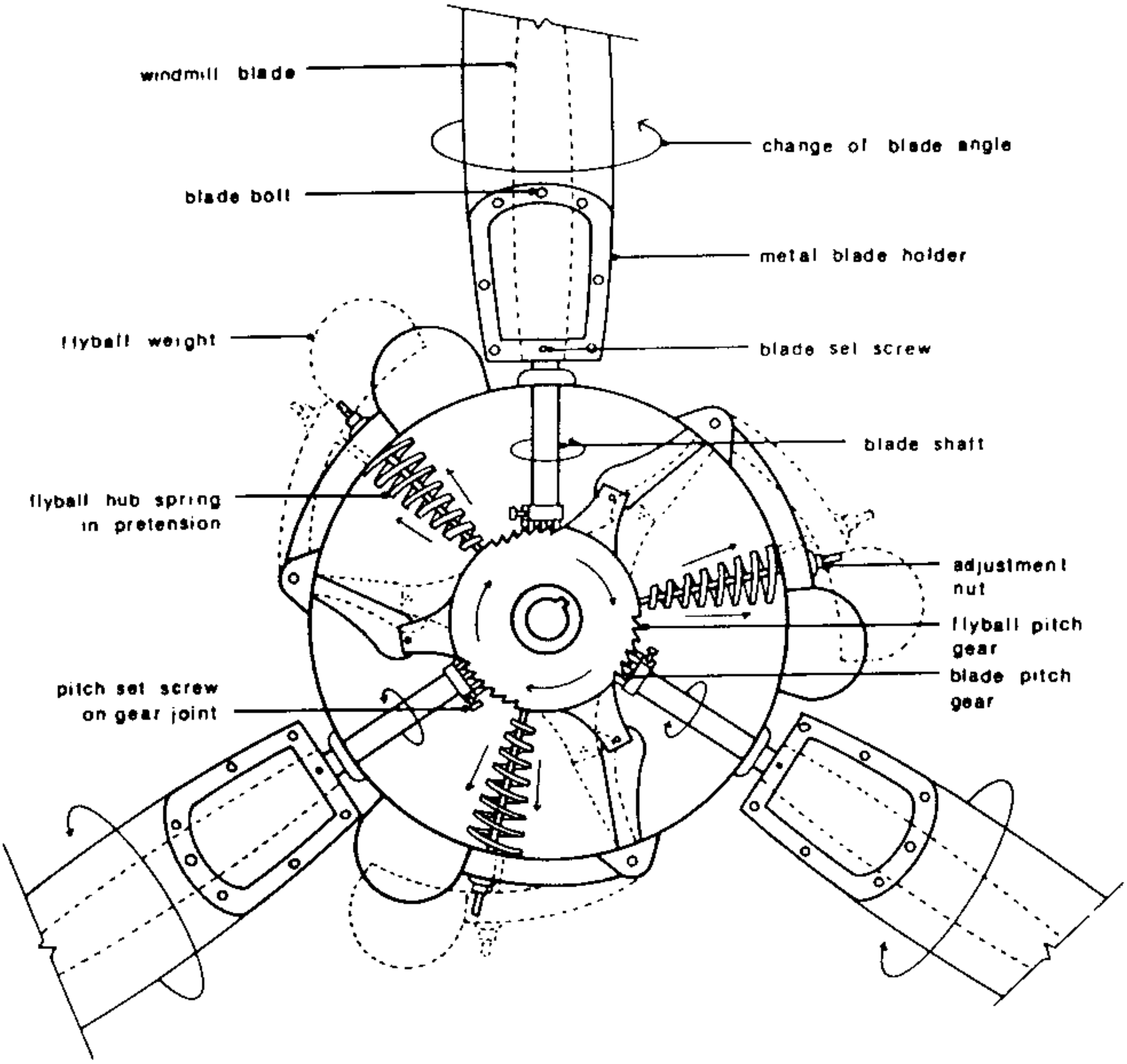
The Hercules windmill is designed to work in low windspeeds, as the windspeed increases the automatic governing device comes into action and operates as follows—

The windwheel, due to its position in relation to the centre of the head gear, is moved slightly at an angle from the direction of the wind by the pressure upon it, this action being assisted by the tail mechanism. As the wind pressure increases so the windwheel is moved further out of the wind, thereby keeping the speed of the windmill within reasonable limits.

During violent storms the windwheel is swung completely out of the wind, the tail assuming a position at right angles to the wheel shaft. As a result, the brake is applied by means of the brake rod and bell crank in the same manner as when the winch is used.

SELF GOVERNING

Wind Power: P.Gipe. Chelsea Green Pub. Vermont USA. 1993. ISBN 0 930031 64 4



Jacobs flyball governor. Centrifugal force throws the weights away from the governor, changing the pitch of the blades via a mechanical linkage.

Why use weights when you don't have to? The blade-actuated governor uses the weight of the blades themselves to change pitch (see Figure 6-23). Unlike the blades on the flyball governor, the blades not only turn on a shaft in the hub, they also slide along the shaft. Each blade is connected to the hub through a knuckle and springs. The knuckle in turn is attached to a triangular spider. As the rotor spins, the blades are thrown away from the hub, causing them to slide along the blade shaft. When they do, the blades pull on the spider, which rotates the blades toward feather. The springs

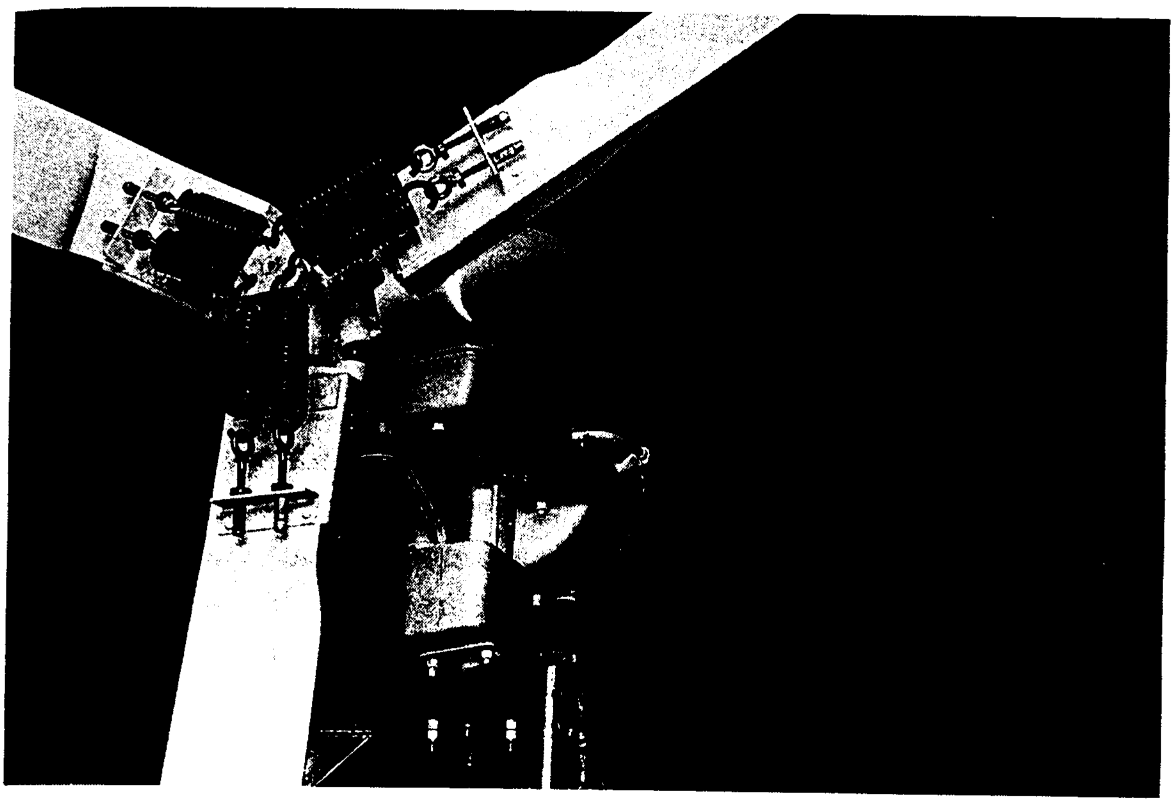
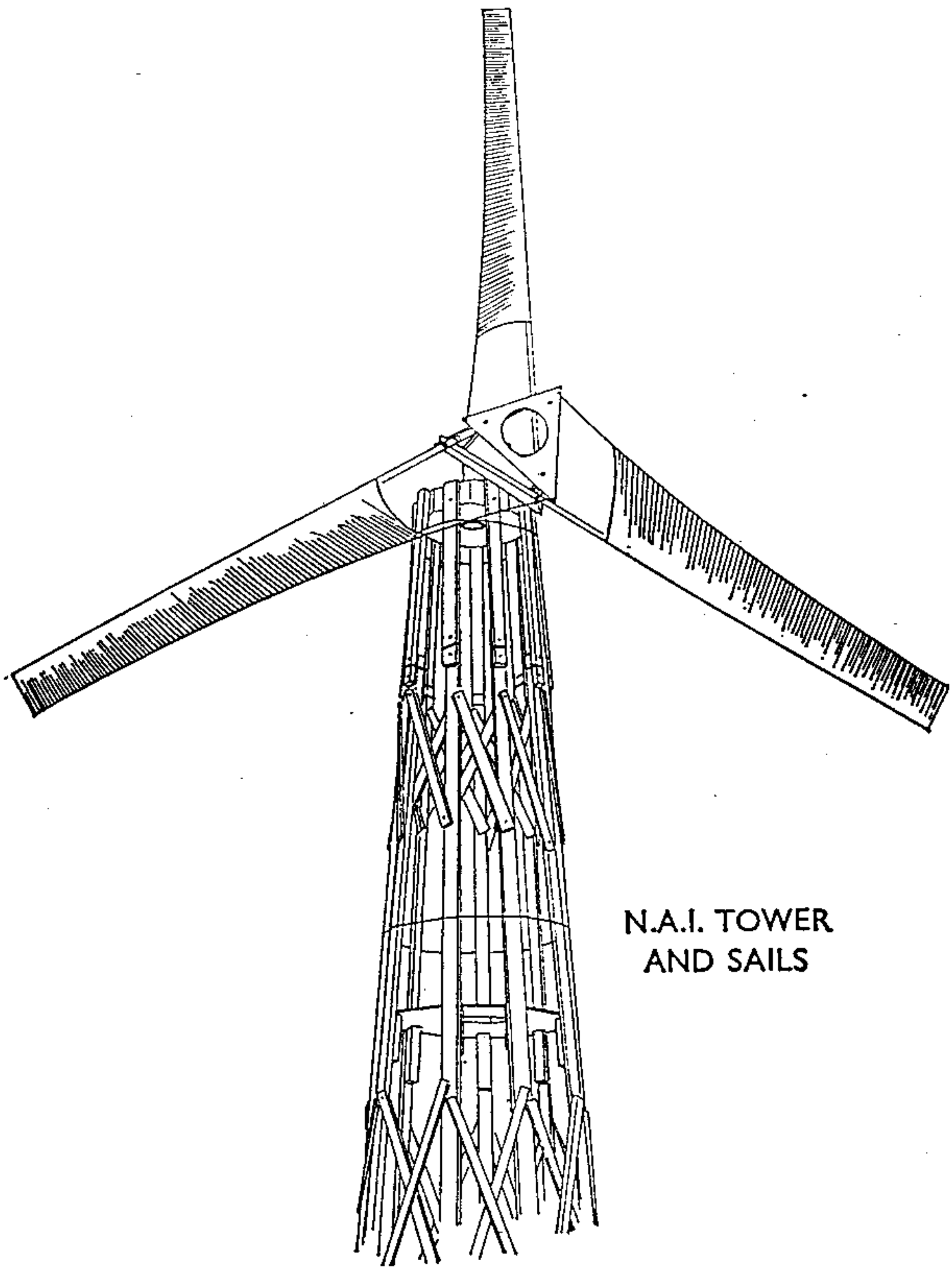


Figure 6-23. Blade-actuated governor. Many of the small wind turbines built during the 1970s used this design, patterned after later versions of the Jacobs windcharger. The force acting on the blades in high winds causes them to collectively change pitch.

govern the rotor speed at which this occurs. Like the flyball governor, the blade-actuated governor works reliably when properly adjusted and built to the highest material standards.



N.A.I. TOWER
AND SAILS

When building windmills, always
overestimate the strength of the wind and the forces involved. It pays to be safe.

This platform problem is so acute that there is a good case to be

Technological Self-Sufficiency: R.Clarke. UK. 1976. ISBN 0 571 11057 6

made for building a tower and not using a mast. The top platform then adds strength to the tower, and another half-way up as well will help even more. The best design I know is for a 26-foot high tower built by the New Alchemy Institute-East on Cape Cod and fully described in the *Journal of the New Alchemists*, No. 2. The basic structure is made from 8 lengths of 4 × 2 timber each 26 feet long (all timber must be treated with wood preservative). The 2 platforms are fixed to the tower by nailing down into short lengths of 4 × 2 bolted to the main uprights (with eye bolts, on the centre platform, to provide a fixing for the guy wires). The NAI wires run inside the tower but anchoring them outside would in my view provide a better hold. The tower is tapered to a shape given by making the top platform an octagon 28 inches across and the centre one a circle of 48 inches diameter. The main uprights are fixed at the bottom with large bolts to 8 bits of telegraph pole 6 feet long driven deep into the ground. The top half of the tower is braced with 16 40-inch lengths of 1 × 3, and the bottom half with 16 58-inch lengths.

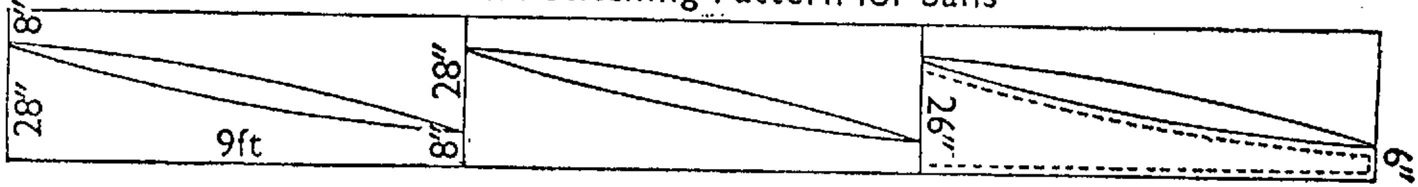
Such a tower (this one was designed for a 18-foot diameter sail machine) will give pretty good service. Bits of wood attached up the lee side will make a safe ladder, and some more pieces mounted all round about 3 feet from the top will give an easy toe-hold for working on the machine. If you want even more strength (and who doesn't?) the price of a third platform will be miniscule and help out of all proportion to its cost. By the time you've finished, such a tower is going to cost £100 or more, but a metal, commercially-available model to do the same job will add up to 3 or 4 times as much when you've finished paying for transport and import duty and all the other extras people can manage to think up. Build your own.

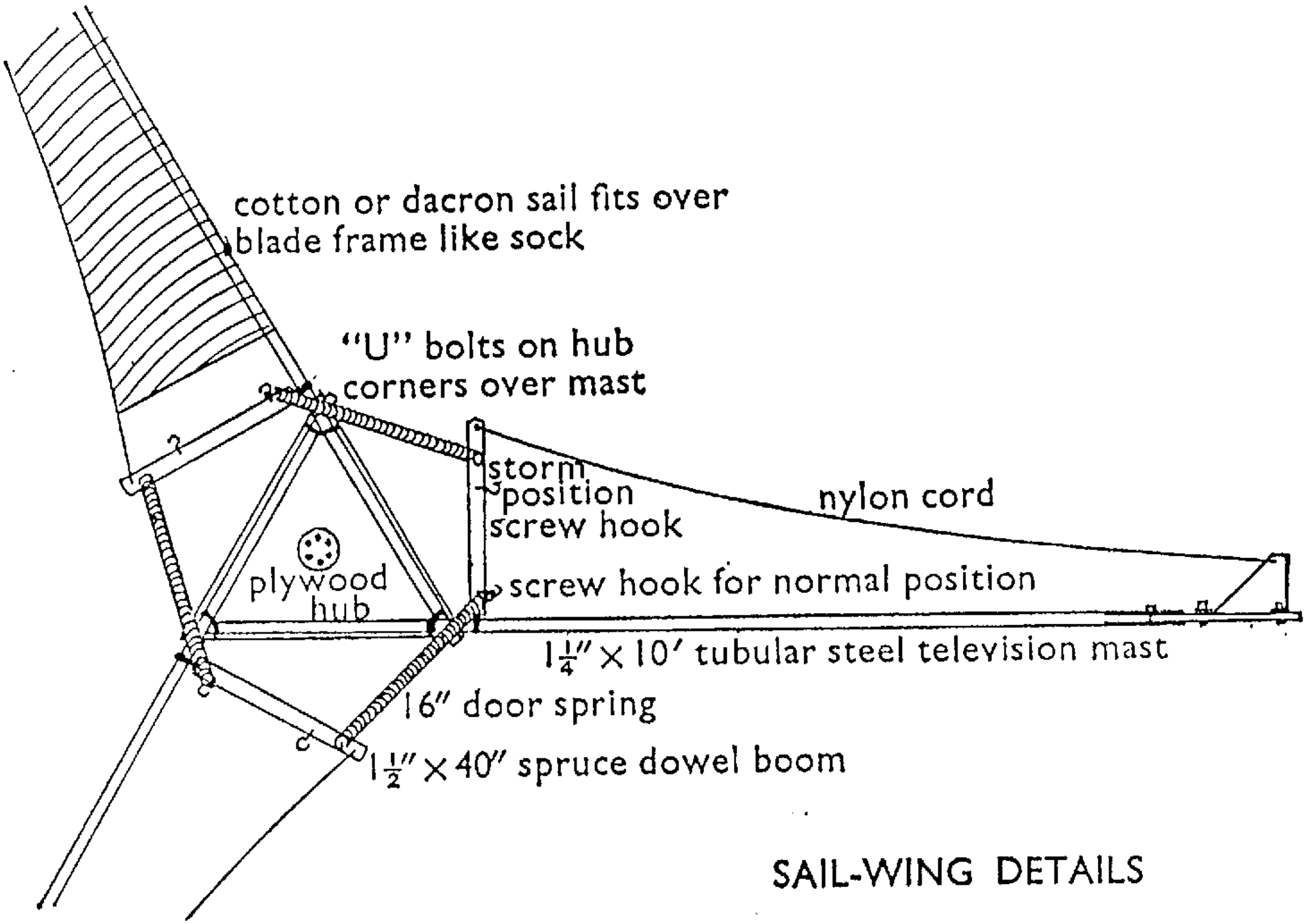
Sails and propellers

There are two nice things about windmill sails. First, they're easy to make, which means they're also easy to replace. Second, they'll never be as strong as the rest of your machine. That's an advantage because in a gale the sail is likely to get ripped up first, and once that's happened, of course, the wind machine will stop turning and no more harm can come to it. A rigid propeller, by contrast, can go on and on turning in a gale until the whole machine disintegrates.

The sailwing idea has been recently developed by a team of

Cutout and Stitching Pattern for Sails





SAIL-WING DETAILS

scientists at Princeton University who were struck by the efficiency of a glider wing, with its blunt, rounded leading edge. The New Alchemy Institute has adapted the idea to make an 18-foot diameter water-pumping mill which works pretty well, even in a very low wind speed. The Princeton idea led to a 25-foot diameter machine, designed to produce 7 kW in a 9 metre per second wind.

The leading edge of the NAI sail is a 1¼-inch diameter steel television mast, while the trailing edge is made from a taut wire or nylon cord. As a result, the shape of the sail changes with windspeed, to take up the most efficient aerodynamic shape. The sail itself, made from cotton or, better, dacron (as in boat sails), slips over the steel and nylon cord frame like a sock. The drawing on page 141 shows the essentials. The steel masts are fixed with U-bolts to a 1-inch thick triangle of plywood, which serves as the hub, each side of the triangle measuring 30 inches. The rest is apparent from the diagram. Note the door springs fitted to give an automatic governing device for high winds. These have two positions, one for use in storm conditions. The NAI design has, however, come through gale force winds in the normal spring position. I would recommend an additional governing device (see next section), so I think you could dispense with the storm position for the springs – not a very practical idea, in any case, for they involve climbing the tower in a high wind to make the adjustment.

This unit has been tried and tested, and if you get into problems write to Marcus Sherman, c/o New Alchemy Institute-East, Box 432, Cape Cod, Massachusetts, for advice. The NAI machine was for water pumping, so the hub was connected to a crank shaft used to power the pump. Our machine will be an aerogenerator, so we will use a different system (see below). But it's worth pointing out now the main disadvantage of sails for electricity generation. The rotor will revolve relatively slowly, and will be far too slow to turn a car alternator at the right speed. Even with propellers, you need to gear up by about 10 to 1. For a sail machine of this type, you will need to gear up 20 or even 25 to 1. But, even allowing for the frictions that introduces, you'll still make more efficient use of slight winds than would a propeller machine.

A SELF-SUPPORTING SWINGING TOWER FOR A 6 VOLT PLANT.

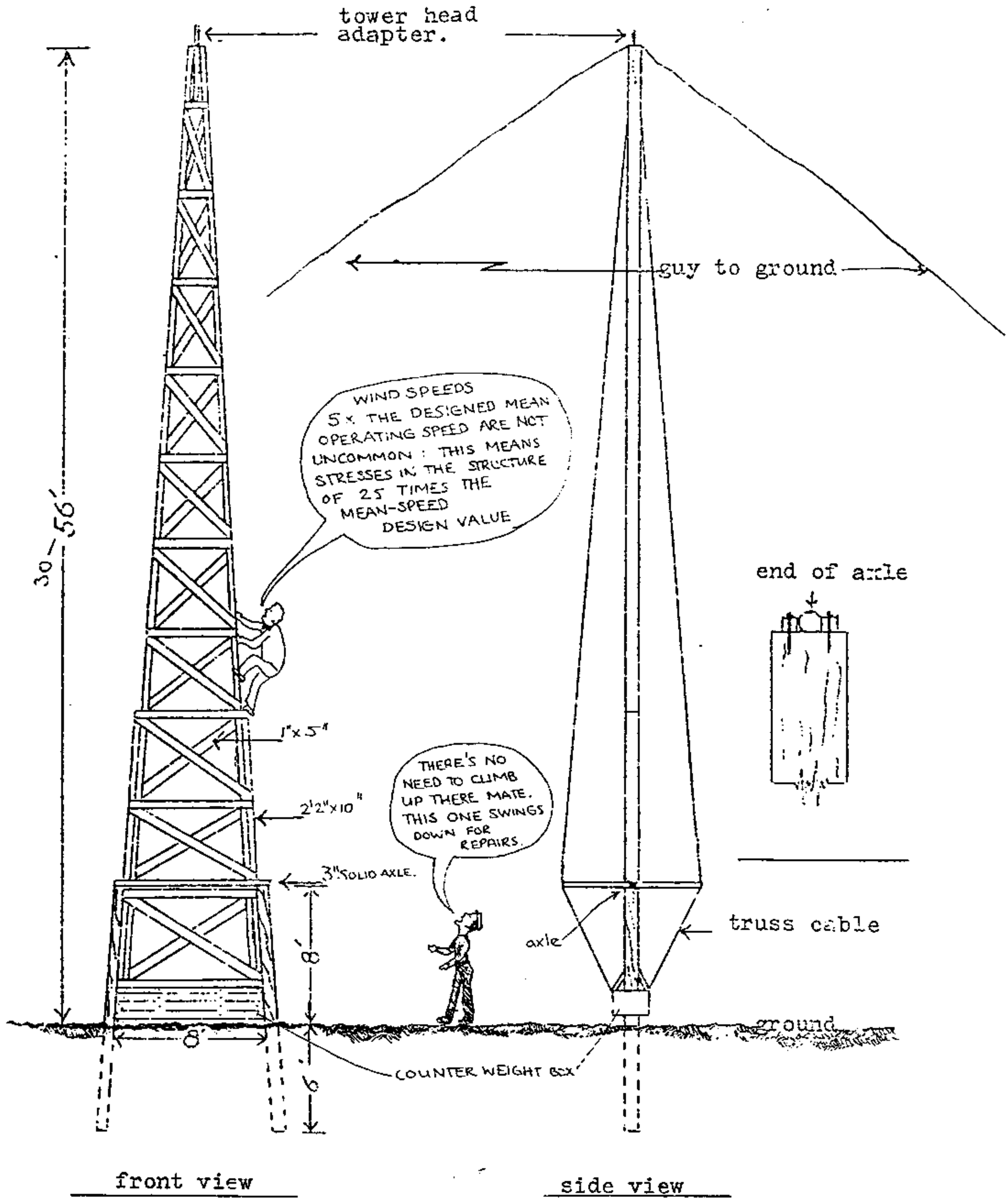


FIG. 5.

Scale: 1/8" = 1'

For Best results locate at least 20 feet above any obstruction within 400 feet. This is important. Farm buildings such as barns may be used to support windmills; but 6'-10' stub towers do not take the machine out of eddy currents. A 12' tower would be a minimum requirement. It should not be mounted on a house where the noise of the plant will be transmitted to the living quarters.

Energy: S.A.Szczelkun. UK/USA. 1973.

TOWER

Home Power [monthly magazine]: Box 130. Hornbrook California USA. May 1992.

Wind

Pole / Pipe Wind Turbine Tower

John Dailey

Having purchased a Windseeker II wind electric turbine, we faced the daunting prospect of erecting a tower. The tower has to be at least 15 feet above surrounding obstacles. In our case this worked out to be 50 feet above the ground. Here are plans for a tower that is inexpensive, easy to build, and can be raised and lowered by a single person.

Our Homestead

Our homestead is located on the north side of the Alaska Range where the gusty and powerful Chinook winds are common. Any tower we built had to be rugged enough to withstand these high winds.

The Tower and Tools and Safety

This tower will support small to medium sized wind turbines. The tower consists of a 20 foot guyed utility pole with a three inch sleeve pipe U-bolted to the top. A smaller diameter pipe, with the wind turbine mounted on top, is winched up through this sleeve. The tower "telescopes" from full operating height to the partially-lowered maintenance position.

You will need some common shop tools, including a good 1/2 inch drill, and a stout 24 foot extension ladder. Please wear a hard-hat and keep your wits about you while you work on the tower. Keep curious kids and loyal pets away. Always have an escape route planned, just as if you were felling trees; the forces and dangers are similar.

Utility Pole Installation

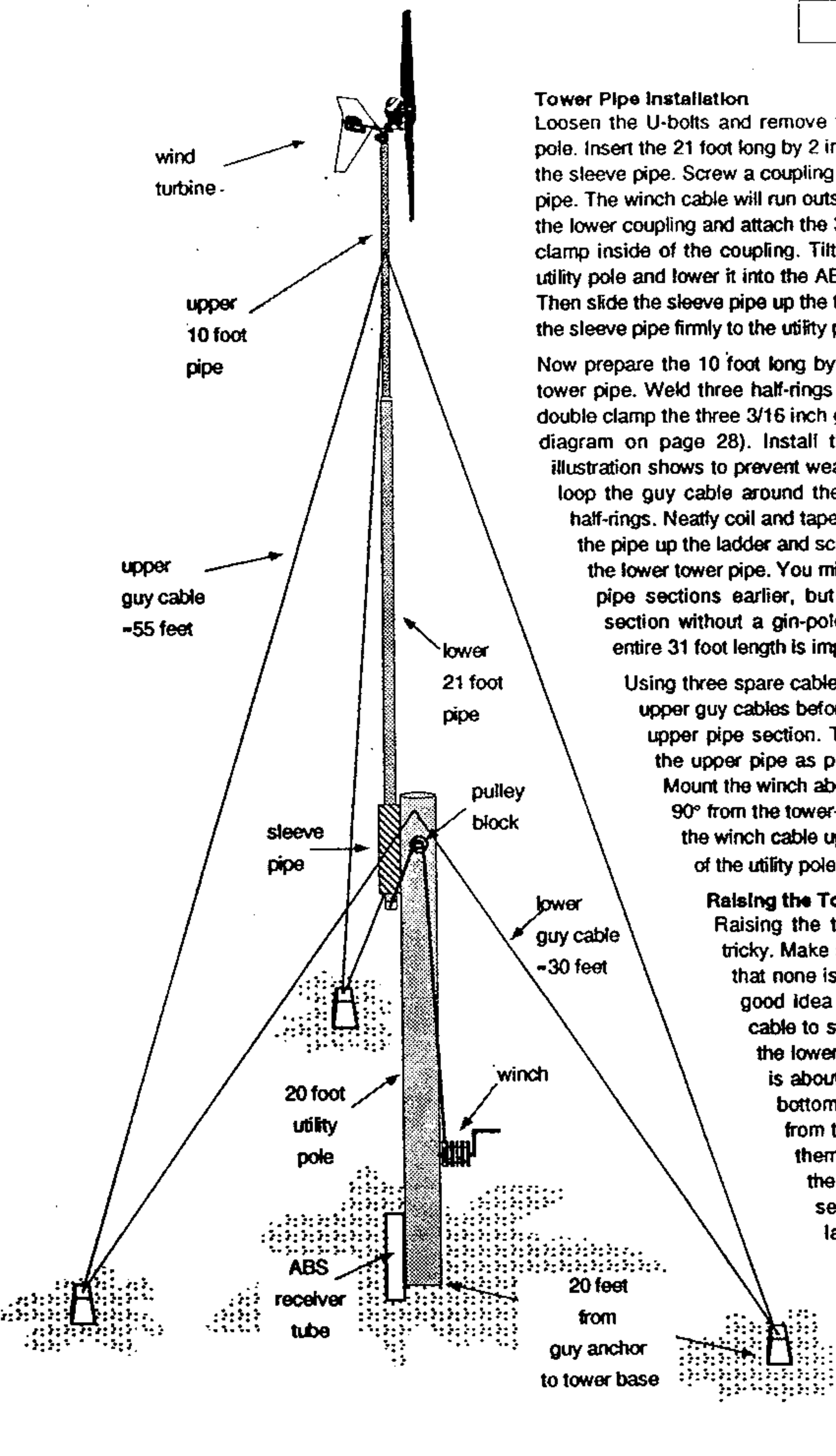
First, stake out the position of your tower and its three guy anchors. The anchors must be carefully placed at 120° intervals. The anchor locations must be at least 20 horizontal feet from the tower's base. If your site is not level, then make sure to place the guy anchor's ground position farther from the tower's base (if downhill) or closer (if uphill) to keep the guy wire at the same angle to the tower.

In our case, earth augers are used to secure the guy wires to the ground. These earth augers have been used for decades by the phone companies to guy their poles. Screw the three augers securing the guys to the ground first, before you locate the utility pole. This allows for change in case you hit a big rock with one or more of the earth augers. Make sure you screw all the augers in deeply and securely. You don't want them pulling out; the success or failure of a tower is a digital event! If your soil is loose, or hardened bedrock, then earth augers are not appropriate and you must use concrete pads for the guy anchors. Be sure to use enough concrete, each pad will take at least 1/4 of a cubic yard of concrete.

Excavate 16 inches deep for a concrete pad to support the utility pole. Don't skip the pad unless you have very firm substrata; vibration from the wind turbine will eventually break down even hard-packed soil. If the tower's base sinks, then the guy wires will become slack and ineffective.

Dig a deeper hole next to the utility pole's base to set in a three foot section of three inch diameter ABS pipe. This ABS pipe will socket the tower's metal pipe when it lowered. Locate the ABS pipe next to the utility pole and radially midway between two of the guys. Bury the ABS pipe so its top is a few inches above grade. Pour a concrete pad at least 4 inches thick and throw in plenty of steel rebar. The downward force is considerable when the wind is blowing hard.

Lay the utility pole out with its bottom near the concrete pad holding the ABS pipe. Drill holes and temporarily U-bolt the 3 foot long by 2 1/2 inch diameter sleeve pipe to the top of the utility pole. Mount the pulley block next to the sleeve and about two feet from the top of the utility pole. The pulley block should be bolted through the utility pole. Use heavy bolts and washers, don't use lag screws. Install the special eye-bolts, used to attach the guy wires to the utility pole, about four inches from the top of the utility pole. Tilt the pole up, and rotate it so that the sleeve pipe is directly above the ABS receiving tube. Tamp dirt around the utility pole's base to hold the pole approximately vertical. Clamp the 3/8 inch guy cables into the anchors and tighten the nuts on the angle eye-bolts to tension the guy cables and plumb the pole.



Tower Pipe Installation

Loosen the U-bolts and remove the sleeve pipe from the utility pole. Insert the 21 foot long by 2 inch diameter lower tower pipe in the sleeve pipe. Screw a coupling on each end of the lower tower pipe. The winch cable will run outside the tower pipe. Drill through the lower coupling and attach the 30 foot winch cable with a cable clamp inside of the coupling. Tilt the tower pipe up against the utility pole and lower it into the ABS receiving tube in the ground. Then slide the sleeve pipe up the tower pipe to the U-bolts. Clamp the sleeve pipe firmly to the utility pole with the U-bolts.

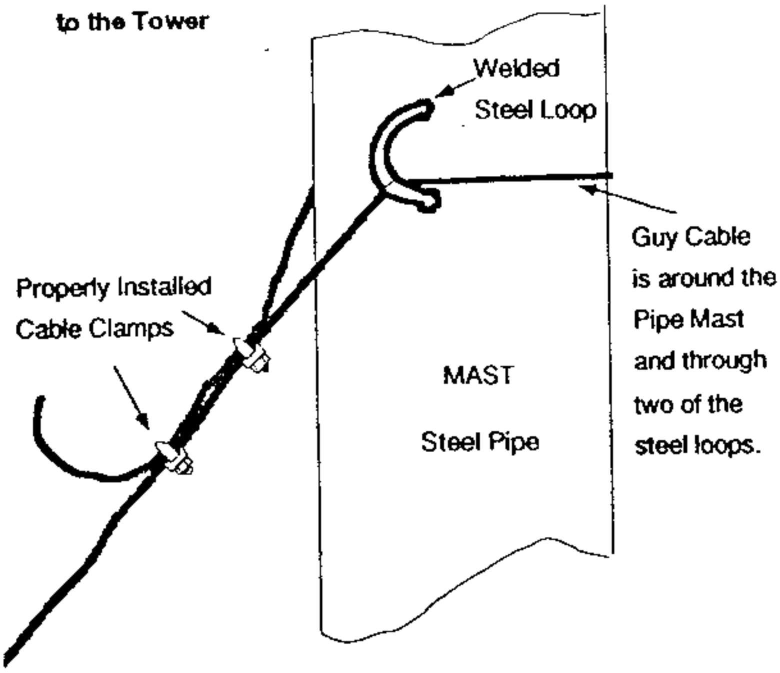
Now prepare the 10 foot long by 2 inch diameter top section of tower pipe. Weld three half-rings 5 feet from the pipe's top, and double clamp the three 3/16 inch guy-cables to the half rings (see diagram on page 28). Install the cable clamps only as the illustration shows to prevent weakening the cable. Make sure to loop the guy cable around the pipe, and through two of the half-rings. Neatly coil and tape the guy wires to the pipe. Take the pipe up the ladder and screw it into the coupling on top of the lower tower pipe. You might think it easier to join the two pipe sections earlier, but tilting up the shorter 21 foot section without a gin-pole is difficult enough; lifting the entire 31 foot length is impossible.

Using three spare cable clamps, temporarily tighten the upper guy cables before leaning the ladder against the upper pipe section. Then install the wind turbine on the upper pipe as per its manufacturer's directions. Mount the winch about chest-high on the utility pole, 90° from the tower-pipe/receiving tube axis. Thread the winch cable up through the pulley block on top of the utility pole, and down to the winch.

Raising the Tower

Raising the tower for the first time can be tricky. Make sure that there is NO WIND and that none is even remotely expected. It is a good idea to have a helper on each guy cable to steady things as they rise. Winch the lower pipe up until the lower coupling is about 2 inches from the sleeve pipe's bottom. Then gently remove the slack from the guy cables and double clamp them. Now raise the tower pipe all the way up until the bottom coupling seats against the sleeve pipe. This last raise should tension the cables fairly tightly. You may have to readjust the cables so that the tower pipe is exactly vertical. Don't over tighten the guys; a few

Attaching the Guy Wires to the Tower



Above: the correct method of attaching the clamps to the guy cables. Note that the U-bolt side of the clamp is placed over the unused, free end of the guy cable.

Parts List for the Hybrid Pole/Pipe Tower

Quan.	*Item*
2+	sacks of ready-mix concrete
1	rebar 5/8 inch by 8 feet
1	treated utility pole, 20 feet long
3	earth augers (guy wire anchors), 4 feet long
1	roll aluminum utility pole guy cable, 3/8 in. by 100 feet
6	cable clamps for 3/8 inch guy cables
3	galvanized angle eye bolts
1	schedule 40 galvanized steel pipe, 2 inch by 21 feet
1	schedule 40 galvanized steel pipe, 2 inch by 10 feet
1	schedule 40 galvanized steel pipe, 2.5 inch by 3 feet
2	galvanized couplings for 2 inch pipe
1	ABS sewer pipe, 3 inch by 3 foot
1	roll 3/16 inch galvanized aircraft cable, 250 feet long
16	cable clamps for 3/16 inch cable
1	small boat winch with mounting lag screws
1	pulley block and bolt, 1,000 pound test
2	custom U-bolts, washers and nuts for 2.5 inch pipe

inches of lateral tower movement under high wind is OK. The three earth augers securing the guy wires to the ground provide a modicum of grounding. But these augers are no substitute for a good grounding system using copper wire and several ground rods.

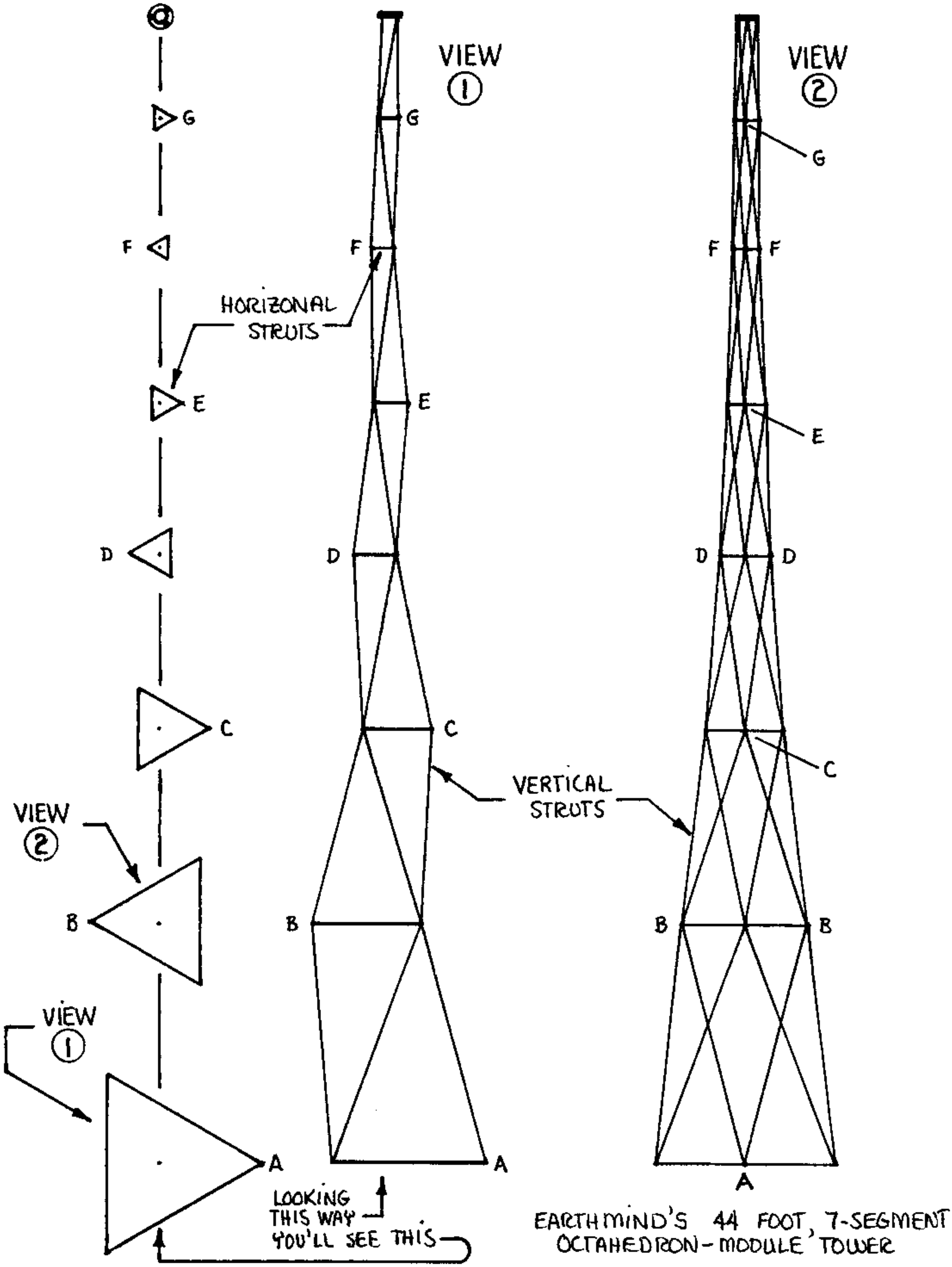
Finally, drill a hole through the utility pole underneath the bottom of the tower pipe coupling and insert a large bolt. Slacken the winch cable and rest the pipe sections of the tower on this bolt. Keep a small amount of strain on the winch cable, just in case this bolt fails.

Operational Considerations

When the wind turbine is in its lowered position, use a few spare clamps to temporarily guy the pipe before you lean the ladder on the top ten foot section. Make sure to winch the tower pipe up and down only during NO WIND conditions. If the sleeve pipe fits tightly enough, then helpers aren't need to raise and lower the installed tower. As the tower reaches full extension, the already adjusted guy cables tighten up and plumb the tower exactly vertical. To safely climb a ladder which leans only on a 2 inch pipe, we bolted a piece of 2 x 4 lumber to the top rung of the ladder. This 2 x 4 has a notch cut in it which fits the pipe.

Access

Author: John Dailey, HC 1, Box 3102A, Healy, AK 99743



EARTHMIND'S 44 FOOT, 7-SEGMENT OCTAHEDRON-MODULE TOWER

	QTY OF STRUTS	LENGTH OF STRUTS	TOTAL FEET	SOURCE OF MATERIALS: # OF 10 FT. SECTIONS	SOURCE OF MATERIALS: SCRAPS	LEFTOVER SCRAPS: QTY	LEFTOVER SCRAPS: LENGTH	CODE
VERTICAL STRUTS	6	10′	60′	6	–	–	–	–
	6	8′	48′	6	–	6	2′	(A)
	6	7′	42′	6	–	6	3′	(B)
	6	6′	36′	6	–	6	4′	(C)
	6	6′	36′	6	–	6	4′	(D)
	6	5′	30′	3	–	–	–	–
	6	4′	24′	–	(C)	–	–	–
SUBTOTAL 1		–	276′	33	–	–	–	–
HORIZONAL STRUTS	3	7′	21′	3	–	3	3′	(E)
	3	5′	15′	2	–	1	5′	(F)
	3	3′	9′	–	1/2 (B)	–	–	–
	3	2′	6′	–	1/2 (A)	–	–	–
	3	1.5′	4.5′	–	(F)	1	6 INCHES	(G)
	3	1	3′	–	1/4 (A)	–	–	–
	3	1	3′	–	1/4 (A)	–	–	–
SUBTOTAL 2		–	61.5′	5	–	–	–	–
SUPPORT STRUTS	6	4′ (V)	24′	–	(D)	–	–	–
	3	3′	9′	–	1/2 (B)	–	–	–
SUBTOTAL 3		–	33′	0	–	–	–	–
TOTAL 1,2,3			370.5′	38	–	–	–	–

Home-built Wind Generated Electricity Handbook: M.Hackleman. USA. 1975.

5 KOMPLETTERANDE KONSTRUKTIONER

5.1 Hjälpmast. För att kunna resa och fälla masten har en permanent hjälpmast monterats i roten av huvudmasten. Hjälpmasten är en A-bock med ett linhjul i toppen. Den är nedtill ledat infäst i huvudmasten och upptar den resande kraften via stållinor. Två av huvudmastens hörnstolpar anknyter till fundamentet via ett gångjärn. Hjälpmastens funktion framgår av fig. 8.

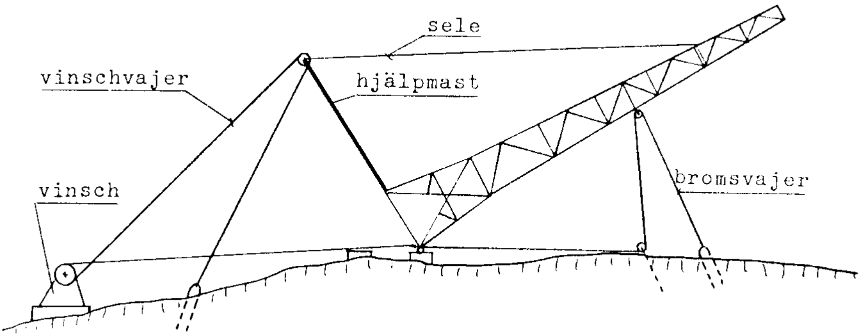


Fig. 8 Hjälpmastens funktion.

Hjälpmastens geometri framgår av fig. 9.

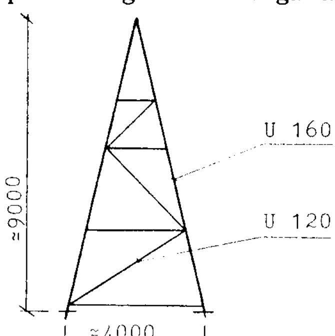
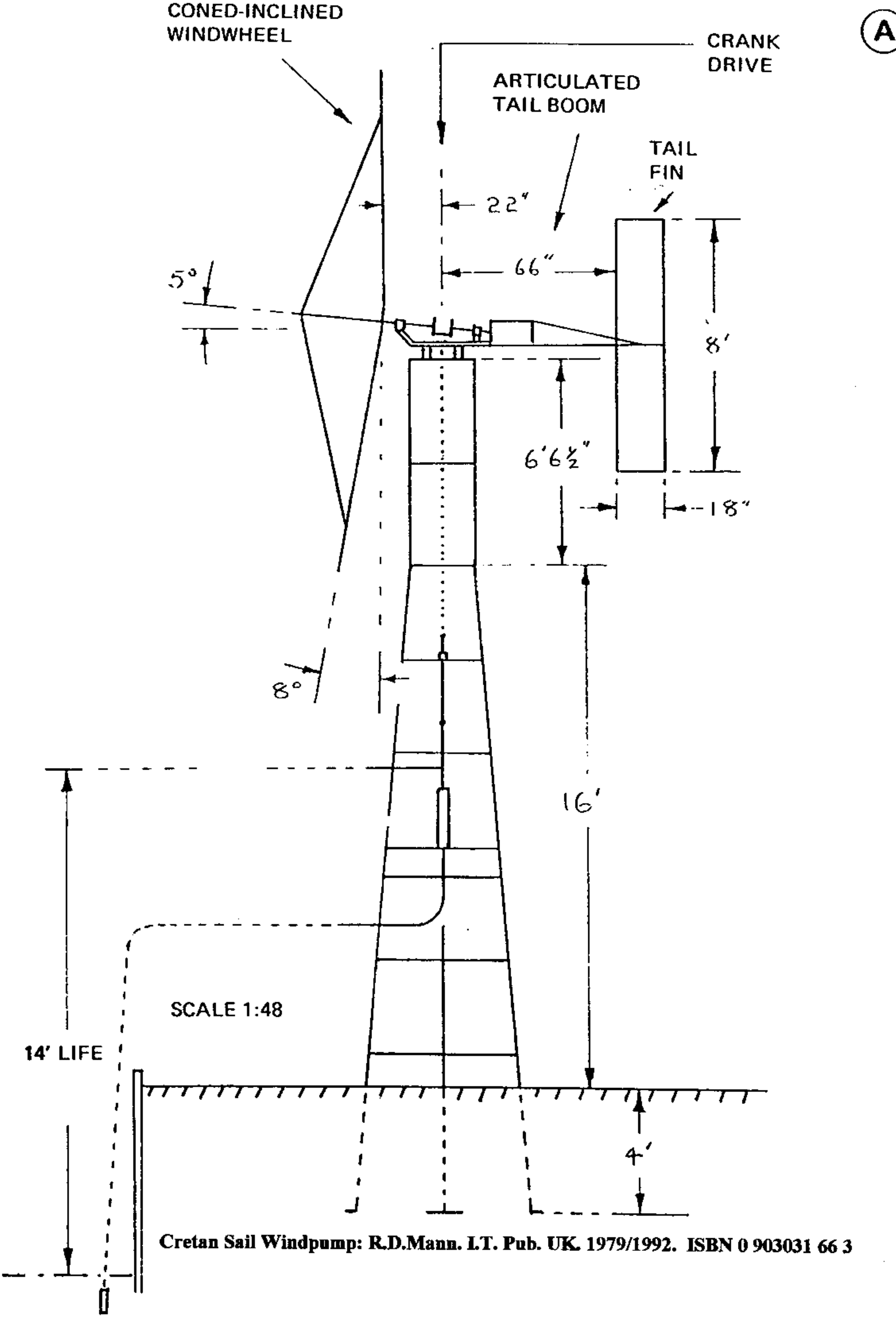
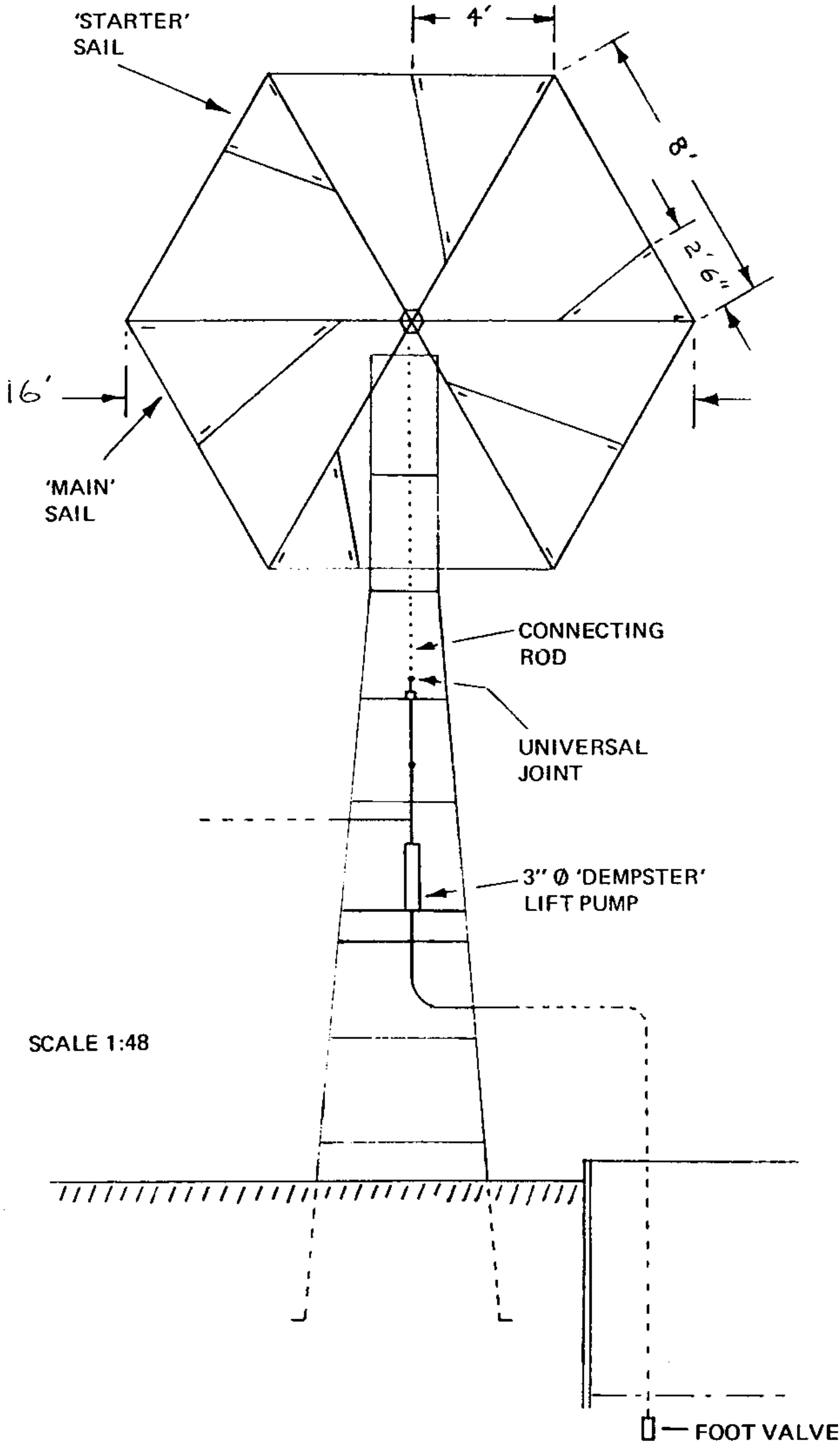


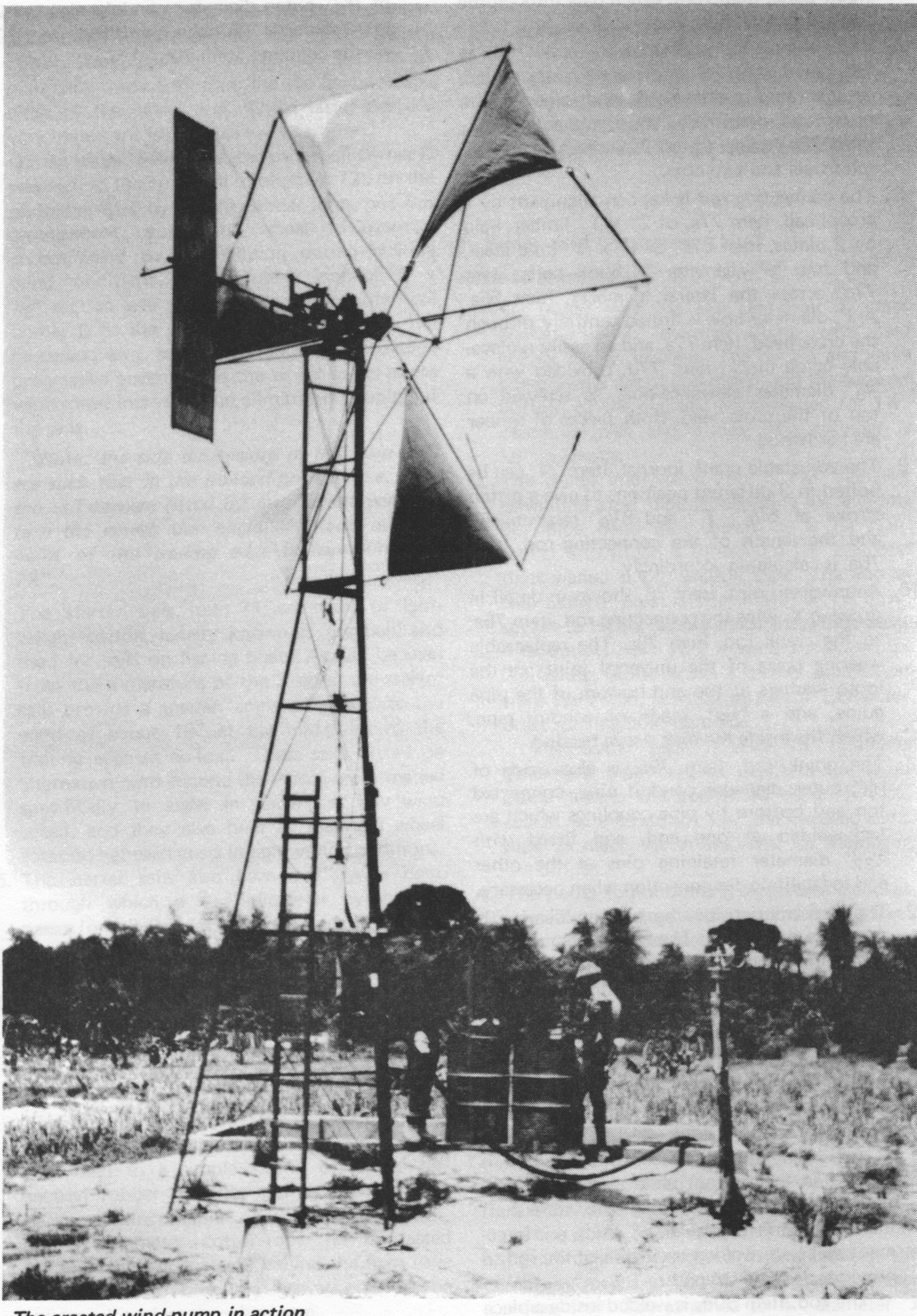
Fig. 9 Hjälpmastens geometri.

Hjälpmasten har dimensionerats som böjd och tryckt stång enligt RIL 90. Resdonen har kapacitet för lyftning av vindkraftaggregat på 900 kg under gynnsamma vindförhållanden.



Cretan Sail Windpump: R.D.Mann. I.T. Pub. UK. 1979/1992. ISBN 0 903031 66 3


'STARTER'
SAIL
4'
8'
2'6"
16'
'MAIN'
SAIL
CONNECTING
ROD
UNIVERSAL
JOINT
3" Ø 'DEMPSTER'
LIFT PUMP
SCALE 1:48
FOOT VALVE



The erected wind-pump in action.

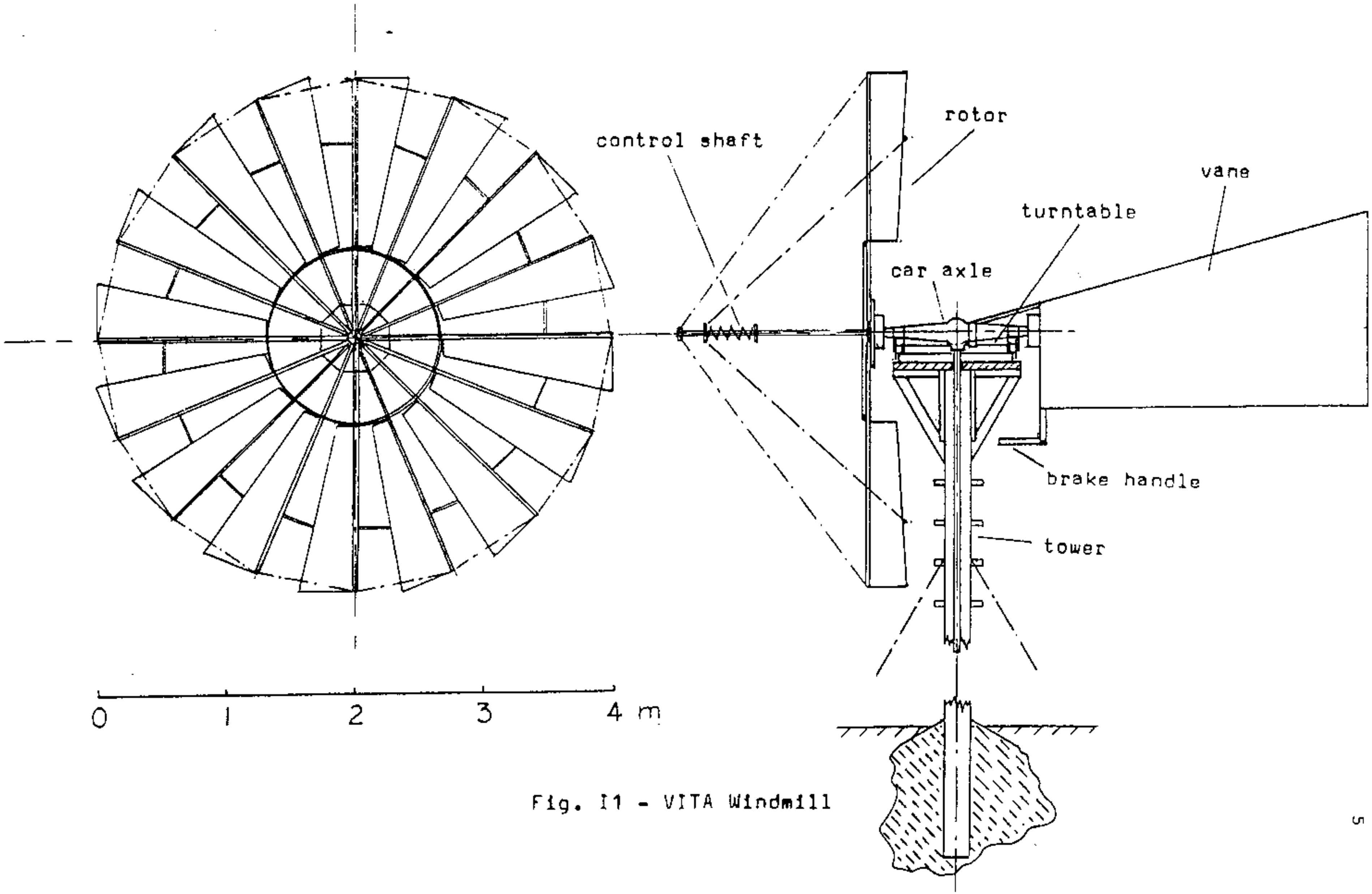
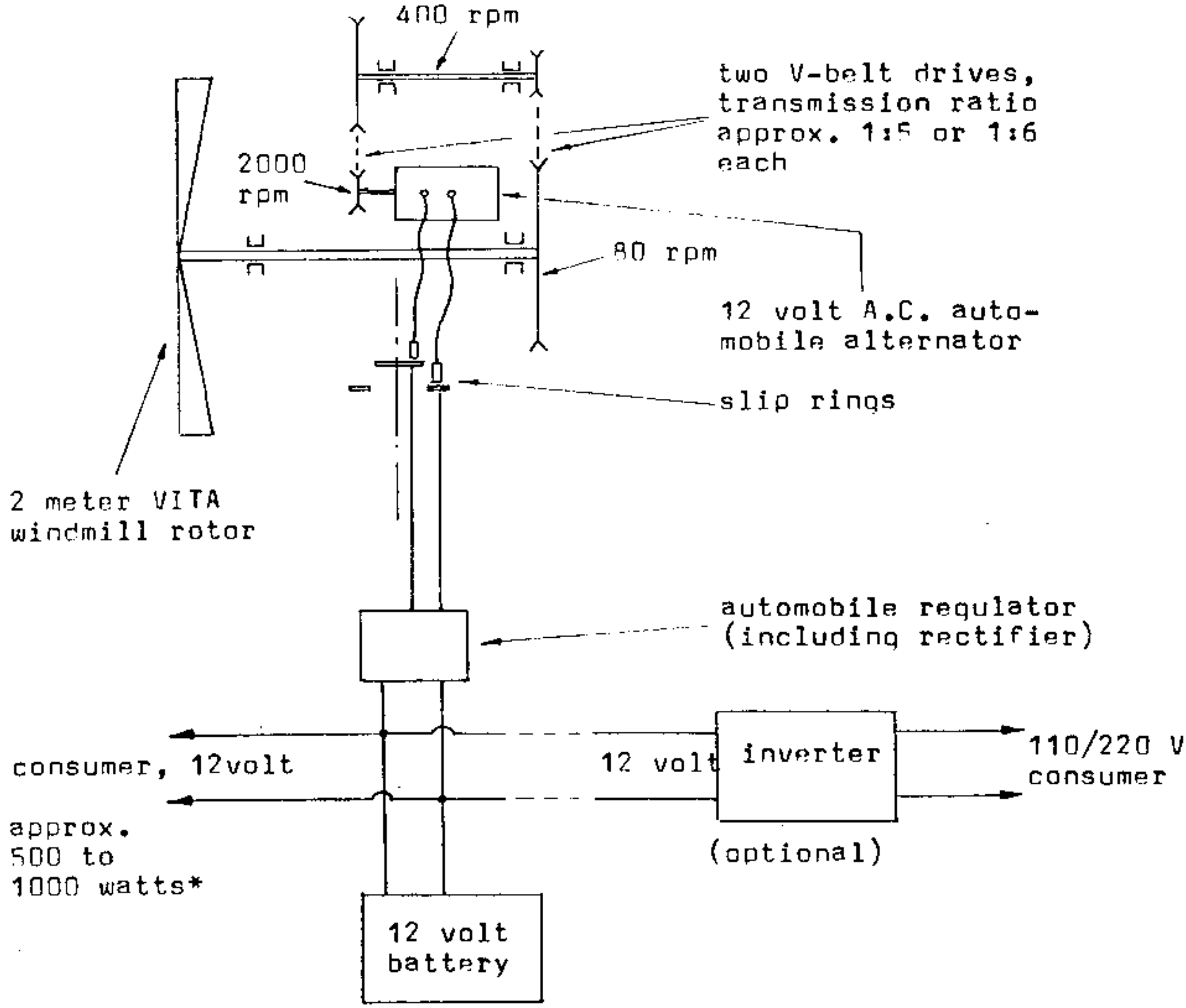


Fig. I1 - VITA Windmill

Low-cost Windmill: VITA. University of California. USA. 1970/77.

Suggestion for

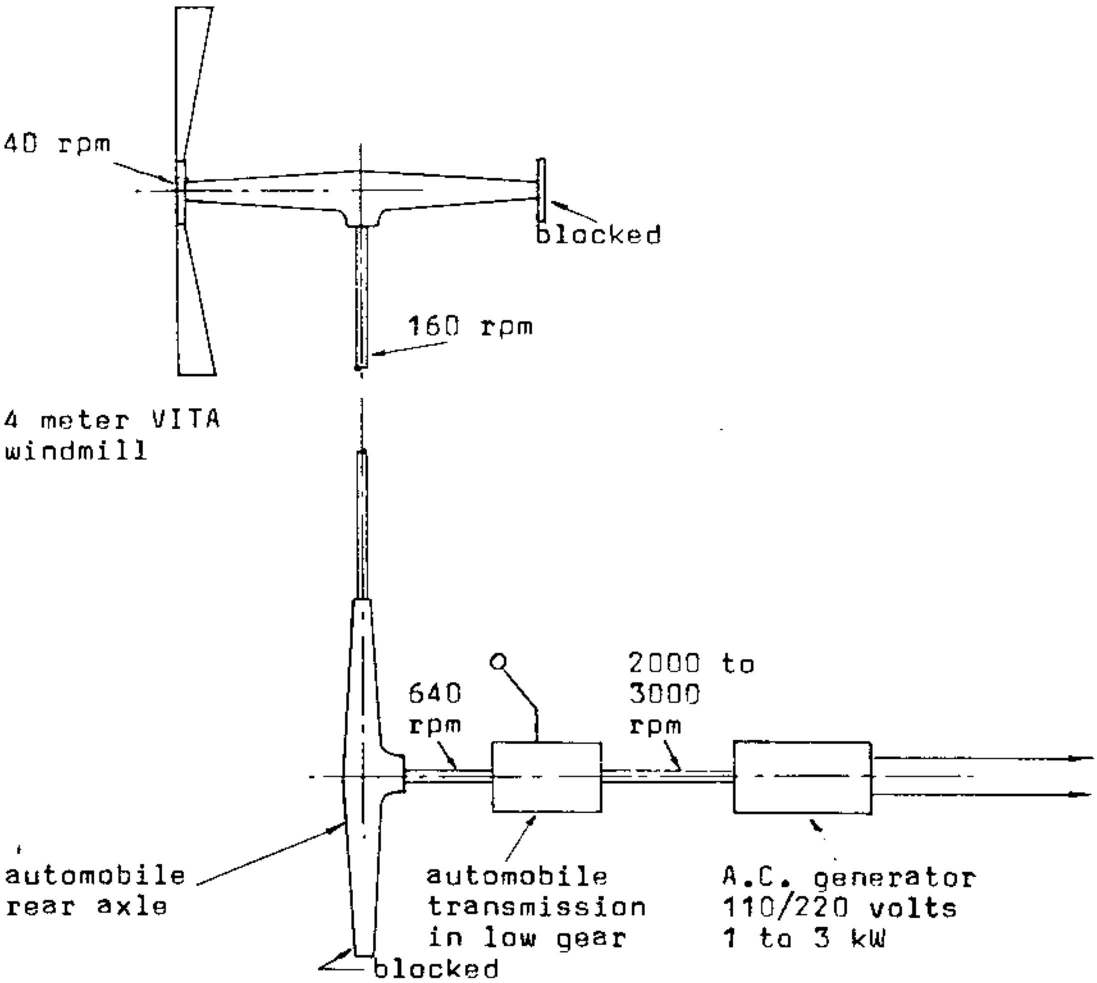
Electric Power Generation Using VITA 2 meter Windmill

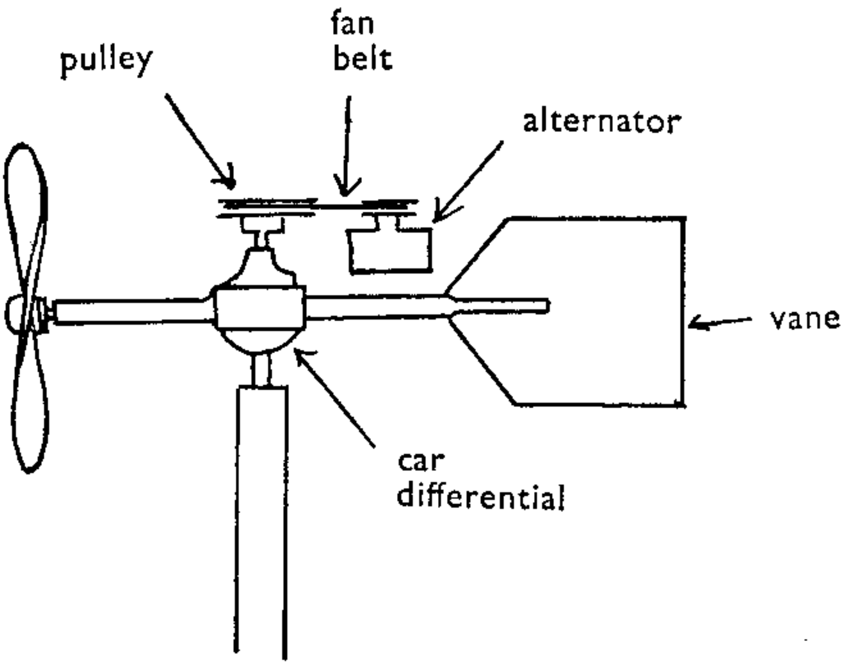


*depends on alternator used

Suggestion for

Electric Power Generation Using VITA 4 meter Windmill





DIFFERENTIAL MOUNTING

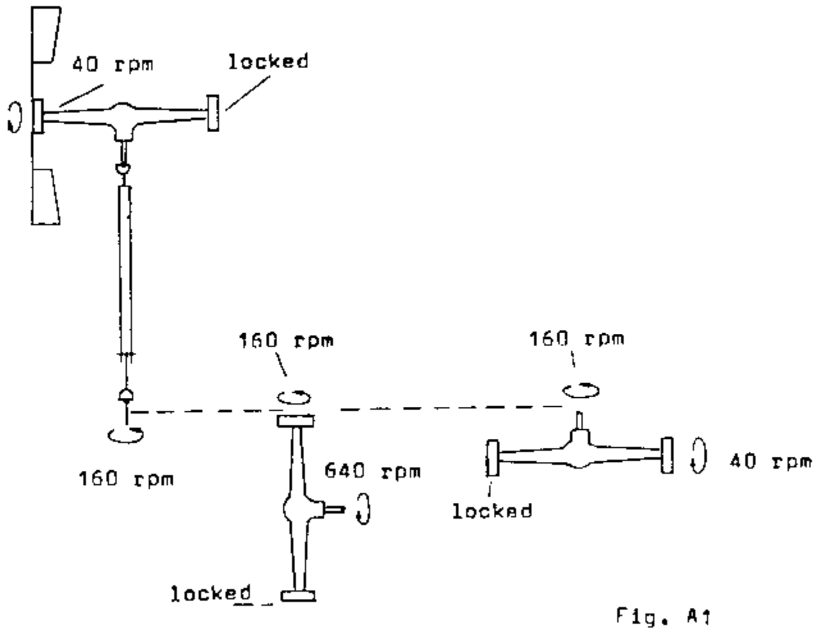


Fig. A1

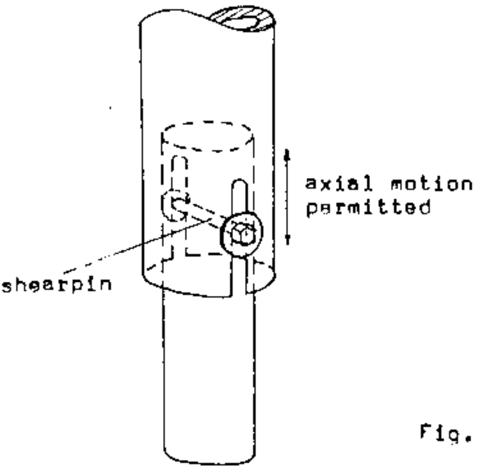


Fig. A2

TRANSMISSION

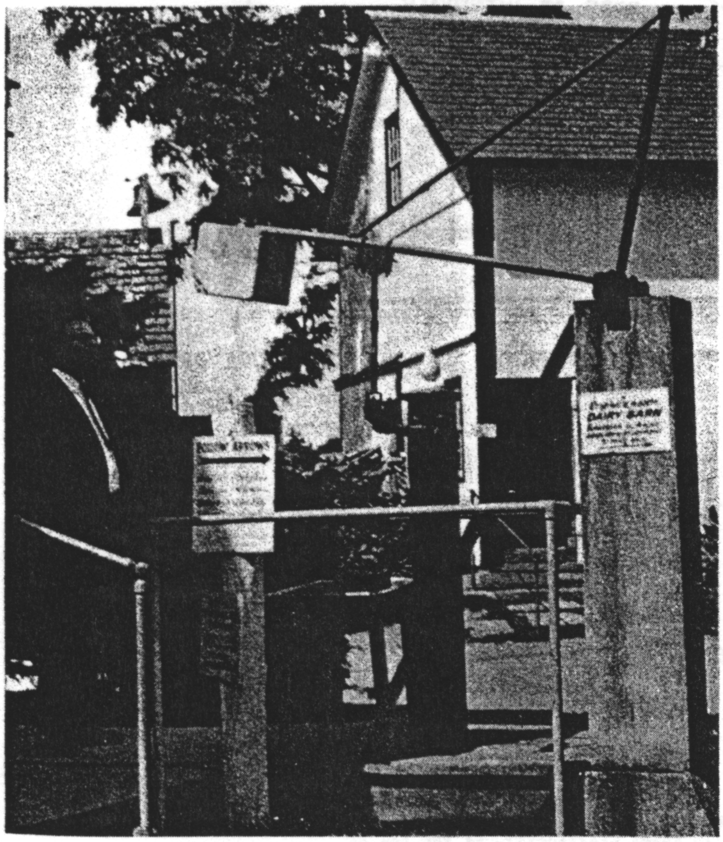
The present design uses a rigid rear axle and differential (from a small car) with mechanical brakes. Other car axles can be used with corresponding modifications. If the wheels have hydraulic brakes, use the master brake cylinder and other components from the car brake system to build a rotor brake system.

Lock permanently the wheel drum on which the vane is to be mounted, by either locking the brake completely and permanently, or by blocking the slip gear. In most cars the rotational speed of the drive shaft will then be approximately four times higher than that of the rotor mounted on the wheel drum.

The drive shaft and the two universal joints are used to transmit the rotor power to the driven machinery (see Fig. A1). The drive shaft can be lengthened by using pipe of approximately 20 to 40 mm outer diameter. Note: Permit some axial motion of the drive shaft to allow for thermal expansion and use shear pin to prevent damage (see Fig. A2).

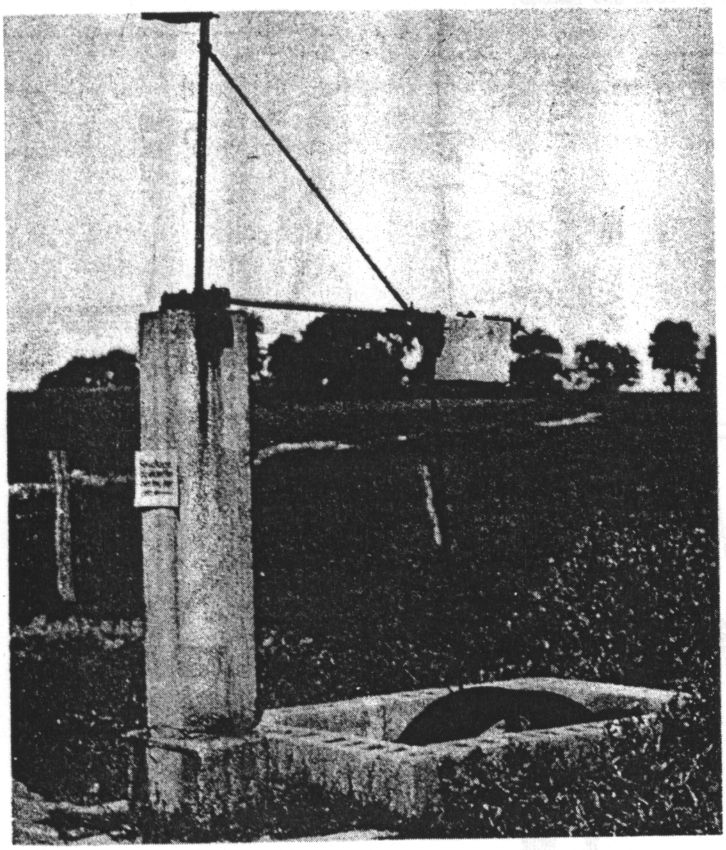
Various possibilities of transmissions using a second automobile rear axle and/or automobile transmission are shown in Fig. A1.

RECIPROCATING WIRE POWER TRANSMISSION FOR SMALL WATER WHEELS



A reciprocating wire can transmit power from a water wheel to a point up to 0.8km (1/2 mile) away where it is usually used to pump well water. These devices have been used for many years by the Amish people of Pennsylvania. If they are properly installed, they give long, trouble-free service.

The Amish people use this method to transmit mechanical power from small water wheels to the barnyard, where the reciprocating motion is used to pump well water for home and farm use. The water wheel is typically a small undershot wheel (with the water flowing under the wheel) one or two feet in diameter. The wheel shaft is fitted with a crank, which is attached to a triangular frame which pivots on a pole (see Figure 2). A wire is used to connect this frame to another identical unit located over the well. Counterweights keep the wire tight.



Tools and Materials

Wire - galvanized smooth fence wire

Water wheel with eccentric crank to give a motion slightly less than largest stroke of farmyard pump

Galvanized pipe for triangle frames: 2cm (3/4") by 10 meters long (32.8')

Welding or brazing equipment to make frames

Concrete for counterweight

2 Poles: 12 to 25cm (6" to 10") in diameter

As the water wheel turns, the crank tips the triangular frame back and forth. This action pulls the wire back and forth. One typical complete back and forth cycle, takes 3 to 5 seconds. Sometimes power for several transmission wires comes from one larger water wheel.

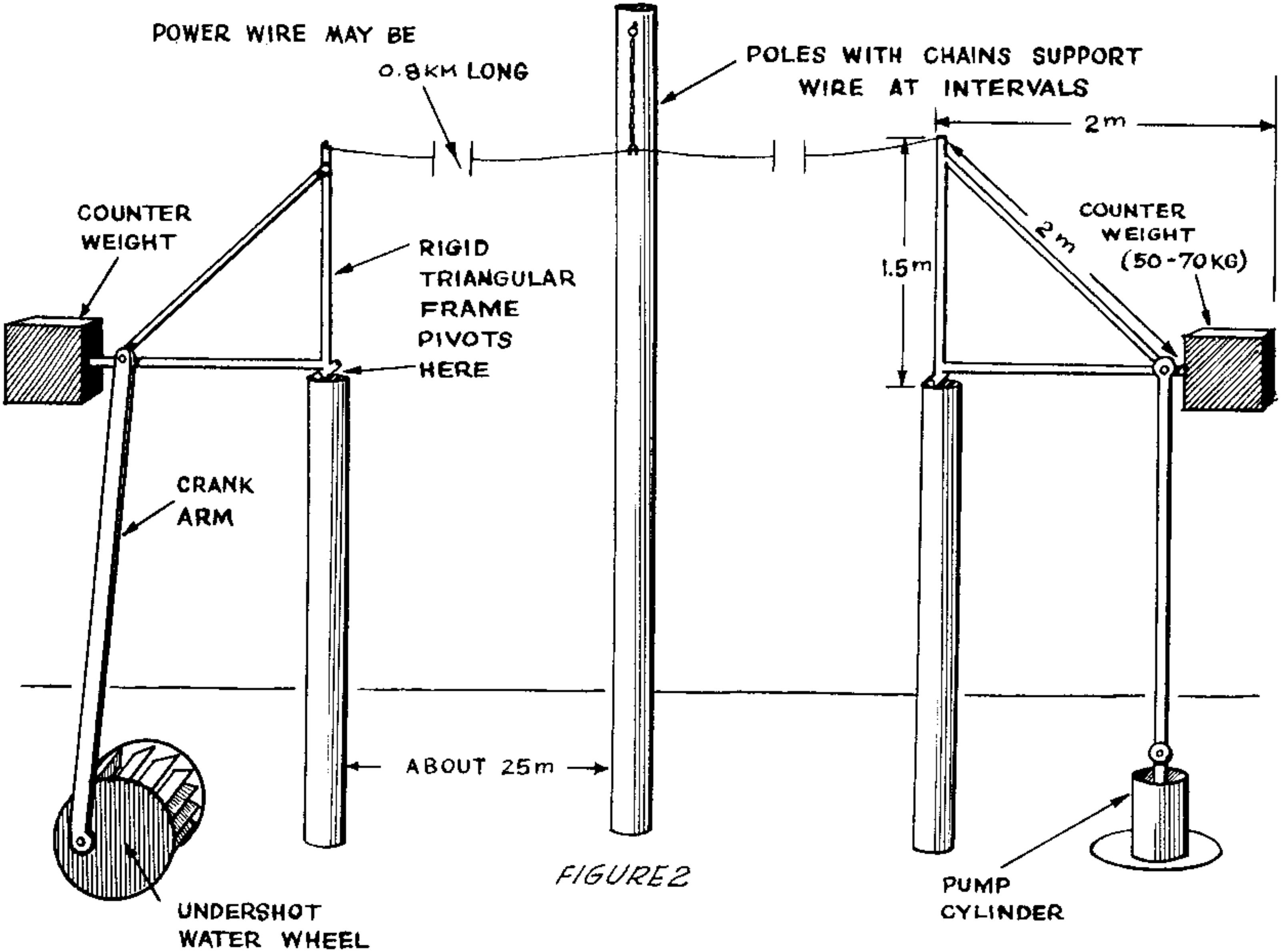
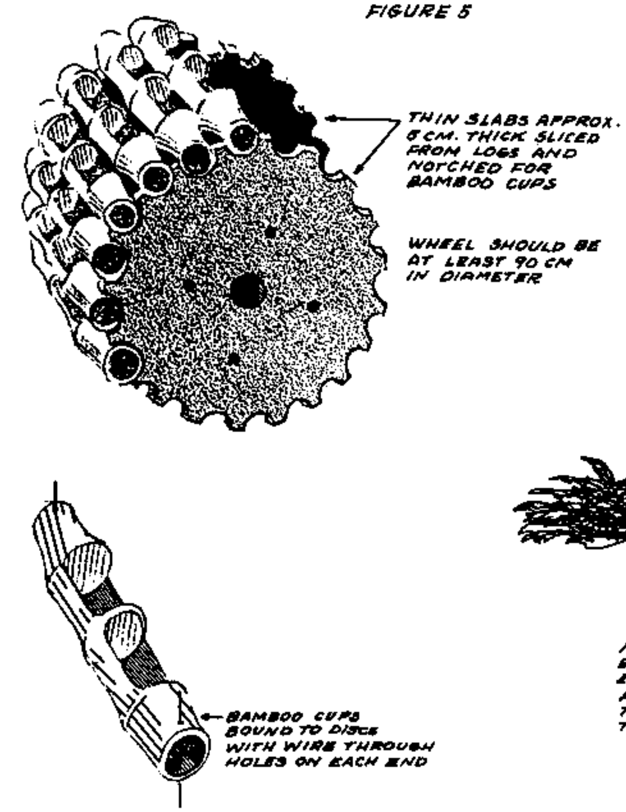

POWER WIRE MAY BE
0.8KM LONG
POLES WITH CHAINS SUPPORT
WIRE AT INTERVALS
2m
COUNTER
WEIGHT
RIGID
TRIANGULAR
FRAME
PIVOTS
HERE
1.5m
2m
COUNTER
WEIGHT
(50-70KG)
CRANK
ARM
ABOUT 25m
UNDERSHOT
WATER WHEEL
PUMP
CYLINDER

FIGURE 2

FIGURE 5



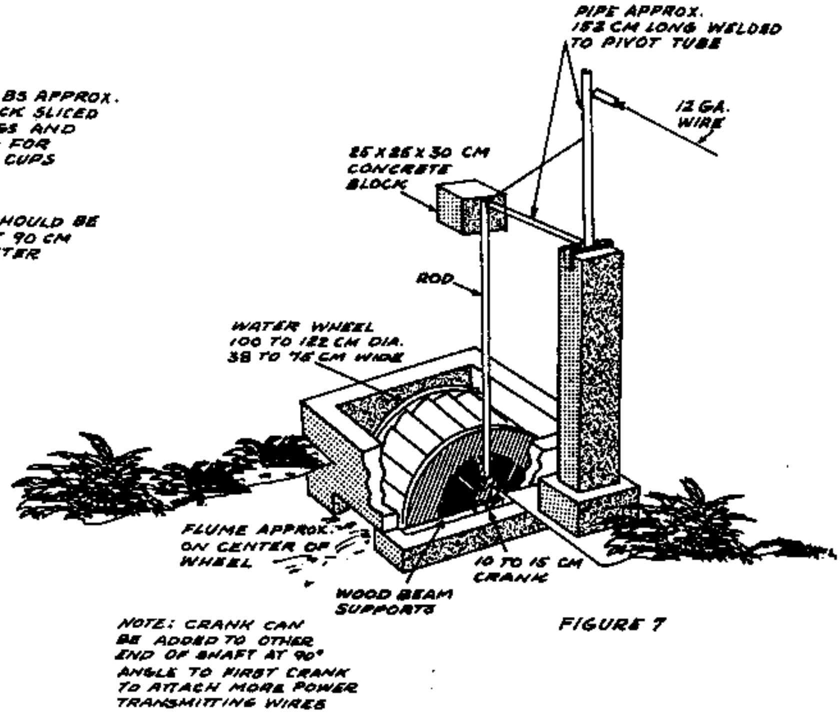


FIGURE 7

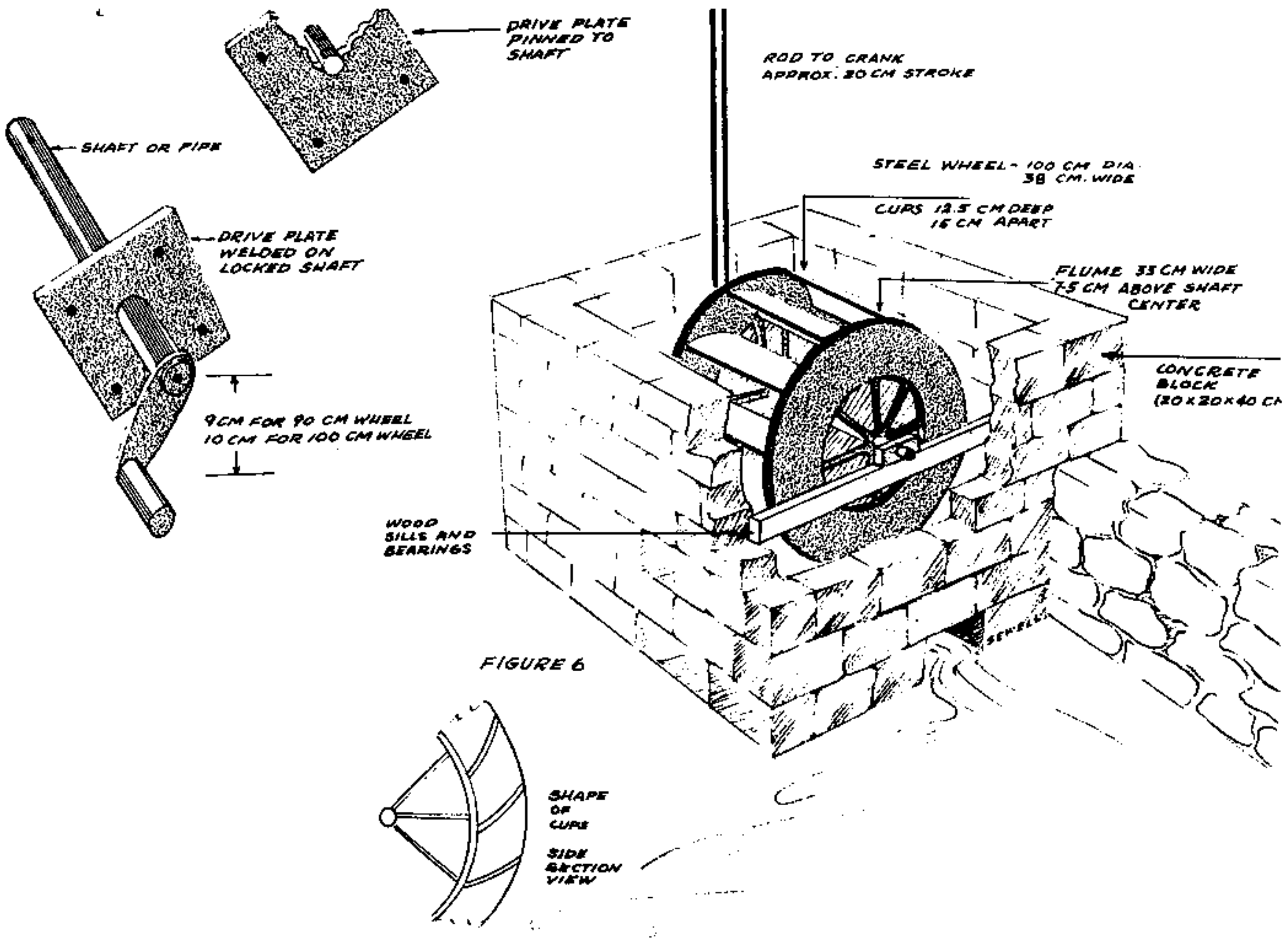


FIGURE 6

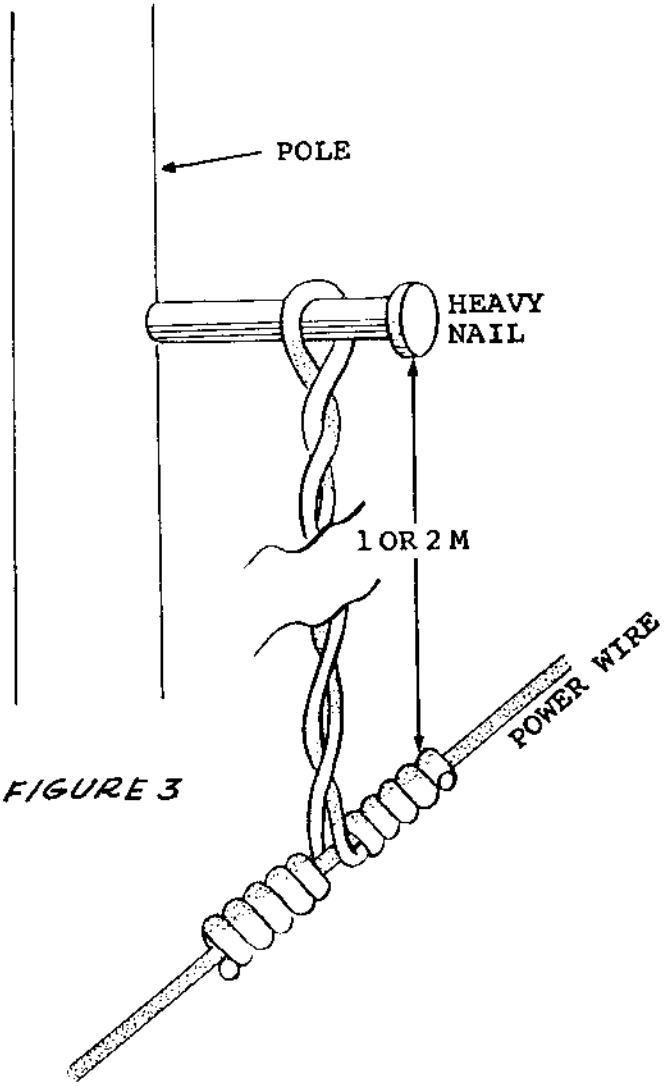


FIGURE 3

The wire is mounted up on poles to keep it overhead and out of the way. If the distance from stream to courtyard is far, extra poles will be needed to help support the wire. Amish folks use a loop of wire covered with a small piece of garden hose attached to the top of the pole. The reciprocating wire slides back and forth through this loop. If this is not possible, try making the pole 1-2 meters higher than the power wire. Drive a heavy nail near the pole top and attach a chain or wire from it to the power wire as shown in Figure 3.

Turns can be made in order to follow hedgerows by mounting a small triangular frame horizontally at the top of a pole as shown in Figure 4.

Water Wheel

Figures 5, 6 and 7 show how to build and install a small water wheel made from wood and bamboo.

Source:

New Holland, Pennsylvania VITA Chapter.

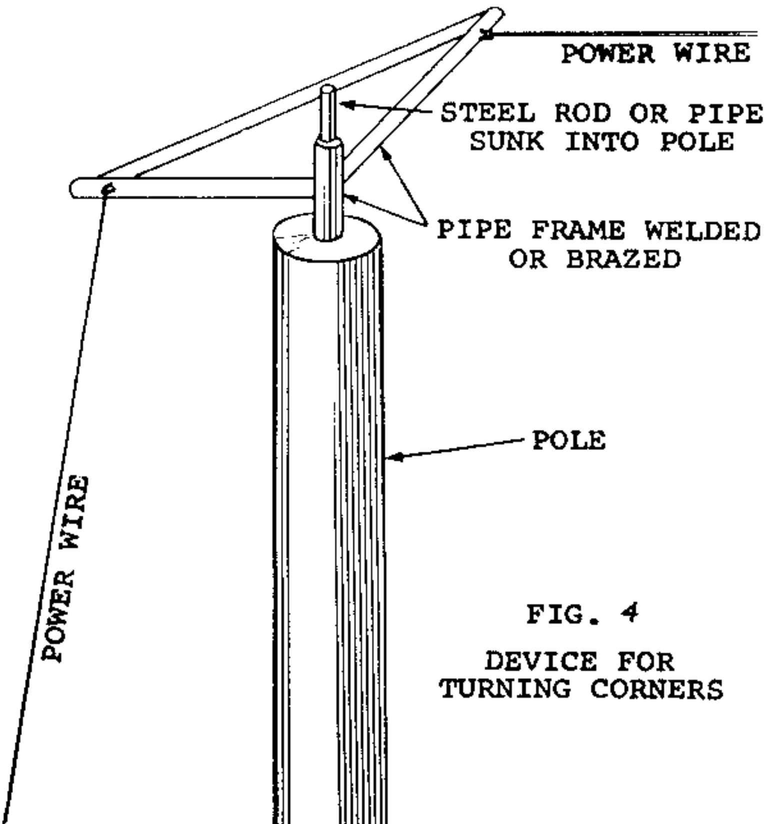
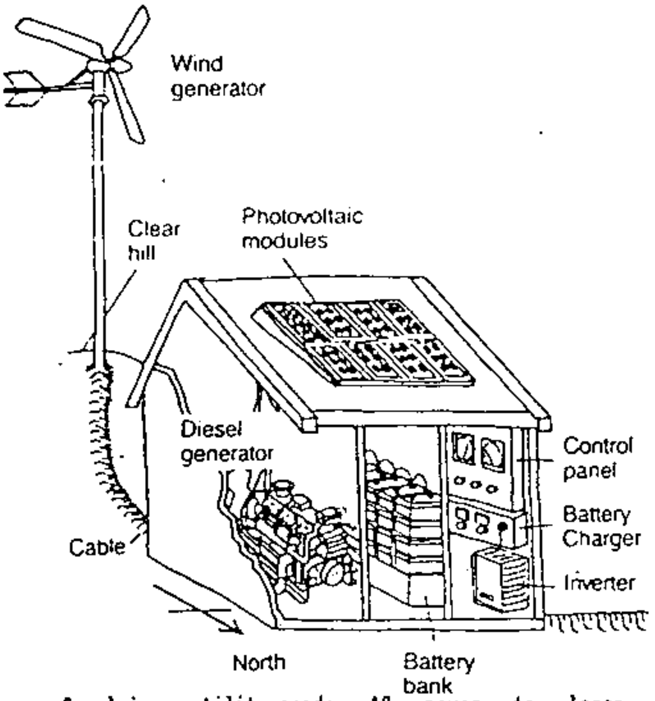


FIG. 4

DEVICE FOR TURNING CORNERS

Remote Area Power Supply



Supplying utility-grade AC power to large stations, remote villages, resorts or commercial enterprises can pose a number of difficulties. Diesel generators have a high running cost as opposed to the high capital cost of installing a large solar array with battery backup. The convention has been to use diesel generators but these usually do not incorporate a battery storage so the generator must be running to have any power. Stations with refrigeration usually run their generator for 10 to 24 hours per day. Those without refrigeration would run it for several hours per night to provide for lighting and television. The problem with such a system is that it wastes fuel.

The system must be sized to cope with heavy demands put on it by a user (eg welding). This load is called the peak load. As well as the peak load, it must also be able to handle the very short term, but very high surge loads caused when an electric motor (such as a freezer, washing machine or pump) starts up. These short term surge loads are often five times higher than the actual power used in normal operation. For most of the time the actual power being used is much less than the peak load that the system was designed to handle.

Diesel Generators

A diesel generator, as the main or back-up power supply, invariably has to be able to handle such peak loads. If, on the other hand, a diesel generator is too lightly loaded it can cause damage to the diesel engine and cause expensive repairs. In some cases a dummy load is turned on (any appliance or equipment to use power) to protect the diesel engine. This load increases fuel consumption for little or no benefit to the consumer. Both oversizing and under-utilization cause fuel wastage.

Generators also require routine maintenance during operation by ensuring regular oil-, air- and fuel filter changes, as well as routine service and operation to manufacturers' specifications. To ensure regular engine operating temperature, the engine must be run with a minimum load of 30%, but ideally with a load of 70-80%. Running of the engine on a low load for long periods will result in carbonization, cylinder bore glazing and poor fuel economy. Engine life will be severely shortened. Well loaded, the engine may achieve 20% - 30% conversion of fuel to shaft power, the remainder is lost as engine heat, exhaust heat, unburnt fuel and noise. Engine protection circuits are included in most diesel-generator systems to ensure the unit will not run in a faulty condition.

The design life of a generator is limited. A diesel generator has a life expectancy of some 10,000 hours before a major engine overhaul is required (typically costing about 50% of the initial cost).

Petrol Generators

Petrol engines in comparison are more light weight, less robust and high revving. The spark ignition system makes for a more portable power supply. However, the system is inherently unsuitable for a continuous stationary power supply. Petrol engines have an expected service life of some 1,000 hours. The engine limitations mean that the generator sets are usually small (0.5 to 8 kVA). Many petrol generators can be converted to run off LP gas which should increase the engine service life and reduce pollution level.

A Hybrid System

The use of a hybrid system, using a generator, solar panels (or wind and hydro) together with a battery bank can give you 'the best of both worlds'.

Generator and Battery Power

The generator lowers the capital cost of the system. The use of a large battery charger powered by the generator to charge batteries can load the generator to make it more efficient and the stored power in the batteries will cut down on generator use. The use of a battery bank can cut fuel costs by 65% to 70%. The use of solar panels to also charge the batteries can further cut down on operating costs.

A large inverter connected to the battery bank provides 240 volt power 24 hours per day or while the generator is switched off. Australian made inverters are available in many sizes including 2, 5, 10, 15 and 25 kVA.

Designed to your Specifications

Our staff can design such a system to meet your requirements. We can supply a generator to suit your situation. In such a system we would normally recommend a generator run on diesel or LP gas.

Village power systems must meet standards for ruggedness and reliability similar to those in telecommunications. Though the weather may not be as demanding as that found on a wind-swept mountaintop, Third World villages are distant in both time and space from the technical support and spare parts found in the developed world.

The benefits of providing even small amounts of power to remote villages are magnified because so little electricity is needed to raise the quality of life. Two 7-meter turbines, which would supply only two homes with electric heat in the United States, can pump safe drinking water for a village of 4000 in Morocco.

The typical village system might use two or more wind machines, batteries, inverter, and backup generator (see Figure 11-8). And like hybrid home light plants, village power systems could also include a solar array. The key is to use as much power as possible directly, instead of storing it in batteries and running it through an inverter. This reduces both initial cost

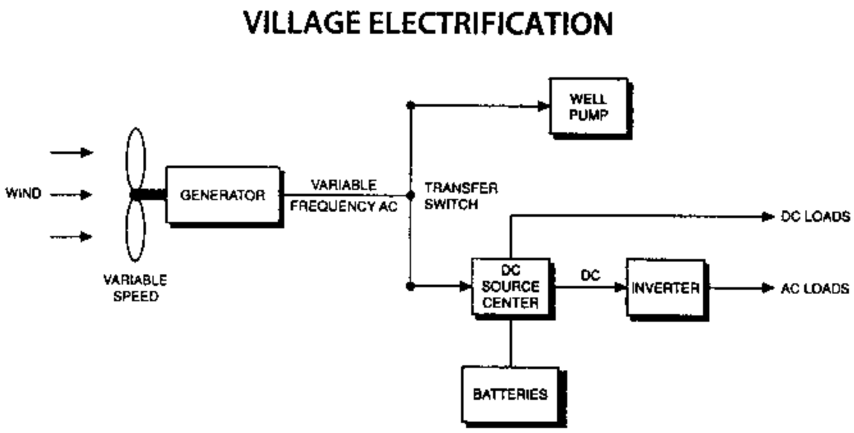


Figure 11-8. One scheme for using small wind turbines to serve a variety of loads in a village electrification program.

and complexity, while delivering more of the wind system's energy to do useful work.

Consider the Mexican village of Xcalac on the Yucatan Peninsula. There Bergey Windpower installed a hybrid power system using both solar and wind energy. Bergey erected Mexico's first wind farm, a 60-kilowatt array of six wind turbines, each 7 meters in diameter. They tied the wind turbines and a 12-kilowatt PV array into a large battery bank, and fed output from the batteries to a 40-kilowatt inverter. The entire $500,000 system offset the construction of a proposed $3.2 million power line to the remote village.

If power is used directly to pump water, grind grain, or run other loads not dependent on utility-grade electricity, the need for batteries is diminished. The batteries and inverter then need to be sized only for those loads that must use constant-frequency AC. In a concept conceived by Bergey Windpower the output from the wind turbine is manually switched from the direct loads, such as water pumping, to the batteries and inverter as needed. For example, the operator monitors the water level in a storage tank and the batteries' state of charge to determine where the power should be directed. The operator is also responsible for starting the backup generator when the power system can't meet demand. Eliminating automatic switches decreases the likelihood that a minor component could fail and imperil the entire system. It also ensures that one person is always responsible for operation of the power system.

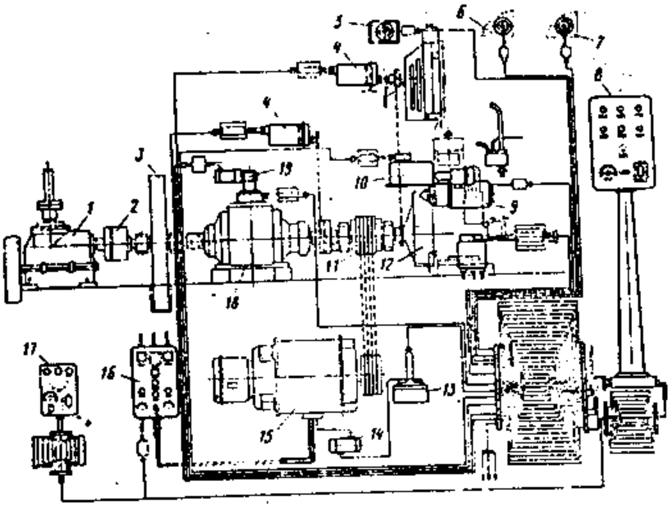
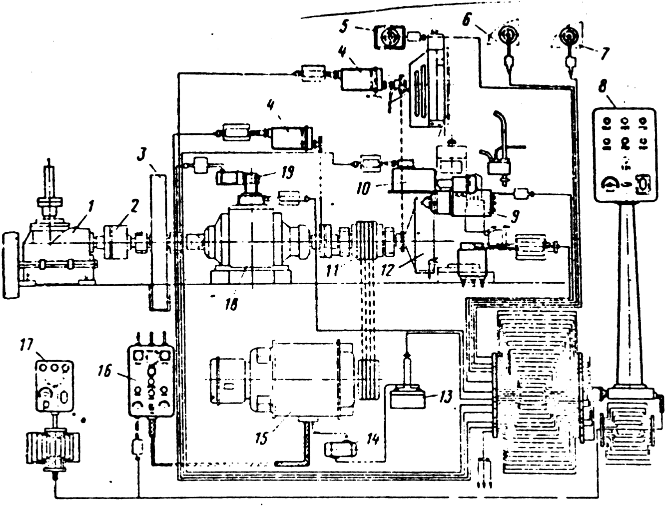


Fig. 141. Diagram of automation of the D-12 wind electric machine with a reserve diesel: 1. wind motor reduction gear; 2. freewheeling clutch; 3. inertial accumulator; 4. centrifugal relay; 5. water level relay; 6. oil level relay; 7. fuel level relay; 8. local control panel; 9. electric starter; 10. stopping device; 11. freewheeling clutch-pulley; 12. diesel; 13. storage battery; 14. rectifier; 15. generator; 16. distributor panel; remoted control panel; 18. infinitely variable drive; 19. servomotor.

To simplify servicing of installations and reduce operational expenditures, it is necessary to provide automatic emergency protection which assures stoppage of the motors with an extreme increase in generator rotation frequency, high water temperature and others. The installation of a remote control and signal panel in the apartment of the duty mechanic reduces the number of operational personnel.

In machines with a power of up to 25 kW, the use of a single generator driven by two primary motors simplifies the electrical part and automation system and reduces energy losses, increasing its output by 506%. The automation layout of the D-12 wind electric station, developed by VIESKh and the Diesel Institute (Fig. 141), provides maintenance of the normal current frequency with the windmill rotation frequency changing and provides the best utilization of the energy of the inertial accumulator due to the use of an automatically controlled stage-free variable-ratio transformer; redistribution of load between wind and internal combustion motors; starting and stopping of the diesel depending on the power of the windmill, reflected by the reserve in kinetic energy of the accumular, and also upon feed-in of an impulse through the relay circuit to the electric starter or stopping device; protection of the diesel from overload, monitoring and maintenance of a set working rate for the diesel and its protection against destructive conditions connected with a drop in lubrication pressure or an increase in the temperature of cooling water of shaft rotation speed; and monitoring of the levels of fuel, oil and water with input of a signal for stopping the engine. The relay part of the layout is executed in the form of local and remoted automatic device panels using standard relays and apparatuses. It also provides the possibility for synchronizing two motors for parallel operation.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Homebuilt Wind-Generated Electricity Handbook: M.Hackleman. USA. 1975.
Delco Light Plant Technical Service Manual: - app. $10
Earthmind 5246 Boyer Rd. Mariposa CA 95338 USA.

Any generator is also a motor, or can be. You should know this by now after reading the control chapter becuz provision must be made there (if the windplant is using a generator and not an alternator) to disconnect the batteries when there is low wind so the batteries do not "motor" the windplant. While we have not yet discussed the SGU controls nor how they are connected to the windplant control box, it will suffice to say that the same provisions must be made to insure that the batteries do not "motor" the SGU if it uses a generator. If we bypass the diode used for this purpose, we will motor the generator in the HESGU. And this can turn over the engine sufficiently to start it. Once the engine starts, it will rotate the generator to an RPM where it will produce electricity (as it is supposed to). At the very least, then, you will be able to hit a switch to start the HESGU engine and, with the right circumstances, you can hook up the system so that it will sense either low batteries or a large load and switch on automatically. Many of the Delco-type Light Plants of the pre-REA period were designed to do just that. The control box on the Light Plant, however, was a complicated affair becuz there are all sorts of desirable features in doing this and a lot of necessary ones. What if the Light Plant failed to start? Would it run down the batteries? What if the Light Plant's engine needed to be choked to start? Or what if it was cold and manifold heating was required? What if the Light Plant was out of gas? A light Plant is not a computer, so some sort of sensing would have to occur if the automatic function of the HESGU were to operate properly under a variety of conditions. The control box for the Delco Light Plant is called the Sentry and I'll list both its sensing capabilities and functions.

1. The Sentry sensed battery voltage and initiated the START function whenever the battery voltage dropped below a certain point. It initiated a STOP function whenever the battery voltage reached a pre-set level (to prevent overcharging the batteries). A manual switch was provided in the control box to override this sensory capability so that the plant could be started and stopped manually. This switch was intended to permit giving the batteries their necessary periodic equalizing charge.

2. The Sentry sensed load conditions. If a heavy load was switched on, it would initiate START before the batteries were drained to the point where the voltage-sensing function (in the Sentry) finally started the SGU. It would also prevent the SGU from starting if a surge current occurred; this will happen whenever large motors are started but, as the normal current they require is far less, it is not desirable to have the SGU start.

3. When low-battery voltage or high-load conditions dictated starting the SGU, the Sentry would initiate the START function. This involved bypassing the antimotor relay (which is a reverse-current prevention relay or a cutout relay, as we have discussed previously), removing the ignition-shorting contacts (which help to stop the engine when it comes time to do so), kicking in a set of starting coils on the generator (which give it more torque), bypassing an ignition coil resistance (to give a beefier spark), activating a cranking switch cutout heater coil (this will, if the engine fails to start, disconnect the starting function and prevent complete draining of the batteries), activating the automatic choke (for a richer fuel mixture), and activating an electric heater in the manifold to warm the carburetor air to assist starting. If the engine did start, and gained speed, it would then remove the bypass of the antimotoring relay, cut out the cranking coils in the generator, bypass the cranking switch cutout heater coil, remove the bypass on the ignition coil resistance (for normal spark), disconnect the manifold heater and allow normal charging

functions. When the batteries were charged or the heavy load was removed, it would sense these conditions and deactivate the antimotoring relay (disconnecting the generator from the batteries) and activate the ignition-shorting contacts (to ground the spark), and the engine would die.

Believe it or not, it was all done with four relays and few other components; sounds like a lot, but all very simple and to the point. You wouldn't think so if you saw the schematic for the control box or looked inside the unit, for sure, but I've indicated all of this to let you know it can be done and was done forty years ago. It's beyond the scope of this book to go into the how and wherefore of such a control box, but I've included a schematic of the Sentry box (courtesy of Delco) for the curious and inquisitive (see Fig. 6-4). The Delco company is still around, but they don't make light plants any more, so they won't be able to provide you with any information, parts, or working units. If you're interested in obtaining a copy of the theory, operation, and servicing of one of the Sentry control boxes, look under the Control listing in the Bibliography; this manual will provide information on construction and operation if you are interested in building your own.

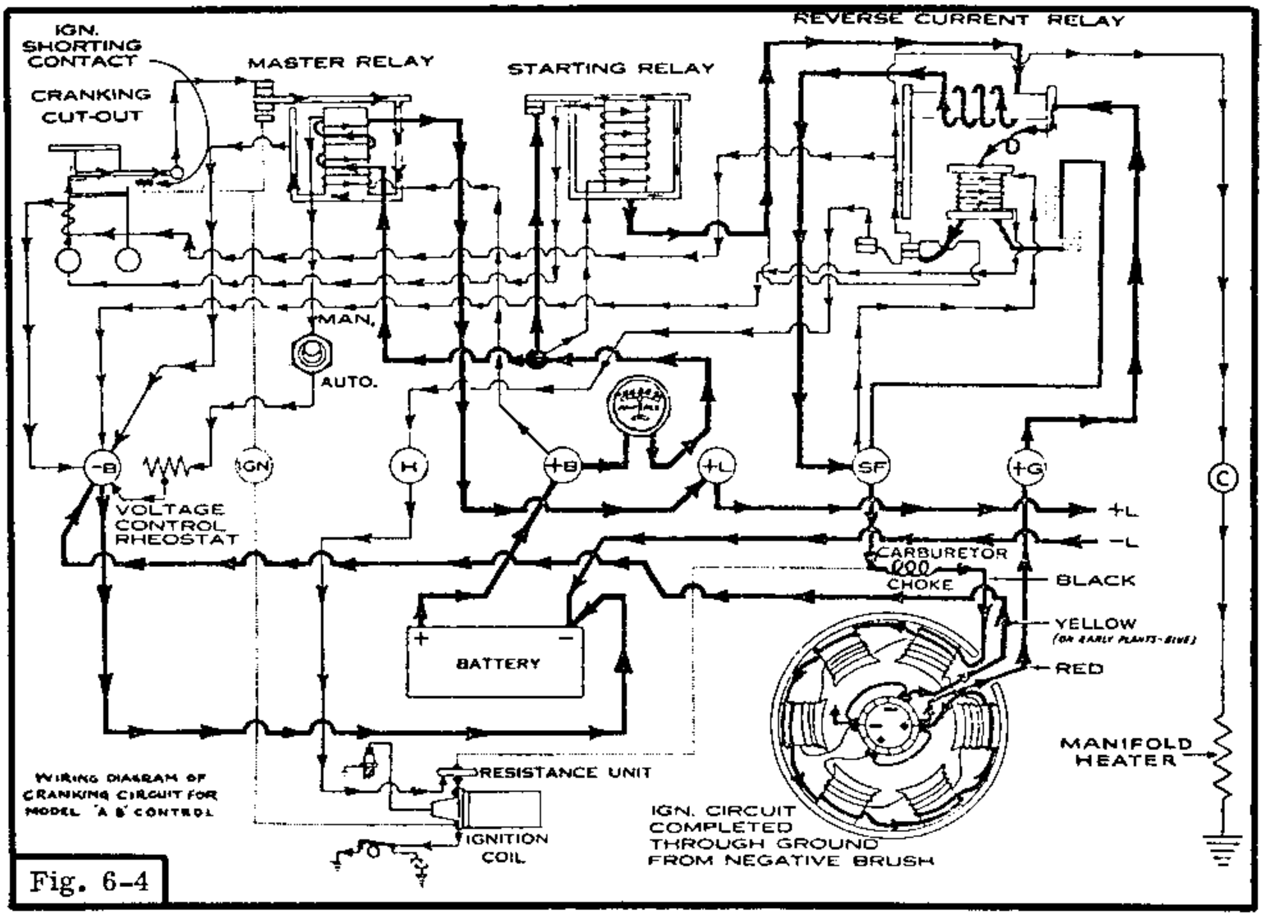
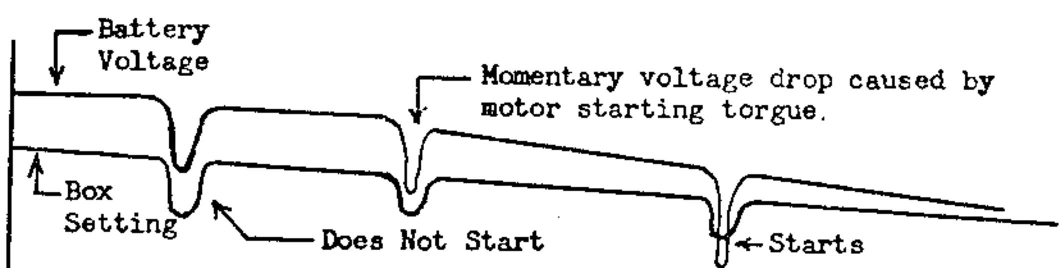
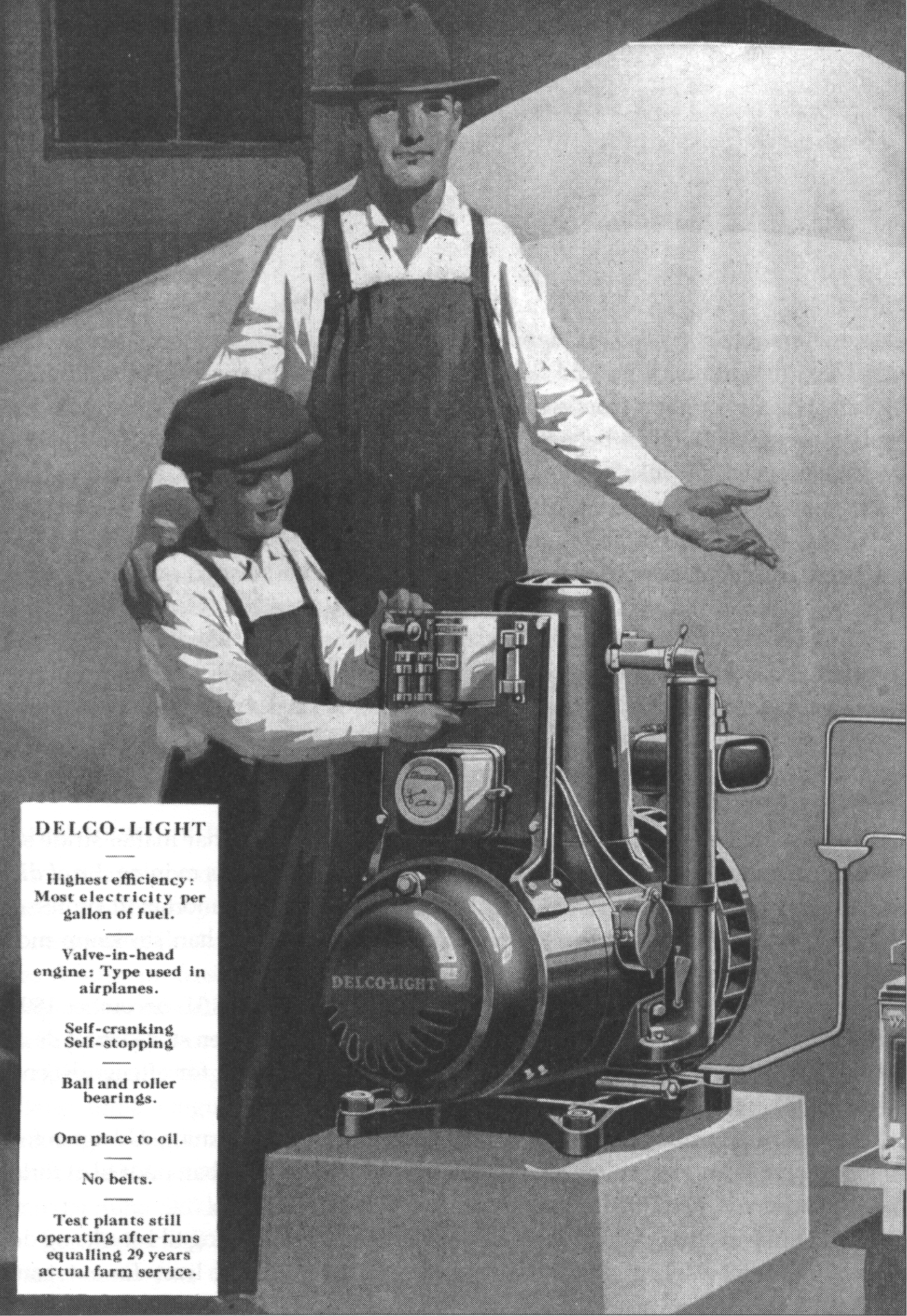


Fig. 6-4

DELCO SENTRY CONTROL BOX

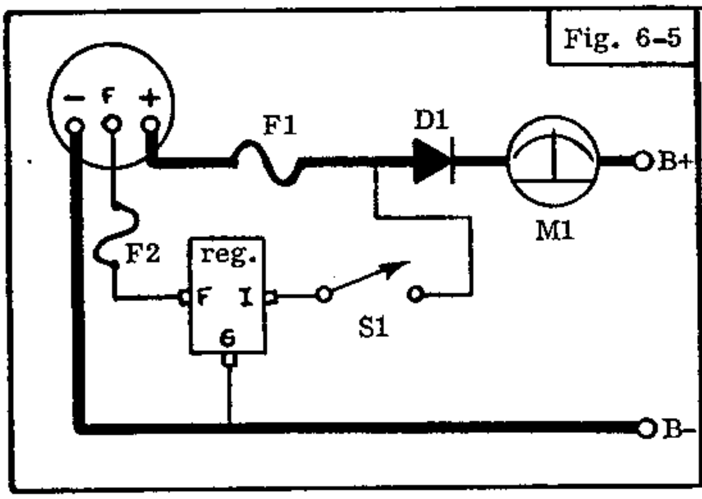


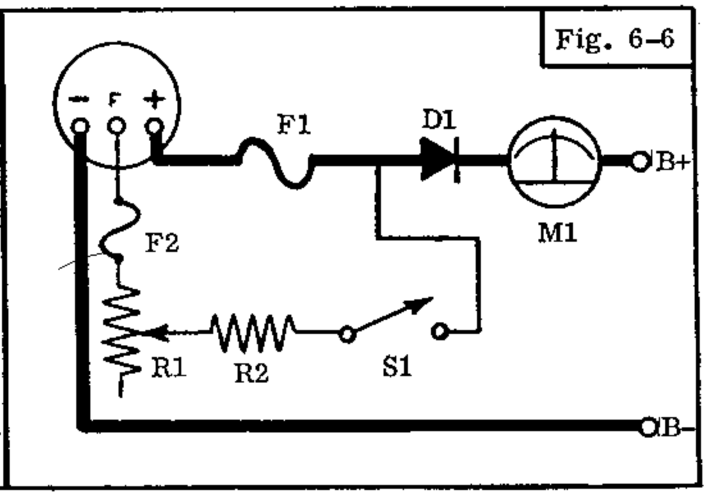
Sentry Box Voltage Setting:-Notice how the heavy current surges momentarily lower the box settings and prevent the engine starting on the majority of the power load cycles.


DELCO-LIGHT
Highest efficiency: Most electricity per gallon of fuel.
Valve-in-head engine: Type used in airplanes.
Self-cranking Self-stopping
Ball and roller bearings.
One place to oil.
No belts.
Test plants still operating after runs equalling 29 years actual farm service.
DELCO-LIGHT

The HESGU Control Functions

Control of the HESGU is situational and will be as complex as what you expect it to do for you. If you're satisfied to go out there, set the choke, yank on the start cord, and set the throttle by hand until the proper amount of current is showing on the windplant's control panel ammeter, you're only going to need a few things -- a diode (for reverse current protection), a field control circuit, and maybe a fuse -- and the installation will be straightforward. If your wind-electric system utilizes 12-volt battery banks, the HESGU will be operating not unlike a car's electrical system and the voltage regulator will take care of the field control functions. Fig. 6-5 illustrates this basic setup. This same wiring diagram will apply to any HESGU which is using a generator or alternator that is designed to put out the voltage of the wind-electric system batteries; i.e., a 32-volt generator (and its voltage regulator) will interface with a 32-volt battery bank. A switch will be needed to turn on field current (like the ignition switch in a car does) after the engine has been started to prevent unnecessary drag in starting.





If you have an alternator that is not designed to operate at the voltage of the battery banks, special consideration must be given to the field control circuit. This is due to the fact that, while an automotive alternator is capable of operating at higher voltages (than the 12 volts used in the automobile), its field circuit is <u>not</u> designed to operate at anything but 12 volts. If the alternator is used, say, in a 32-volt system, its field must not be operated at 32 volts or it will fry. The simplest means of getting 12 volts from 32 volts (for the fields) is to put a resistor (or rheostat) in series with the 32 volts and adjust it to give the field 12-14 volts (see Fig. 6-6). A voltmeter can be used to adjust the rheostat, or the current in this circuit can be measured (with an ammeter) until it reads the same as it would if 12 volts were connected to the field.

Note that a voltage regulator is not shown in Fig. 6-6. A 12-volt regulator will not normally be usable in a 24, 32, or higher-voltage system without replacing its bias resistors or adjusting the tension on the relay (which only works for some of the heavy-duty voltage regulator relays). Unlike the automobile environment, however, the SGU will be operating at a constant RPM; if the charging rate is watched, a voltage regulator is not necessary. Remember: When you want to give batteries the equalizing charge, you bypass the windplant voltage regulator. You can't take great liberties with either the windplant or the SGU when this is happening becuz of the danger of over-voltage or over-current, but the situation is identical whichever one is doing the equalizing charge.

Fuses are required in the power circuit (F1) and field circuit (F2) in the schematics, Fig. 6-5 and Fig. 6-6. Fuse F1 should be rated for the maximum current rating of the generator (or alternator) or just above the maximum current (below the alternator/generator rating) that you expect to generate. Fuse F2 should be rated just above the normal field current consumption;

insure that this fuse is inserted in the circuit when you make the adjustments on rheostat Rl or you risk frying the field coils before the HESGU is ever brought into service. Fig. 6-7 is a table which lists the values for Rl and R2 for various voltages when a 12V (approx. 3a field) alternator is used. It is desirable to use two resistors -- one fixed and one variable -- in the field circuit whenever higher voltages are used; otherwise a large rheostat must be used to dissipate the additional heat. By using the two resistors, the fixed resistor can serve to dissipate most of the heat and the rheostat can allow the fine adjustment of field current without being physically large.

OPERATING VOLTAGE OF SYSTEM	RESISTANCE		COMPUTED WATTAGE		SAFE WATTAGES	
	R1	R2	R1	R2	R1	R2
12 volts	0-5Ω	N/A	3 watts	N/A	5 watts	N/A
24 volts	0-5Ω	4Ω	3 "	36 watts	5 "	50 watts
32 volts	0-5Ω	7Ω	3 "	60 "	5 "	75 "
36 volts	0-5Ω	8Ω	3 "	72 "	5 "	100 "

If this simple arrangement for controlling the HESGU is acceptable to you, you can mount these few components in the control box for the windplant; Fig. 6-8 illustrates how this can be connected into the windplant's circuitry (see 5-23 from Control chapter) so the ammeter for the windplant will read the HESGU current as well. The main power-dissipating resistor in the field circuit of the HESGU (R2) should be located outside the control box for cooling purposes or, if located inside the box, it should be mounted where it will not excessively heat other components.

Diode Dl is required for antimotoring protection if a generator is used, but it must also be inserted for an alternator arrangement; it is used to prevent voltage spikes from the alternator (which can blow its diodes) if Fl should blow. This protection is not afforded if the field circuit is connected to the main power line at any other point than between the diode Dl and fuse Fl.

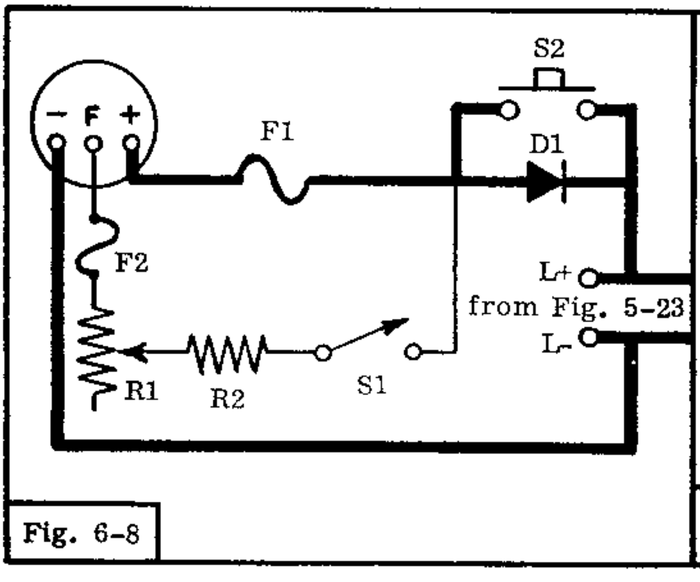


Fig. 6-8

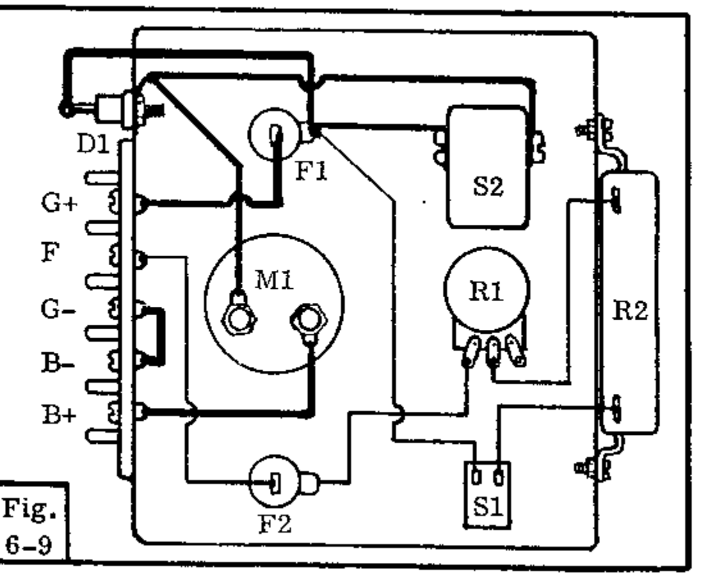


Fig. 6-9

A separate control box for the HESGU is shown in Fig. 6-9; a separate ammeter (to the windplant's control box) monitors SGU output current. A toggle switch turns on field current and the rheostat (Rl) is used to adjust field current; the power-dissipating resistor (R2) is mounted behind the panel. Power and field fuses are also mounted here. Throttle and choke controls can be mounted on this box much like they are on lawnmowers. A PTS (Push-To-Start) switch can be added to either circuit if a generator is used for the HESGU and not an alternator. This should be a circuit breaker or knife switch becuz it must handle a large amount of current when it bypasses the antimotoring diode. This can also be the manual-start switch if the generator is large enuff to motor the engine to starting speed. The Delco Light Plants utilizing the Sentry automatic-start unit had generators equipped with dual field coils which gave the required torque necessary to overcome the drag in the engine caused by cylinder compression. If your engine has good compression and your generator doesn't have a lot of "oomph," you may be stuck with the manual start. If you're bound-and-determined to automate the HESGU, it'll mean a beefier generator or smaller engine or a combination of both.

If your situation calls for higher power or automated functions -- starting, stopping, and control -- then take a look at the MOSGU.

MOSGU

No, this is not some Eastern-based, philosophical sect. MOSGU (Multi-Operational Standby Generator Unit) is again my own terminology and it refers to a large SGU which has some additional features. Anyone installing a wind-electric system in a remote area is going to need power not only to construct and install this alternative energy system, but to supply electricity, heat, and light for the facilities in the interim. Most of us could not afford to purchase a SGU of the size required to take care of all these functions, little knowing that we may already possess one. Okay, what am I talking about? Why, an automobile engine, of course! Before you pooh-bah the idea, read on.

Suppose that you removed an automobile engine from its natural habitat and placed it into a box that is specially built to mount and accommodate it. Now, suppose that you connected a panel to it that allowed you to remote-start and otherwise control the functions of the engine from a distance Further, suppose that you hooked up a number of umbilical cords to it -- hoses for the cooling system, electrical wires from its generator or alternator, ducting into the space around the engine, and an exhaust pipe -- and buried the unit. Right away I think you will see that this would have some advantages. The noise problem is minimized. The environment of the engine is closed and dust and weather protection can be assured. Where do the umbilical cords go? Well, the exhaust would be opened (after passing through a muffler of sorts) to the atmosphere. The cooling system is hooked to a tank which also happens to be a household hot water tank. The ducted tubing serves to remove waste heat from the engine and, operated with a blower (which can be an adaptation of the fan on the engine itself), the ducting can be terminated in your shop or habitat to provide space heating. The exhaust will vent a lot of heat, so let's extract some of that, and generate some steam (from a water jacket) to be used for cooking. And we'll hook up some batteries to the generator or alternator on the engine and use that to supply a stored energy for use when we need it. Since the engine will not be used to propel a vehicle, we can seriously consider adding a few more generators and alternators to the engine itself and gain a lot more electrical power that way. Maybe, we'll even add a 110 VAC, 60-cycle generator to the engine and, by regulating the engine speed about a certain RPM, we can be assured of a large, utility-size electrical capacity for emergency or occasional use.

Well, that may all sound a bit abstract but the idea is there. In an automobile, the heat is always considered a nuisance and is got rid of while driving. What you may not realize, however, is that an automobile engine is very inefficient if we were to consider the percentage of the energy that results in motive power from the original quantity of gasoline that fuels it. An approximate figure would be 5-15%. Not very good for a society which sees itself as being practical and pragmatic, is it? The rest of the energy goes into making noise, vibration, and heat. In cold weather, some of the heat would be used in the interior of the vehicle, but this is really a very small amount compared to the total amount of heat the engine produces and wastes. In actuality, of course, the engine wastes nothing. It is we--who design, build, and operate the engine-- that waste the energy that it produces from the gasoline. And it is we who can change that habit when we have need and otherwise see the light. Copy?

Keeping in mind that an automobile engine is more efficient as a heater than it is as a source of transportation, we have only to make a few modifications, and we can make good use of that energy and the gasoline that produces it. A conservative estimate of the efficiency of MOSGU is about 85%, and that is a five- to tenfold increase in efficiency. We'll take it all slow and easy as we go through the various components of the system so that you can actually fabricate a working system from it.

The MOSGU Engine

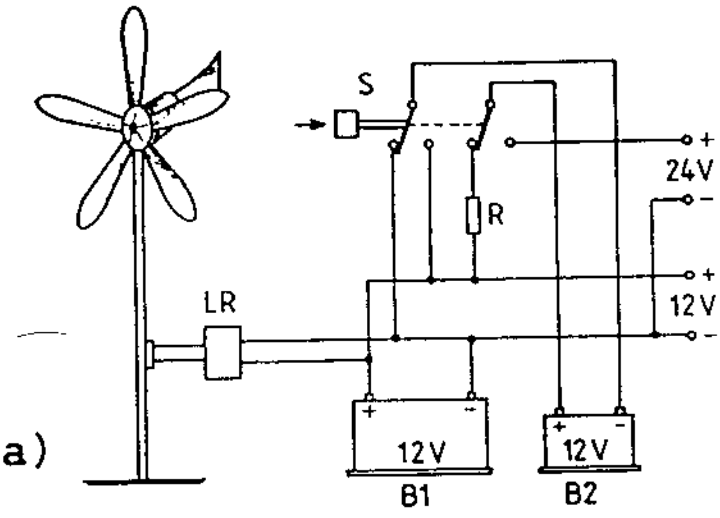
Selection of the engine to be used with the MOSGU is pretty much a matter of situation. If you can't afford to go out and find one that will be ideally suitable for use, then you may have to do with the one you have access to. If you have a car that you're not using and plan to have hauled away, then it may be what you'll use. Used cars may go for a pretty fair amount out of a used car lot, but the money those folks pay for the cars is really not all that much. Trade-in value of any car will be higher than the cash value it might have, so check out the situation carefully. If the engine is pretty well shot, then get rid of it. The most basic requirement for the MOSGU engine is that it be in good, if not excellent condition. The environment of the MOSGU is certainly a lot easier on an engine than the automobile is, but one that won't last more than a few more days on the road isn't going to last a heck of a lot longer when used with the MOSGU.

It's going to take a certain amount of energy to set up the engine for use in the MOSGU, so start out with something this side of junk if you're going to get any benefit from using it as an SGU. I offer the following parameters for those of you that might have access to various engines, or are willing to scout around for one that will provide reliable service.

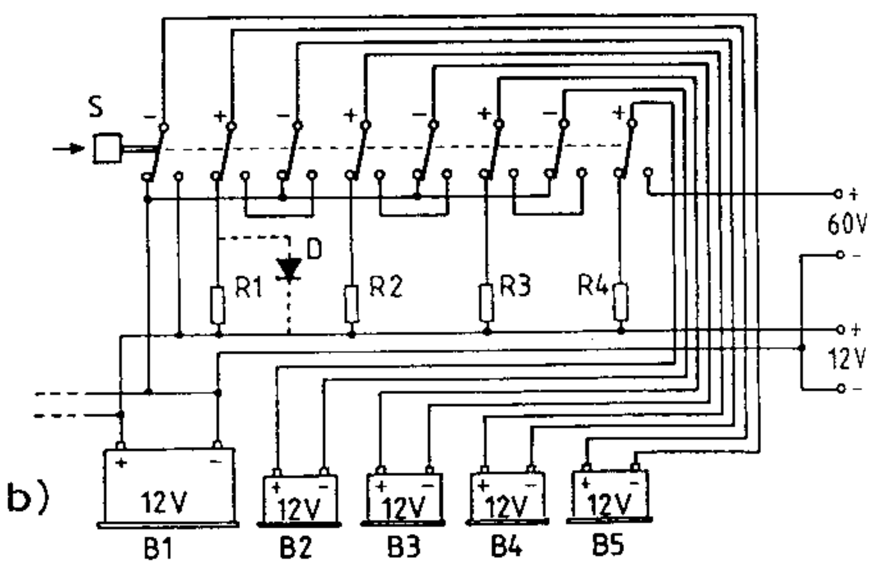
Engines of small physical size and small horsepower are much preferred to the gas-guzzling V-8's found in most Detroit monsters. For this application, a 40HP engine is more than sufficient, and anything over 100HP is wasteful. I will grant that it doesn't matter all that much whether it is wasteful or not becuz the advantage of the MOSGU is that it does make use of the waste heat. But small is beautiful -- whether it's the engine you select, the money it may cost, or the amount of energy required to carry out some of the other little necessities. To be effective, the MOSGU must be located in a closed environment, and that means getting the engine out of the vehicle and into the receptacle that houses the MOSGU. A 40HP engine is work enuff. A V-8 is absurdly unmanageable. A 4-banger (4 pistons) is much preferred to a V-8. If it can't be helped, a 6-banger is the next choice. There are good 2-bangers around -- very small cars and motorcycles use these -- but I suspect that becuz of their relative scarcity, they will be more expensive than a good four- or six-banger. I don't know much about motorcycles, so check with someone who does for more info on that size engine. Maybe that person can swing something for you.

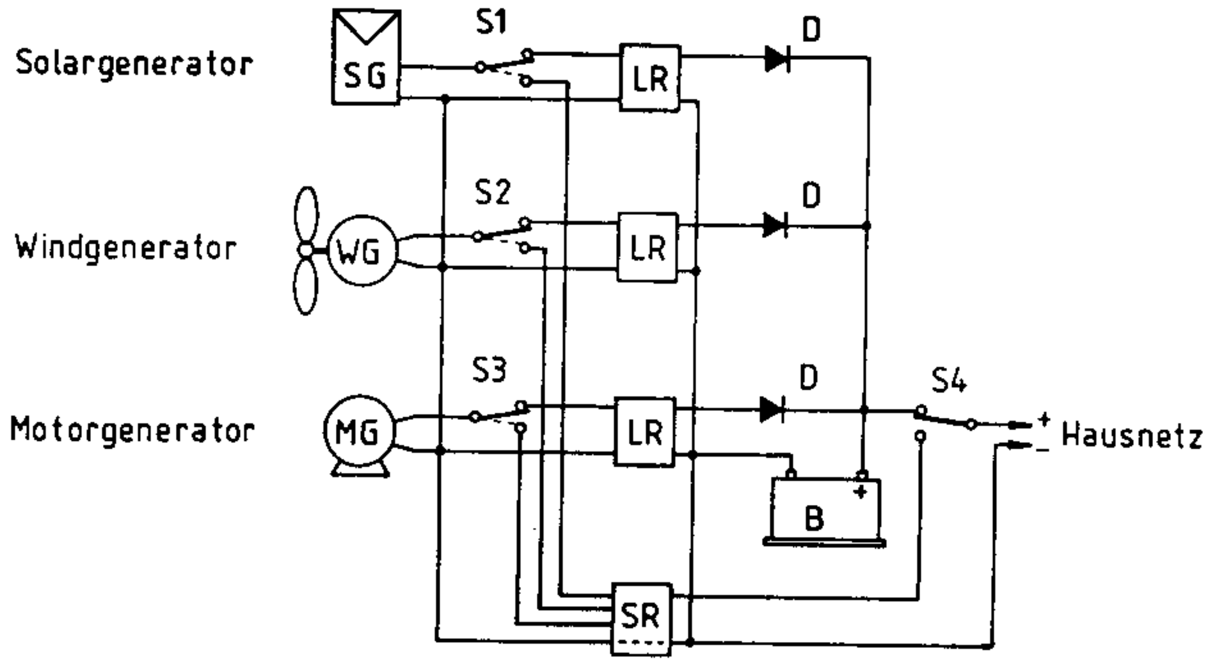
NB:

SGU: **Standby Generator Unit.**
HESGU: **Horizontal-Engine Standby Generator Unit.**
MOSGU: **Multi-Operational Standby Generator Unit.**

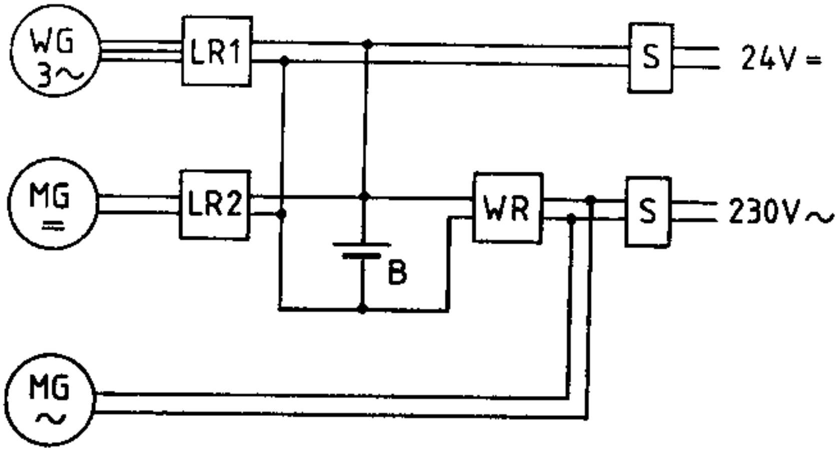


Zweitspannung für eine Inselanlage: a) wenn die Kontakte des Schalters S in eingezeichneter Position sind, ist Batterie B2 über Widerstand R an die Hauptbatterie B1 angeschlossen und wird somit über den Laderegler LR gleichzeitig mit der B1 geladen. Wenn Schalter S in der Pfeilrichtung umgeschaltet wird, verbindet er Batterien B1 und B2 miteinander in Serie, was eine Ausgangsspannung von 24 V ergibt. b) Auf dieselbe Art läßt sich z.B. mit Hilfe von 4 zusätzlichen Batterien (B2 bis B5) eine 60 V-Zweitspannung erhalten. Die Kontakte des Schalter S verbinden in der eingezeichneten Position alle Batterien parallel miteinander. Batterien B2 bis B5 sind jedoch auch hier nicht direkt, sondern jeweils über einen Schutzwiderstand (R1 bis R4)) an die Hauptbatterie B1 angeschlossen. Wird der Schalter in der mit Pfeil angegebenen Richtung betätigt, schalten sich alle Batterien in Serie zu einer Nennspannung von 60 V um. Eventuelle zusätzliche Schottky-Dioden D (die jeweils jeden der Widerstände R1 bis R4 überbrücken müßten) bilden einen Bypass in Richtung der Stromabnahme von Batterien B2 bis B5 zu den Verbrauchern, wenn die Kontakte des Schalters S in eingezeichneter Position stehen. Diese zusätzlichen Dioden verhindern Leistungsverluste an den Widerständen R1 bis R4 bei der Stromabgabe; Widerstände R1 bis R4 sind als Schutzwiderstände beim Laden der Batterien B2 bis B5 im Einsatz. Sie verhindern zudem beim Rückschalten des Schalters S Stromstöße, die durch Spannungsdifferenzen zwischen einzelnen Batterien verursacht werden (die während der seriellen Verschaltung besonders zwischen B1 und den restlichen Batterien entstehen)





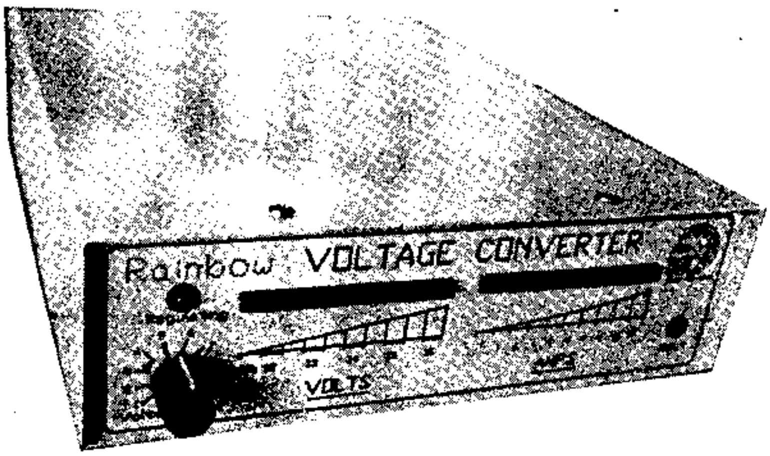
Alle drei Generatoren können hier wahlweise entweder die Anlagen-Batterie B laden (über Laderegler LR) oder sie können über einen separaten Spannungsregler SR das Hausnetz direkt mit elektrischer Energie versorgen. Die Nennspannung aller drei Generatoren muß in diesem Fall (als Ladespannung) relativ hoch dimensioniert sein und kann daher ohne einen zusätzlichen Spannungsregler (SR) das Hausnetz nicht direkt versorgen. Mit Schaltern S1 bis S3 kann jeder der Generatoren wahlweise entweder an seinen Laderegler LR oder an den gemeinsamen Spannungsregler SR angeschlossen werden. Schalter S4 schließt das Hausnetz wahlweise entweder an die Batterie oder an den Spannungsregler an; Dioden D sind Schottky-Dioden (ihre Funktion wurde bereits an anderen Stellen erklärt)



Zwei Motorgeneratoren teilen sich die Stromversorgung einer größeren Anlage, die für einige der fest installierten Verbraucher mit einer Gleichspannung von 24 V, für die restlichen Verbraucher und Steckdosen mit einer 230 V-Wechselspannung ausgelegt ist. Windgenerator WG, wie auch das Gleichspannungs Motoraggregat MG= sind nur für den 24 V-Gleichstrom zuständig (somit auch für das Laden der Anlagenbatterie B); von dieser Batterie wird auch der Wechselrichter WR betrieben, der das 230 V-Hausnetz versorgt. Während Spitzenzeiten kann bedarfsbezogen das zweite Motoraggregat zugeschaltet werden, das direkt eine 230 V-Wechselspannung erzeugt

RPC Microgrid

(100V DC)



Where there is a requirement for a number of small power systems (eg dwellings) within a few kilometres of each other, it is now possible for each dwelling to have its own power autonomy while sharing generation and surplus power. This century old idea now has a new viability thanks to the invention of a wonderful new transistor, the power mosfet, and a magnet which does not conduct electricity, ferrite.

It is based on a 100 volt DC power distribution and generation system with 12V or 24V battery banks at individual sites (eg house sites). Voltage converters ~~act~~ as two way interfaces between the battery banks and the 100 volt distribution lines. Arrays of panels along with other energy sources (eg shared hydro, wind turbine or back-up generator) provide the power source. The individual 12V or 24V battery banks can also be boosted with their own dedicated solar panels.

A Microgrid can mean more effective outlay of capital through shared resources, greater overall efficiency by better utilisation of available power and greater freedom of choice with such things as placement of solar panels (eg if dwellings happen to be in shaded areas).

Public and Private Interests

One big advantage of a microgrid system is sociological. There is a clear interface between the microgrid which would typically be in public control (village council, body corporate, company, etc) and everything on the other side of the DC/DC converter could be private and run without reference to the operation of the microgrid. The consumer has free choice of earthing, voltage, amount of storage, whether to have an inverter, private generation capacity, or co-generation. Any consumer cannot exhaust public stores of power or have it entirely to themselves. It can allow any consumer to use what is surplus to requirements of other consumers.

The RPC Microgrid

The RPC microgrid is designed for 100 volts DC and to transport average rather than peak power. Also it has quite relaxed voltage constraints, remaining functional for levels between 70 and 130V DC. Wires can be sized at a compromise between power wasted and capital invested. Peak power is supplied by local batteries. If the grid is powered from renewable energy sources, local batteries can supply the loads during periods of low wind or sunshine.

What the Voltage Converter Does

DC/DC converters are used in computer power supplies, optimisers, LCBs (pump maximisers), and some inverters.

Specifications

- Power shared between consumers;
- Will operate with the line between 70 and 130 volts;
- Short circuit proof;
- Protected against reverse polarity of both battery and distribution line;
- Input/output isolation to 5000 volts;
- Adjustable regulation of battery charge;
- Will run without a battery;
- Will deliver amps into a battery which is flat;
- All day efficiency above 80% (as against peak efficiency);
- Integral voltmeter and ampmeter;
- Lightning resistant;
- No holes in the case (vermin proof);
- 12 or 24 volt models available;
- 10 amp charge rate at full line voltage;

Rainbow Power Company Australia: 1992/1993.

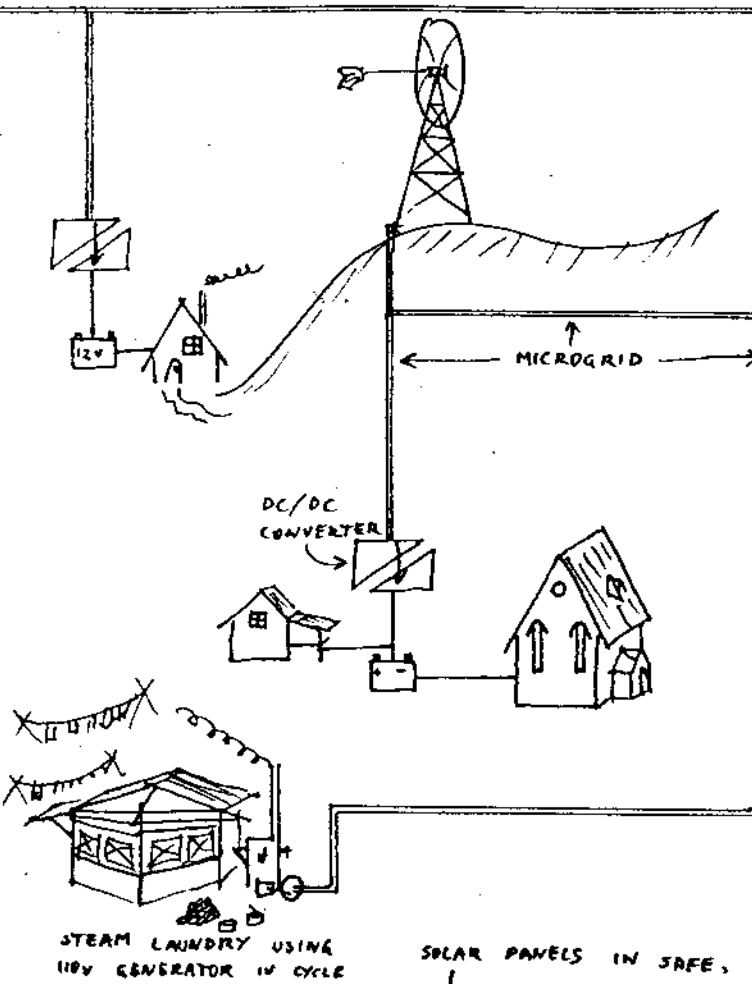
Development of Microgrid

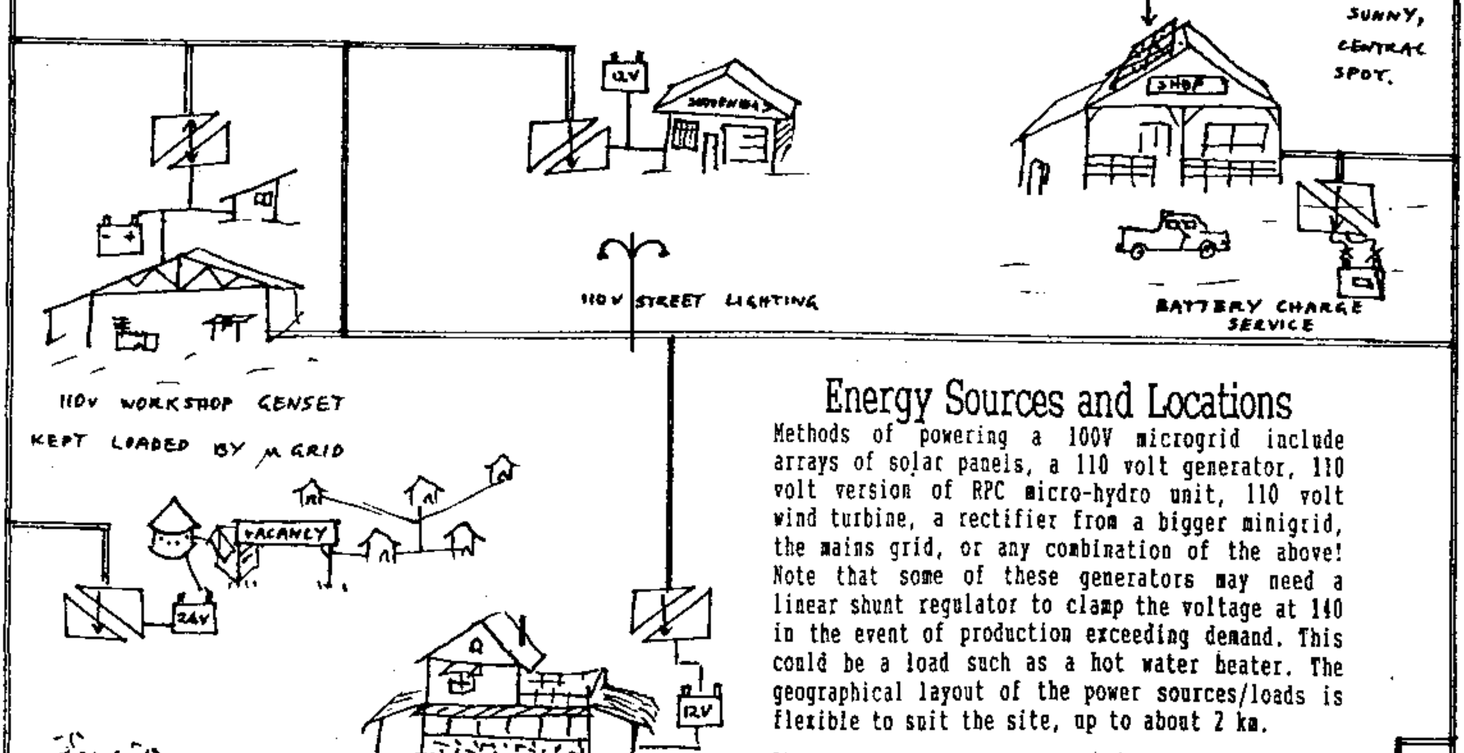
After experience of running grids on 32V AC, 60V DC, 100V DC, and 240V AC we have decided that 100V DC is the best standard because:

- it suits transistors well;
- the voltage is high enough to keep wire size reasonably small;
- it is covered by Extra Low Voltage wiring standards; and
- being DC it is far easier to feed power into the grid without worrying about phase or stability.
- Faults do not take out the whole system. They simply isolate sections of it;
- Fault finding is easy;
- Alteration is easy, and
- Expansion is easy.

A disadvantage of DC is that transformers cannot be used to simply convert voltage up and down again to transmit power long distances.

This has now changed with the advent of modern power electronics and we now have the DC/DC converter which is the equivalent of the transformer, but can actually do more because the ratio of input to output voltage is not fixed and can be continuously varying according to requirements. Behaviour under fault conditions can also be configured so that the system is self managing.





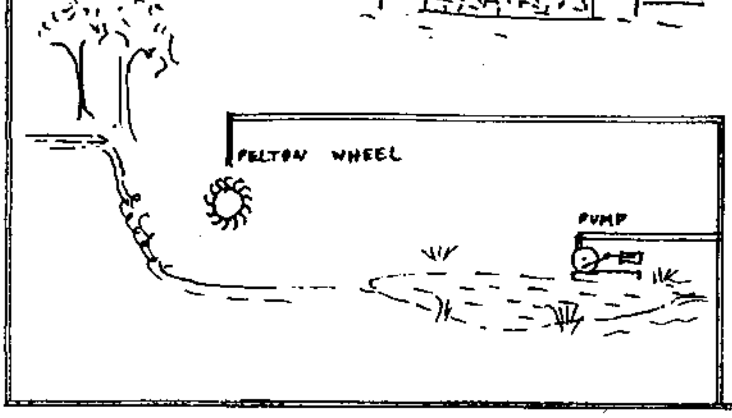
Energy Sources and Locations

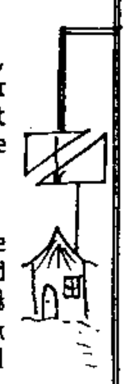
Methods of powering a 100V microgrid include arrays of solar panels, a 110 volt generator, 110 volt version of RPC micro-hydro unit, 110 volt wind turbine, a rectifier from a bigger minigrid, the mains grid, or any combination of the above! Note that some of these generators may need a linear shunt regulator to clamp the voltage at 110 in the event of production exceeding demand. This could be a load such as a hot water heater. The geographical layout of the power sources/loads is flexible to suit the site, up to about 2 km.

The loads, as well as the points of generation, can be anywhere required as long as the conductor cross-section is appropriate to the current flowing in that section of the grid. This is one of the key practical advantages of the system.

Disadvantages of AC distribution

The mains power in eastern Australia is an example of a very large AC grid. Such a grid must be sized to supply peak loads to remote areas with 5% voltage tolerance. This means it uses very thick cable, very high voltage, and lots of capital outlay.





12V or 24V?

To reduce the size and cost of your stand alone power system it pays to have lights and a number of appliances such as a radio, digital timer, laptop computer and ceiling fan that are designed to operate at a low DC voltage such as 12V or 24V. There is a larger range of 12VDC appliances than 24VDC.

Question: Should I choose a 12 volt or a 24 volt stand-alone power system?

Reply: The voltage you choose would be based primarily on one or more of six factors.

Limitations to Battery Size

1. Battery Bank Size. With solar panels as the primary energy source, it is usually recommended to have a minimum of 5 days battery storage with the battery bank still retaining a minimum of 50% charge after the end of those 5 days. The largest single battery bank available will provide 550 amp-hours over a 100 hour period to be 50% discharged at the end of that period. It is not recommended to increase storage capacity by connecting two or more battery banks side by side (in parallel). By doubling the battery voltage, the current (amps) from the loads is effectively halved, so doubling the voltage has the same effect as doubling the amp-hour storage capacity of the battery bank without having the battery bank connected in parallel.
2. Size of Inverter required to meet expected 240VAC loads. For any particular battery voltage there is a limit as to how large an inverter is available. With higher battery voltages larger inverters are available.
3. Cable size and length to carry DC loads. Doubling the voltage effectively halves the DC loads and halves the voltage drop. Because the battery voltage is doubled the percentage of the voltage drop in relation to the battery voltage is only a quarter of the percentage drop with the lower battery voltage. Unless the cable runs are exceptionally long or the power draw (amps) of the loads is exceptionally high this consideration would not be an issue.
4. Voltage of charging source. If a large wind turbine or large DC generator is incorporated into the system then the system voltage will be dictated by the availability and voltage of these charging sources.
5. Number of solar panels required. Solar regulators are generally limited to 30 amps maximum.
6. Maximum Charging Rate. The maximum charging rate for a battery bank is usually 10% of its amp-hour capacity measured at the 10 hour rate. A 600 Ah battery should therefore not be charged at more than 60 amps.

The battery voltages generally used for stand alone power systems are 12V, 24V, 48V, 110V and 240V DC.

Recommendations to Overcome Limitations

Some techniques for overcoming some of the aforementioned limitations:

1.1 Batteries may be placed in parallel with a battery isolator between the charging source and the batteries. You would then use one battery bank for some of the loads and the other battery bank for the rest of the loads. You may, for example connect all DC loads to one battery bank and inverter loads to the other.

1.2 Batteries may be placed in series with separate charging sources, regulators and loads. With this technique you can also have the advantage of being able to use both the individual and the combined voltages. You may, for instance, have 12VDC and 24VDC loads and/or use a 24V to 240VAC inverter. You may also have solar panels to charge either or both 12V banks and a 24V wind turbine to charge both banks.

1.3 Less battery storage and more reliance on generator back-up.

2. You may be able to overcome the inverter shortcoming by having several inverters or having inverters that can operate in tandem such as the larger model of InvertaPower.
3. Instead of opting for a higher voltage, an increase in cable size could also have solved the problem.
4. See recommendation 1.2 above.
5. This limitation can be overcome by having several solar arrays separately wired through separate regulators. It must be remembered that maximum charging rate of most battery banks is 10% of their amp-hour capacity (see limitation 6:).
6. This limitation can be partially overcome by adopting the recommendation 1.1 above. If one battery bank is full and the other is not, you would still have to throttle down the charging rate to 10% of the capacity of the one battery bank.

Both the battery voltage and the Amp-Hour storage capacity of your battery bank should be appropriate to your needs. Avoid placing many small batteries in parallel. Battery cells connected in series is OK.

SUMMARY

The Basics of Stand-Alone Power

Power input from Solar Panels and other power sources need to be more than the power consumption at the worst time of year.

Partial shading of solar panels will significantly reduce their output.

More or bigger battery storage does not necessarily mean a better or more reliable power system. The opposite may be the case. The battery storage needs to relate to the size of your charging source. In the case of a solar-electric power system it should not be more than 100Ah of storage for each 50W - 60W Solar Panel. You should not ever take the lead-acid battery bank beyond 50% discharge and you should have some reserve for a rainy day or two (usually at least 5 days of power reserve).

Keep the battery bank in a well ventilated position not too far from where the power is used (it can usually be further from the charging source) and OUT OF REACH OF CHILDREN! Battery acid can cause serious injury.

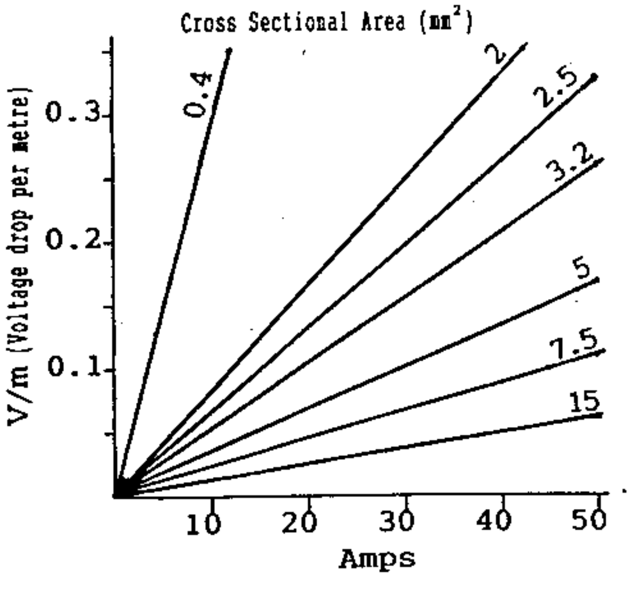
The power supplied by a battery bank presents just as much of a potential fire hazard as a 240V grid connection. Ensure that all cabling is properly fused.

Do not make multiple connections onto the battery. You should connect all house wiring to a set of links and have only one set of heavy duty (eg 15mm) cables connecting these links to the battery bank. You may also connect the inverter and 240 volt battery charger directly to the battery bank.

The wires to the battery bank should be soldered into corrosion resistant lugs of a suitable size and bolted onto the battery terminals. Use a marine battery terminal if necessary (see p47).

Smear (petroleum jelly (eg vaseline) or grease on battery terminals before bolting on connections.

Voltage Drop. Battery based systems providing very low voltage (eg 12V) DC power are very susceptible to unacceptable voltage drop due to undersized wire and poor connections. A voltage drop of 1 volt or more is considered too much. Check all connections and upgrade the wire if necessary. Following is a voltage drop graph:



Unless you have a power system that is very much larger than your basic needs; it is recommended to have some form of back-up. This back-up may be in the form of a petrol or diesel generator and a large battery charger (at least 20A charge). Other options include a steam engine or being prepared to revert to kerosene or candles in case the state of charge of the battery goes too low.

If you have lots of 240V appliances of less than 350W and a few of more than 1000W (eg washing machine, iron, vacuum cleaner, circular saw) it may be a good idea to operate a petrol or diesel generator for the large appliances a few hours per week (with a battery charger also connected) and a small inverter for the small appliances. A large inverter may cost as much as a petrol generator. The generator would provide back-up power when the state of charge of the battery bank is low (eg after days or weeks of overcast weather). The smaller inverter would mean better power efficiency with the smaller appliances and the convenience of being able to turn them on and off with a switch.

Inverters and Generators produce a dangerous voltage. Do not use the same kind of plugs and sockets for extra low voltage DC (eg 12V or 24V) and 240V AC as this could cause a lethal accident.

It is recommended to have an amp meter to measure the charge into the battery bank or at least to know that it is still working. It is also recommended to have a volt meter to see at a glance how your system is behaving (with a 12V system it should be between 12V and 15V).

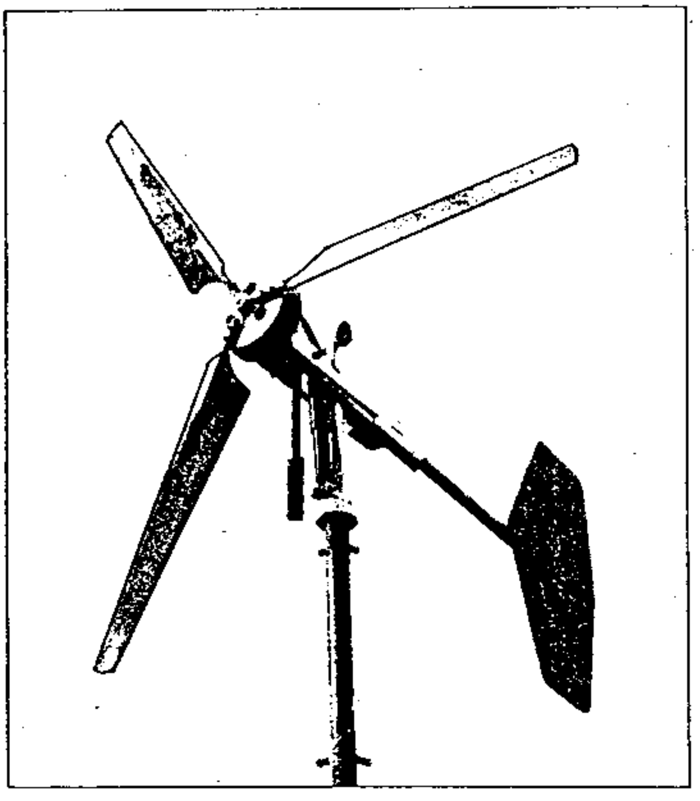
It is recommended to have a regulator to prevent your battery from overcharging. A switching or shunt regulator is suitable for solar panels, but with most other charging sources a shunt regulator is recommended.

12V DC appliances are nearly always more energy efficient than their 240V counterparts. Operating all the lighting (fluorescent lights with dedicated inverters built into them) and as many as possible of your appliances from the battery voltage can mean a significant saving in power and the overall cost of a stand-alone power system. 12V DC fridges and pumps use between one quarter and one fifth of the power of 240V AC pumps and fridges powered through an inverter. A 12V Laptop Computer consumes between one fifth and one tenth of the power of a 240V Desktop Computer. A 12V Colour TV consumes about half the power of an equivalent 240V TV. A portable battery operated cassette deck usually draws about one fifth of an amp and a battery operated radio usually draws about one tenth of an amp if connected to a 12V source. The same kind of appliances in 240V may draw many amps from the battery bank (via an inverter).

Generate heat by other means (eg burning some kind of fuel) because it would be very expensive in order to have a large enough solar electric system to generate very much heat with electricity.

Fluorescent lights with a built-in dedicated inverter use between one sixth and one seventh of the power of an incandescent light of the same brightness (measured in lumens).

Wind Generators



The Power of Wind

Air moving at 40 Kph through one square metre theoretically has an energy content of 400 watts if it were stopped. The power extracted from the wind cannot exceed 59% of the power in the wind. 37% is the practical limit.

Wind Variations

Whereas with Solar or Hydro-electric power the batteries receive some recharge on a daily basis, at times there may not be any significant wind for charging the batteries for weeks on end. Winds are notoriously variable, and ***most installations must include an auxiliary generating system*** to recharge the batteries in low wind periods.

Winds are the result of differences between temperatures in the atmosphere, the turning motion of the planet and the varied topography of the earth's surface. The winds that are significant to a discussion of wind-plants may be divided into two categories: the planetary winds and local winds.

Planetary Winds

Planetary wind systems, normally called prevailing winds, are those great moving air masses that dominate whole areas and show constant directional characteristics, varying only with the movement of high or low pressure systems and with the seasons of the year.

In many locations these are the dominant winds, and good wind-plant sites are those that take maximum advantage of prevailing winds. Included among such sites are exposed hill tops; shore lines facing the prevailing winds; an open plain or plateau; the floor of an open valley running parallel to the prevailing winds, or the windward side of a gently sloping hill.

Local Winds

Local winds, by contrast, are caused by temperature differences created by local topographic conditions. Land-sea breezes, for example, will blow from the land towards the sea by night, simply because land temperatures are more subject to change than the great mass of the ocean.

Mountain and valley breezes are caused by the same local effects. On a warm sunny day winds may rise strongly off the floor of a valley and up the slopes of adjacent hills. The best site for a wind-plant is one where dominant planetary wind patterns are reinforced by local winds.

Site Evaluation

In order to know if a wind powered system is either feasible or cost competitive you need to have some facts and figures. Because of the site preparation and work that needs to go into a wind tower, you need to have done all of your home-work before you take the big step. Unless you have a particularly good wind site, it is recommended that either you have a hybrid system (ie wind and solar or wind and diesel) or no wind system at all.

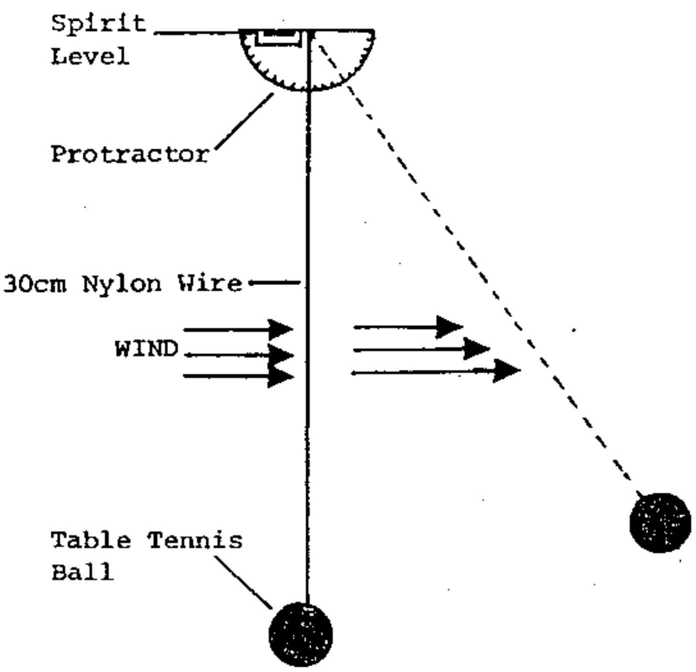
In order to find out if you have a good wind site you may need to spend a few hundred dollars on an anemometer to give you the data. If you want to save yourself this cost or do a feasibility study on whether even the cost of the anemometer is worth it, then the following information may be of use to you.

A Simple Evaluation Method

A very simple method of measuring the strength of the wind can be carried out as follows. You need 30 cm of thin fishing line (or similar), a table tennis ball, a protractor, and a spirit level. You fix the ball to the end of the fishing line, and fix the other end of the fishing line to the centre of the protractor. When the wind blows the ball moves and the angle of the line changes. By reading the angle on the protractor and using the chart below you can estimate the strength of the wind. The spirit level is used to make sure that the top edge of the protractor is horizontal.

Measuring the Wind

Angle	m/s	Kph	Description
90°	0.0	0.0	Calm; smoke rises vertically
85°	2.6	9.3	Light breeze; smoke drifts; leaves rustle
80°	3.6	13.1	Gentle breeze; leaves and twigs in motion
75°	4.5	16.2	Moderate breeze; raises dust and loose paper
70°	5.3	18.9	Fresh breeze; small trees sway
65°	5.9	21.4	Fresh to strong breeze; crested waves form on inland waters
60°	6.6	23.9	Strong breeze; large branches in motion
55°	7.3	26.4	Strong breeze; difficulty with umbrellas
50°	8.0	28.9	Near gale; whole trees in motion
45°	8.7	31.4	Near gale; impedes progress
40°	9.5	34.2	Gale; Breaks twigs off trees
35°	10.4	37.4	Gale;
30°	11.5	41.3	Strong gale; slight structural damage
25°	12.8	45.9	Strong gale; tiles lift off roof
20°	14.4	52.0	Storm; seldom experience inland
			Anything beyond this is a violent storm or a hurricane accompanied by widespread damage

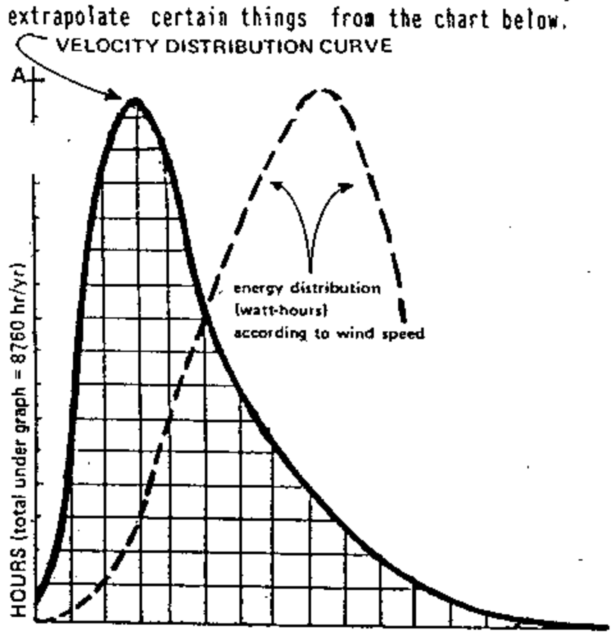


Getting Results

Sampling the wind variations over a period of a few weeks will not necessarily give an indication of the yearly wind cycle. Since most people don't want to twiddle their thumbs for a year while taking readings, then approximate schemes must be found. A good start (after talking to the locals) is to establish a correlation between your site and the nearest meteorological station that you can obtain wind-speed data for. A period of one month is hopefully a sufficient time to take measurements over to establish this correlation.

Does the average of the figures acquired at the weather bureau equal the ten year average for that month? If it is not even close you may end up with particularly optimistic or pessimistic results. You may either keep collecting data until you find a good, consecutive period that, at the weather bureau station, averages out to close to the ten year average for that month, or adjust the figures for that month from the weather bureau and your site by the same amount to be a little closer to the ten year average.

Now find what factor you should multiply the selected weather bureau data by to get the yearly average. Multiply the average at your site by this number as well to get a close approximation of the yearly average. To ensure that a wind generator produces a worthwhile output, an annual average windspeed in excess of about 15 kph is desirable. Knowing the average wind speed, we can immediately extrapolate certain things from the chart below.



The chart is called the velocity distribution curve. It is a similar shape for all wind power locations, and gives a good indication of the amount of time the wind blows at a particular wind speed.

Having established the relationship between wind-speeds at the two sites, you can also use the meteorological bureau figures to estimate the seasonal variations at your site. This information can give you an idea of the seasonal variations of the output of the wind-plant.

Wind Velocity and Rotor Diameter

The power from the wind increases as a function of the cube (third power) of the wind velocity. Increasing the diameter of the rotor increases the power output as a square function. Power from the wind can be derived by the formula:

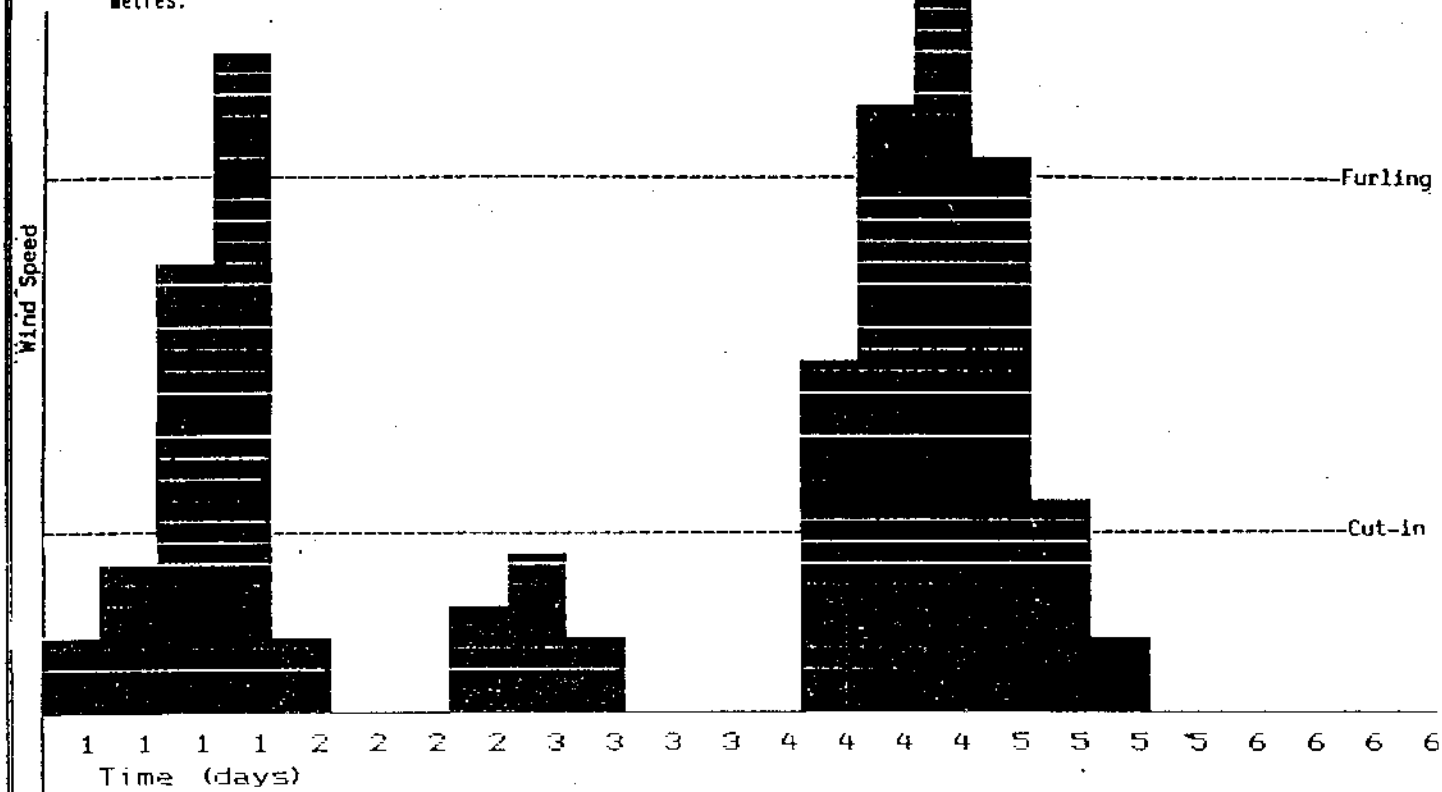
$$W = 14.3\ PAV^3$$

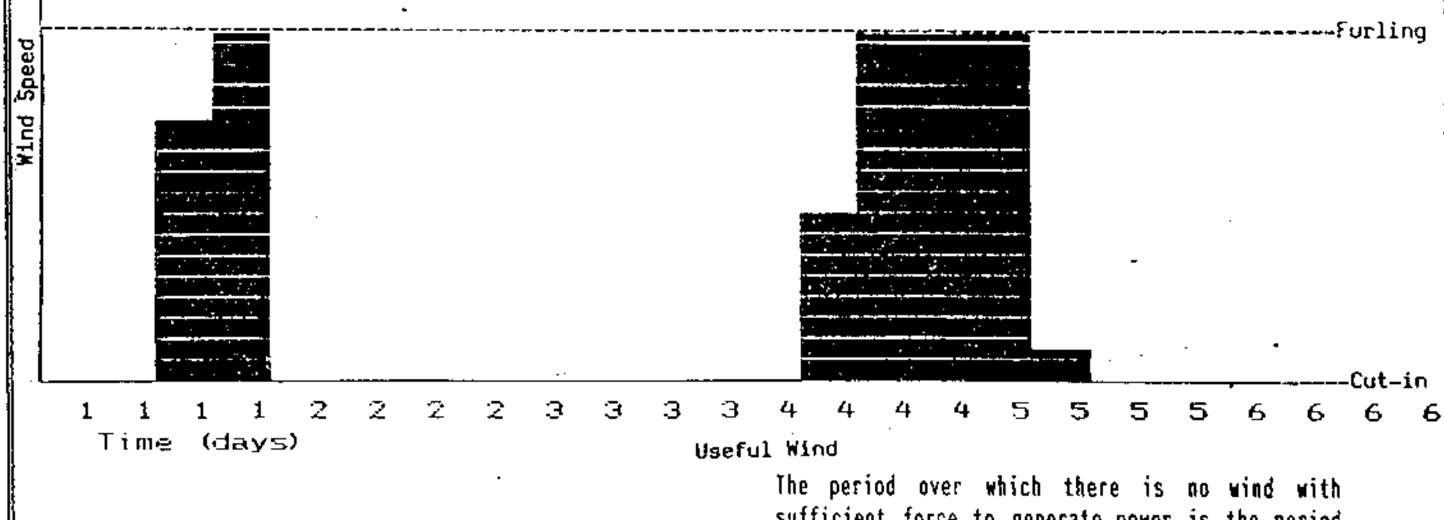
where:

- P = air density (2.3×10^{-3})
- A = area swept by turbine blades (sq. metres) = radius (m) squared x 3.1416 (π)
- V = wind velocity in kph

The air density figure is for sea level. Power from a 30 kph wind will be 10% less at an elevation of 1,000 metres, 25% less at 3,000 metres.

The following graph was generated from a wind survey, taking 4 wind samples per day (sunrise, midday, sunset, 10 pm) over 6 days. This graph was then modified, using the characteristics of the wind generator considered for the site. The information used was the cut-in wind speed and the furling wind speed. The cut-in wind speed is the amount of wind required before the generator starts producing power. The furling wind speed is the amount of wind required to produce the maximum power that the generator is capable of; any wind in excess of this will not generate more than this maximum.





Useful Wind

The period over which there is no wind with sufficient force to generate power is the period when either the battery storage or another energy source must provide the required power.

Choosing the Correct Tower Height

The two most important considerations in planning the tower height for a wind turbine are avoidance of turbulent air flow produced near ground level by the 'roughness' of the terrain over which the wind flows, and avoidance of excessive ground drag which lowers wind velocity near the ground and severely restricts the performance of a wind turbine.

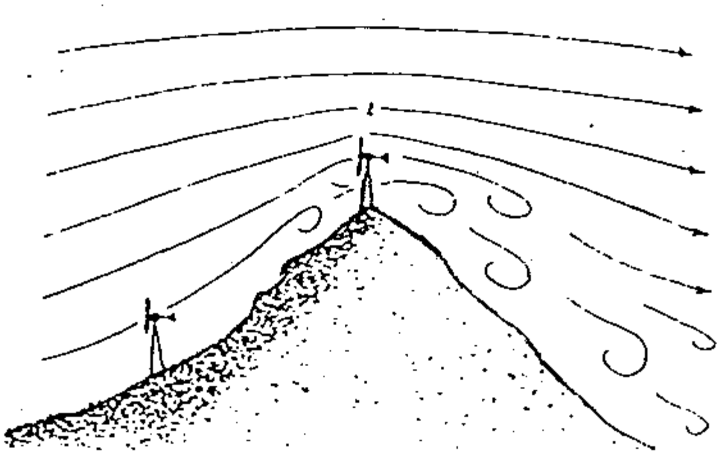
Turbulence

A wind turbine must never be located such that it is subject to excessively turbulent air flow. Light turbulence will decrease performance since a turbine cannot react to rapid changes in wind direction, while heavy turbulence may reduce expected equipment life or result in wind turbine failure. You can detect turbulence by streaming a long ribbon from a guyed pole or mast to see if it streams easily in high winds from various directions. The mast should be roughly as high as you would envisage the wind tower to be.

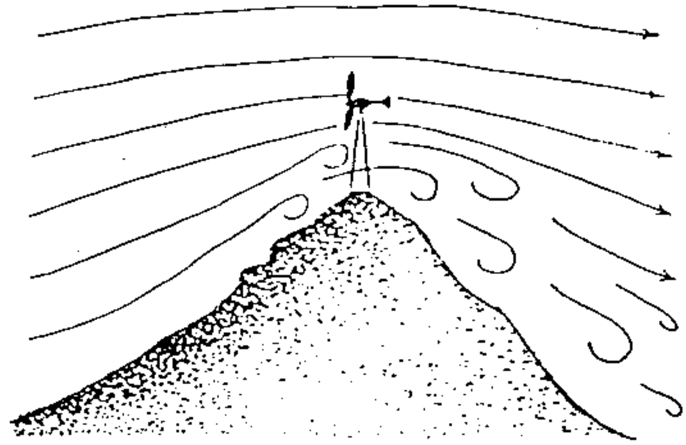
Turbulence may be avoided by following a few basic rules:

1. If possible, the wind turbine should be mounted on a cleared site free from minor obstructions such as trees and buildings for at least 100 m in all directions and free from any major obstructions such as abrupt land forms for at least 200m. Even over clear ground, however, the minimum recommended tower height is 12 metres.
2. If it is not possible to avoid obstructions as above, tower height should be increased to a value of approximately 9 metres greater than the height of obstructions within 100 metres.
3. A good "rule of thumb" is to locate the turbine at a minimum height of three times that of the tallest upwind barrier.

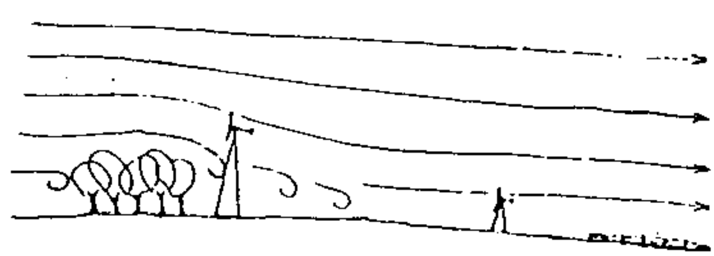
The drawings which follow illustrate some of the do's and don'ts of siting and tower height with respect to turbulence.



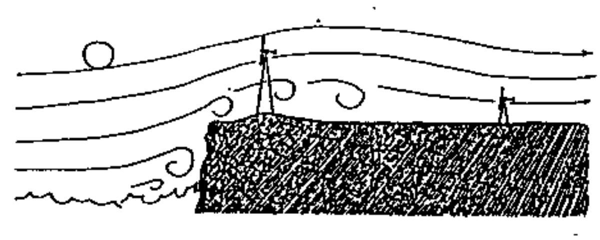
High, rough hilltops may produce substantial turbulence in the windstream. Tower number 1 is located on the relatively gentle smooth lower slope and will be clear of most turbulence when the windstream is left to right in the drawing, but will be in the wind shadow of the hill when the wind reverses. Tower number 2 is too low and while exposed to high velocity winds is also located in severe turbulence which may destroy the wind generator.



This drawing illustrates the proper location and height for a tower on this hill. It is fully exposed to the high velocity winds and is above the region of harmful turbulence.



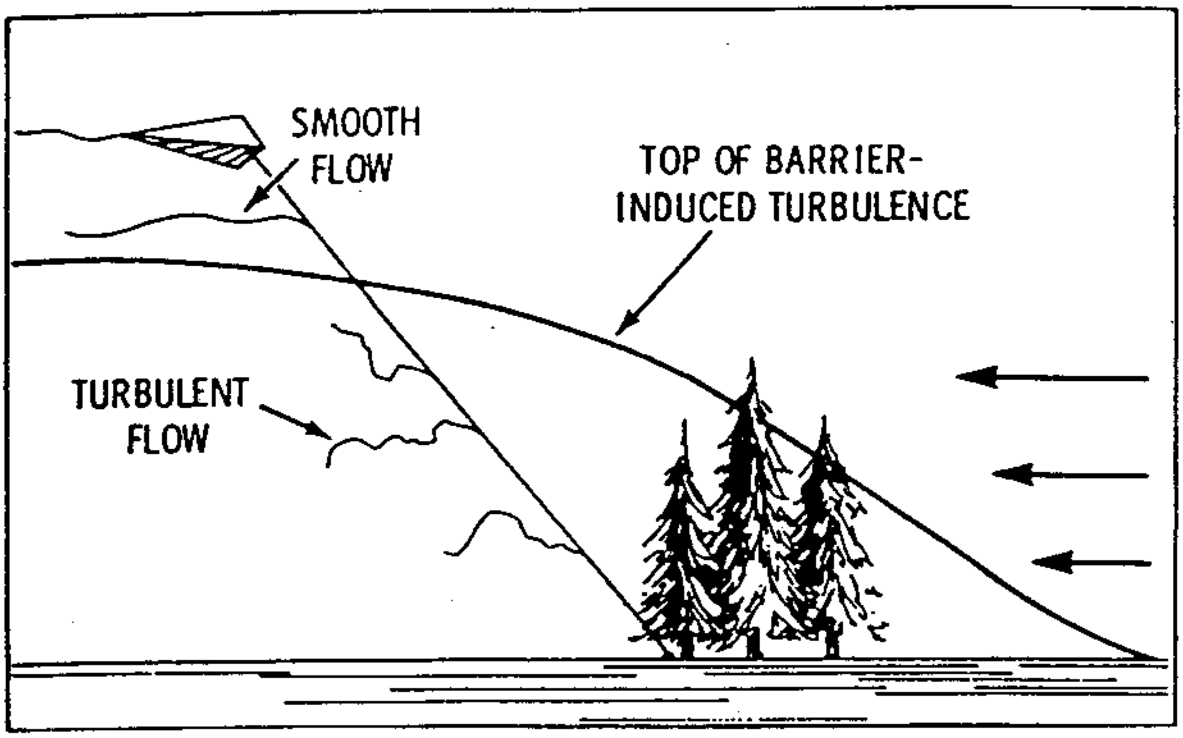
The grove of trees in this example will produce turbulence. A higher tower close to the trees places the wind generator above the turbulence. A shorter tower is safe if placed far enough away from the trees.



Severe turbulence may be created by the sea cliff in this example. As above, a higher tower will be required near the cliff while a shorter tower will be safe if placed at a great enough distance from the cliff.

The Kite Test

A sturdy kite with a strong string and crepe paper ribbons or strips can give a good indication of air turbulance.



Wind turbulance can be visualized by studying a small river with many disturbances such as bolders. The wind follows the same flow pattern.

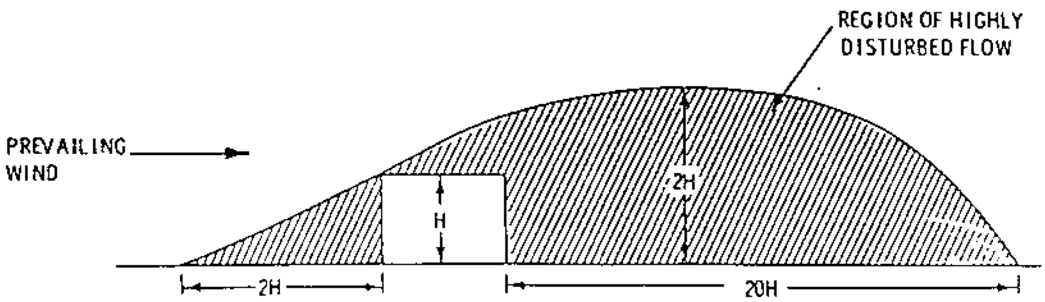


FIGURE 1. Zone of Disturbed Flow Over a Small Building (Frost and Nowak, 1977; Van Eimern et al., 1964)

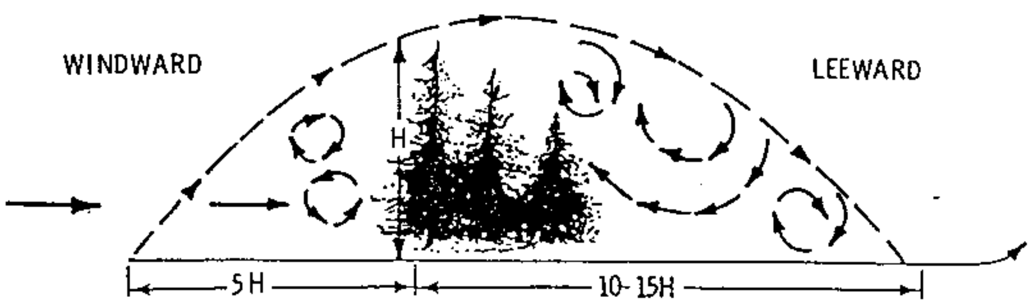
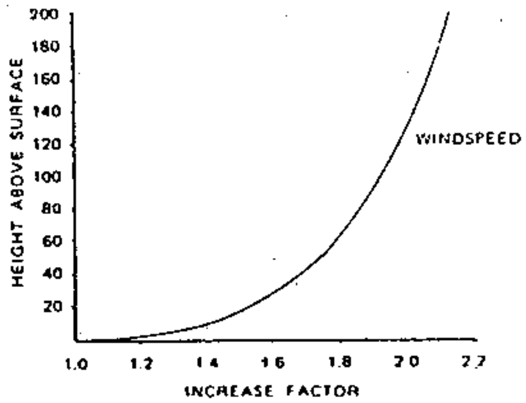


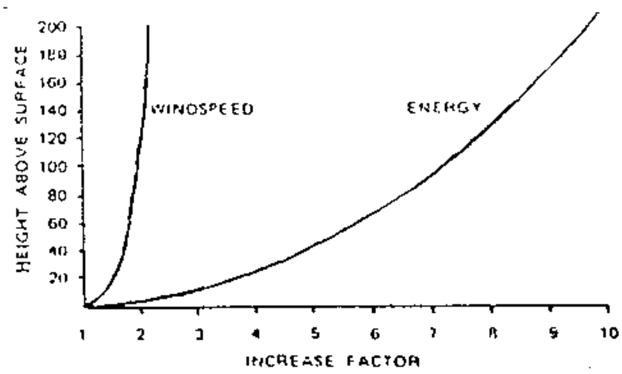
FIGURE 2. Airflow Near a Shelterbelt (Van Eimern et al., 1964)

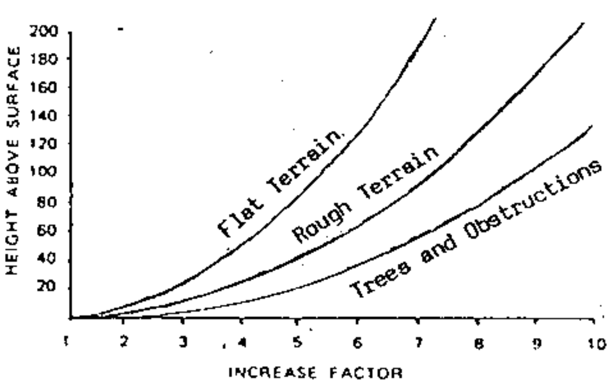
Ground Drag

The avoidance of ground drag will increase performance dramatically. Up to a considerable height, the least expensive way to increase your power output from a wind turbine is to increase tower height. A generally recognized 'rule of thumb' is that wind speed increases as the 1/7th power of the height above ground. The following curve illustrates this theoretical increase in wind speed with increasing height above ground:



As an example in the use of this curve, if a windspeed of 15 kph were measured at 2 metres above the surface, the windspeed at 40 metres height can be predicted from the curve. At 2 metres height, the 1/7th power is 1.104, and at 40 metres it is 1.694. Dividing 15 kph by 1.104 and then multiplying by 1.694 yields the predicted windspeed of 23 kph at 40 metres. However, the energy in the wind, and therefore wind generator output, is proportional to the cube of the windspeed. So, in this example, by increasing the tower height from 2 metres to 40 metres increases the wind-turbine output by 3.6 times.





Tower Construction

The smaller wind generators (up to 100 watts) can be mounted on a sturdy pipe with guy wires. The larger machines would need a more substantial tower in which case it is advisable to contract a person experienced in the erection of wind generator towers. Check with the local Council to see if there are any regulations concerning the erection of poles or towers, especially if you live in an urban area.

Safety

Do not place a wind-plant in a turbulent area, to avoid severe stress on wind turbine components and tower.

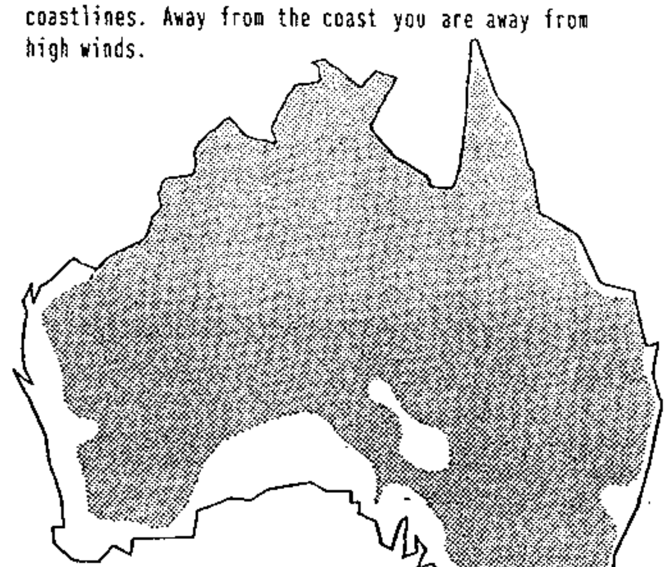
All the controls, necessary safety (governing and feathering) devices to protect against excessively high wind speeds, instruction manual etc should come with the machine that you purchase. What may not be provided is a suitable regulator to prevent your battery from being overcharged.

Noise

Wind generators may produce a fair amount of noise, particularly in high winds. Beyond a couple of hundred metres, the noise of the wind itself generally drowns out the noise of the wind generator.

Australian Wind Assessment

High wind areas are often associated with coastlines. Away from the coast you are away from high winds.



Annual average windspeeds of 5m/s or less at 20m height.

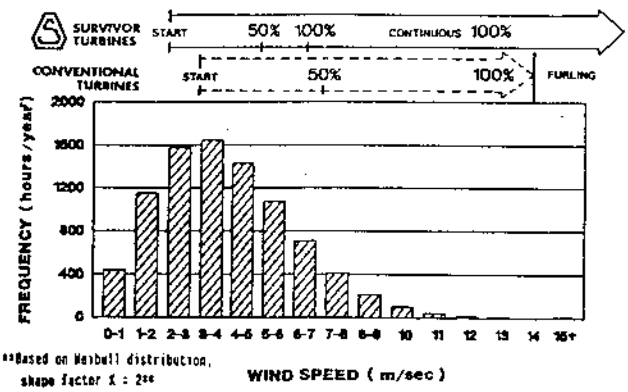
* Based on annual average wind speed map from P.R. Nadebaum "Wind Power Assessment" (Dept of Primary Industries and Energy, Canberra 1989)

SURVIVOR

The Survivor wind turbine was developed to solve the problems that have plagued wind machines from the beginning. ***Over 90% of the land mass of the world has "low to moderate" wind speed,*** below 5 m/sec average. A typical wind speed profile for Australia shows that the wind averages between 2 and 6 m/sec.

TYPICAL WINDSPEED PROFILE:

At 4.0 m/sec windspeed, showing turbine performance

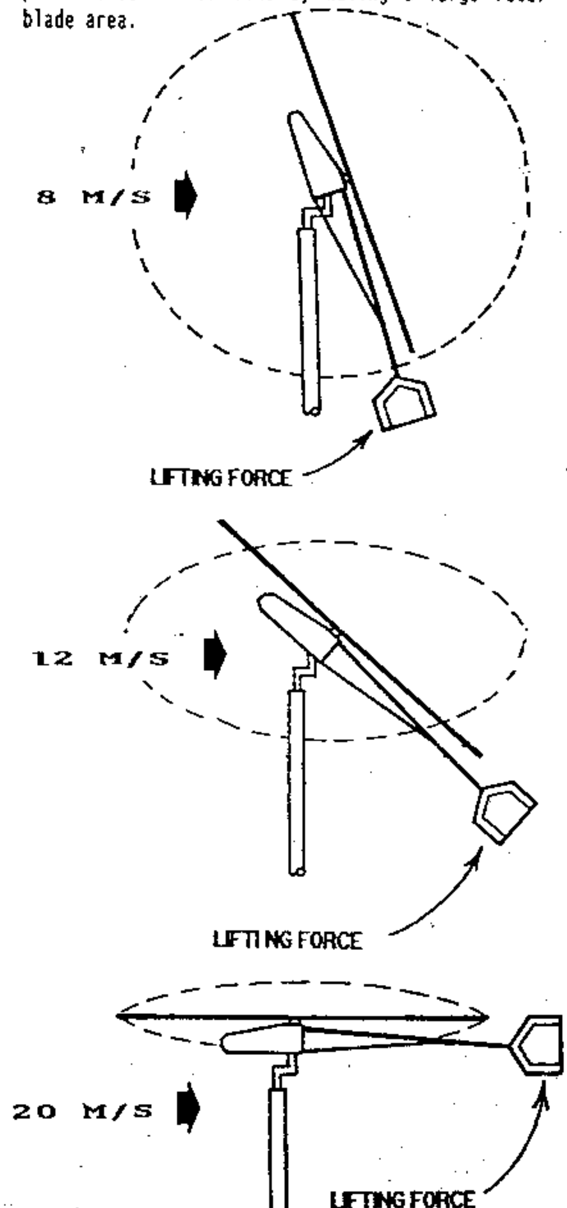


SURVIVOR TURBINES WILL DELIVER:

- **Produce dependable power nearly anywhere** because they use a much larger rotor area to capture the energy of the wind.
- **Produces power in 2.5 m/s winds.**
- Reach 100% of rated power before conventional turbines achieve 50%.
- **As wind velocity increases, rotor spins at constant speed** without sophisticated braking equipment.
- **Operate at 100% power in storm conditions** where others furl or stop.
- **Storm damage is virtually eliminated** by design. The variable rotor area adjusts to meet the wind speed which greatly reduces the stress of high wind.
- **Maintenance is nearly nil** as there are no mechanical governors or braking systems to fail. In short there is **No Scheduled Maintenance.** A little oil or grease every five years is usually adequate.
- **Costs are greatly reduced,** due to the simplicity of the design. Equipment payback is usually less than 3 years.
- **Simple to install.** We recommend the Survivor "Tilt" tower as it is easy to install and you don't need a crane. All work is done at ground level.
- **Easy to operate.** Power generated is DC and is easily stored in a battery bank.
- **Guaranteed performance.** The Survivor new technology solves the problems of the past and is manufactured in Australia, assuring you of quality and service.

Ingenious Design

The Survivor wind turbine is a very clever design of down-wind variable axis turbine which allows the force of the wind to lift the rotors up into a more and more horizontal plane as the strength of the wind increases. This effectively decreases the wind-swept area and allows the turbine to continue producing a maximum output whilst decreasing the wind force on the components thereby decreasing stress on both the turbine and the tower. The Survivor was designed to acheive optimum performance in low wind by having a large rotor blade area.



Designed to survive the storm in style
And keep powering all the while.

SURVIVOR WIND TURBINE

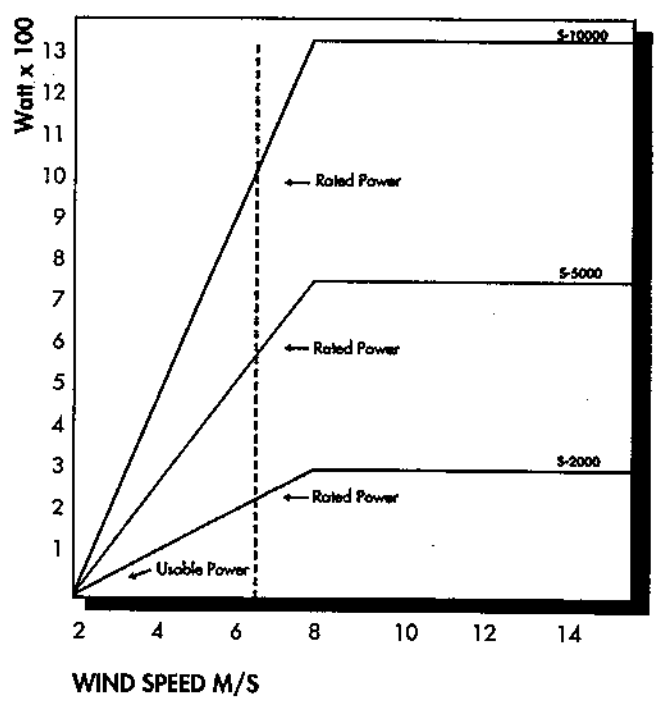
The Survivor wind turbine is a very clever design of down-wind variable axis turbine which allows the force of the wind to lift the rotors up into a more and more horizontal plane as the strength of the wind increases. This effectively decreases the wind-swept area and allows the turbine to continue producing at maximum output whilst decreasing the wind force on the components. This decreases stress on both the turbine and the tower. The Survivor was designed to achieve optimum performance in low wind by having a large rotor blade area. Produces usable power in 3 m/s winds. As wind velocity increases, rotor spins at constant speed without sophisticated braking equipment.

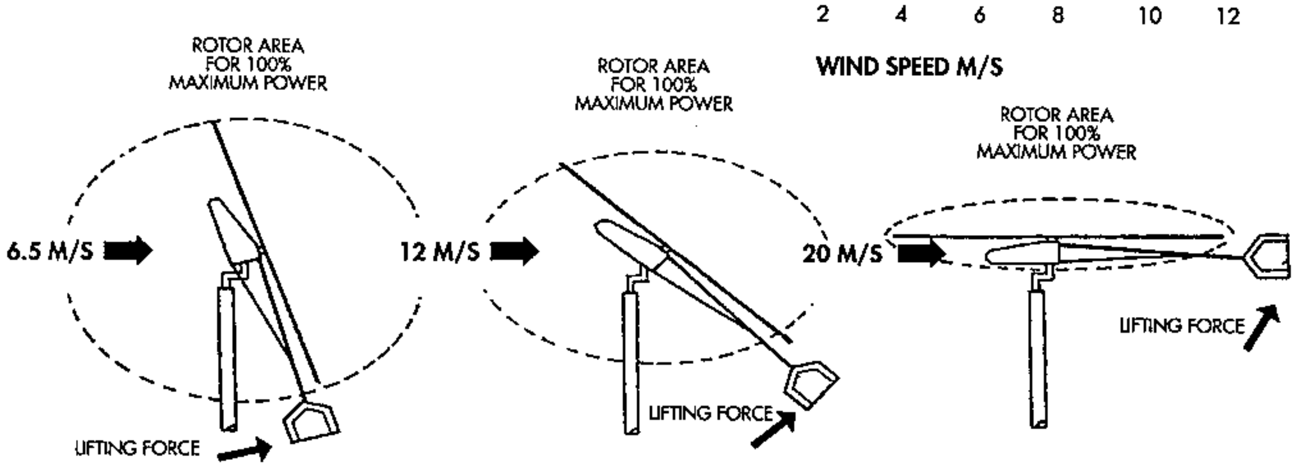
Designed to survive the storm in style and keep powering all the while.

SPECIFICATIONS	S-2000	2-5000	S-10000
Usable Power (3 m/s)...........	10 watt	35 watt	85 watt
Rated Power (6.5 m/s)	200 watt	500 watt	1000 watt
Max Output (8 m/s)..............	340 watt	800 watt	1400 watt
Type	V.R.A.	V.R.A.	V.R.A.
Rotor Diam	2.4 m	3.5 m	5.1 m
Rotor Material........................	F/glass	F/glass	F/glass
RPM Variable	150-450	60-350	60-150
Speed Control........................	V.R.A.	V.R.A.	V.R.A.
Gearbox Increase	3 : 1	2.78 : 1	6 : 1
Total Weight..........................	39 kg	60 kg	186 kg
Cyclone Rated	Yes	Yes	Yes
Alternator..............................	Field	P.M.	Field
....	Excited	(Sealed)	Excited
Output	12-24V DC	24-48V DC	24V DC

VOLTAGE REGULATIION Useful Load Diversion
Solid state load controller
with voltage protection.
Details subject to change without notice.

OUTPUT CURVE





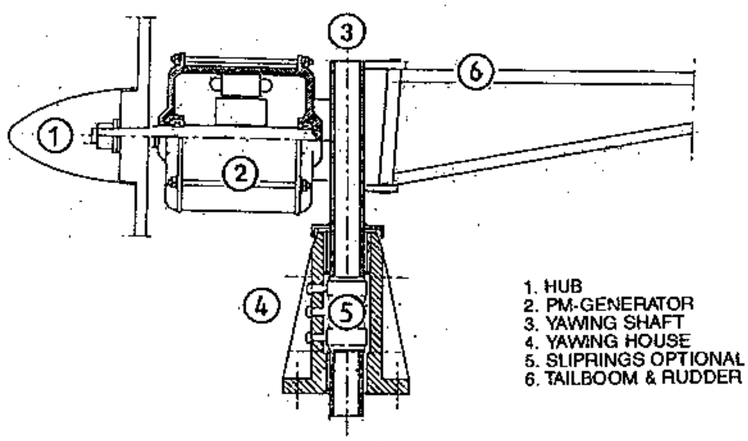
SURVIVOR WIND TURBINES

RESHAPE

Shaping a sustainable future
Renewable Energy Small Heat and Power Equipment Pty Ltd
ACN 010610661

70 Cullen Street
Nimbin NSW 2480 Australia,
Telephone (61) 66 891 088
Fax (61) 66 891 109
Electronic Mail DIALCOM 6007: BLM001

DATA
600 W Ole WINDFLOWER



TYPE: Front runner with tail
Heavy duty quality

ROTORDIAMETER: 2.0 m

BLADES: 6 massive GRP blades
Top rotor efficiency
Cp= 0.47 measured

REVOLOUTIONS: 0-700 rpm

STRUCTURE: Stainless steel. Seewater resistant aluminium

GENERATOR: 600 W synchronous
Brushless • Permanent magnets
10 poles • 3 phases • 24 V AC
(optional voltages) • IP 55 protection

CHARGING CONTROLLER:
35 A rectifier • Voltage control • Dumpload
Brake switch

CUT-IN WINDSPEED: 3 m/s

BRAKE: Electrical brake

TOWER: Optional

SECURITY:
Yaws out of the wind at high windspeeds and by ruanways

POWER CURVE:
3 m/s: 10 W • 5 m/s: 60 W • 7 m/s: 170 W
9 m/s: 370 W • 12 m/s: 600 W

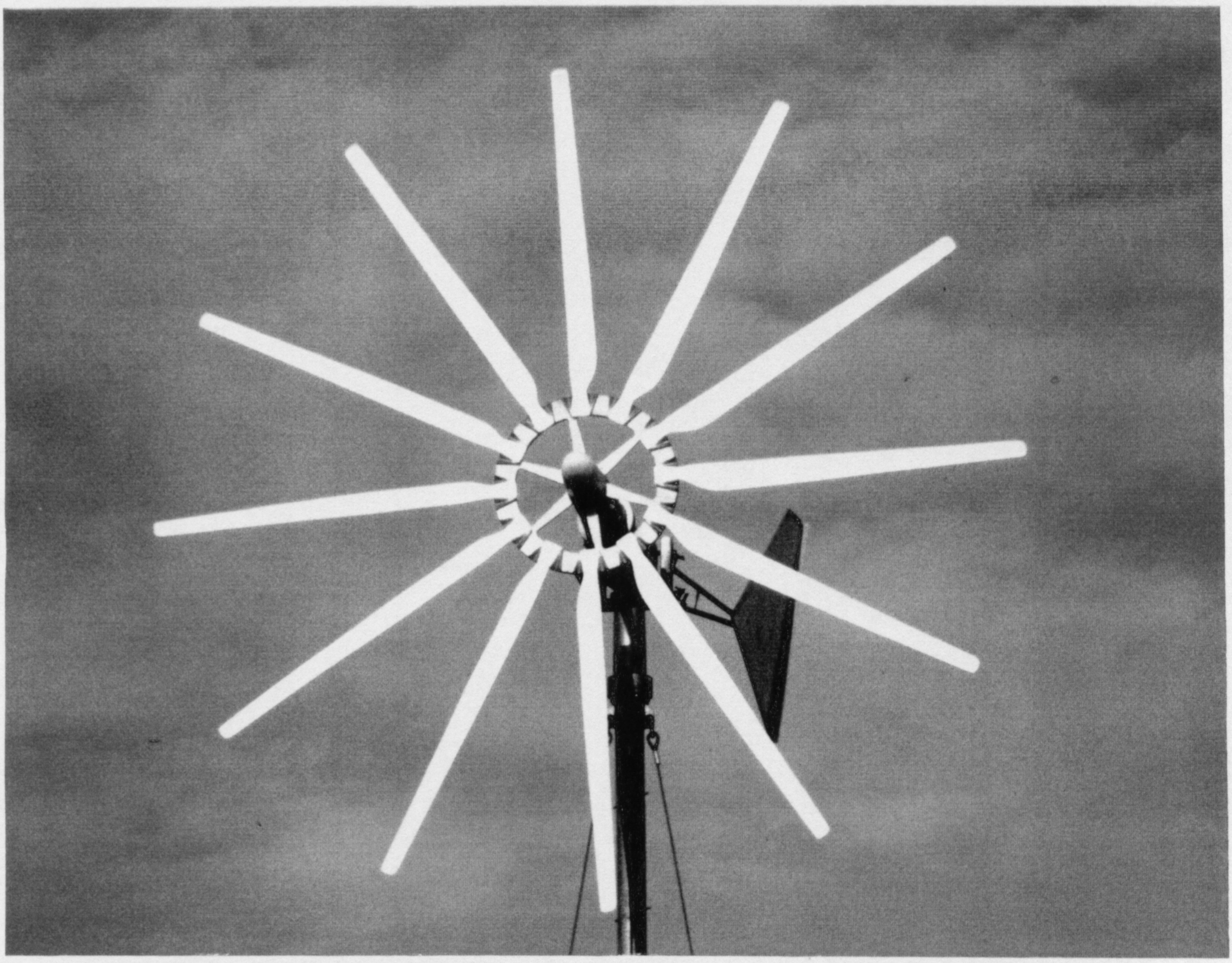
ENERGY PRODUCTION:
(Northern European conditions) by average windspeed of
4m/s: 875 kWh/year
5m/s: 1.175 kWh/year
6m/s: 1.550 kWh/year
7m/s: 2.125 kWh/year

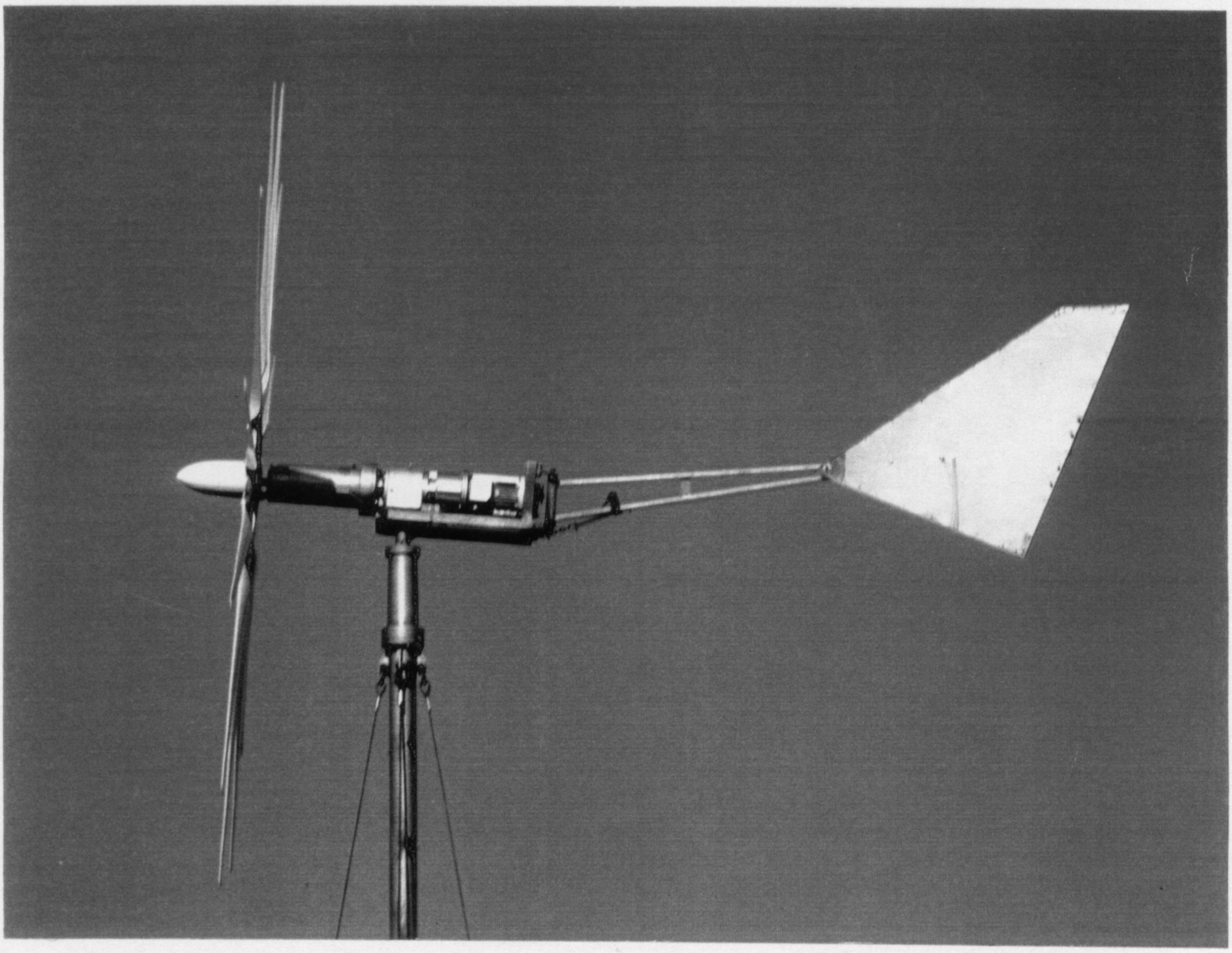
WEIGHT: 35 Kg Nacelle

WARRANTY: 2 years
against defects in workmanship

SALES VOLUME: 20 turbines (May/95)

Specifications subject to change without notice

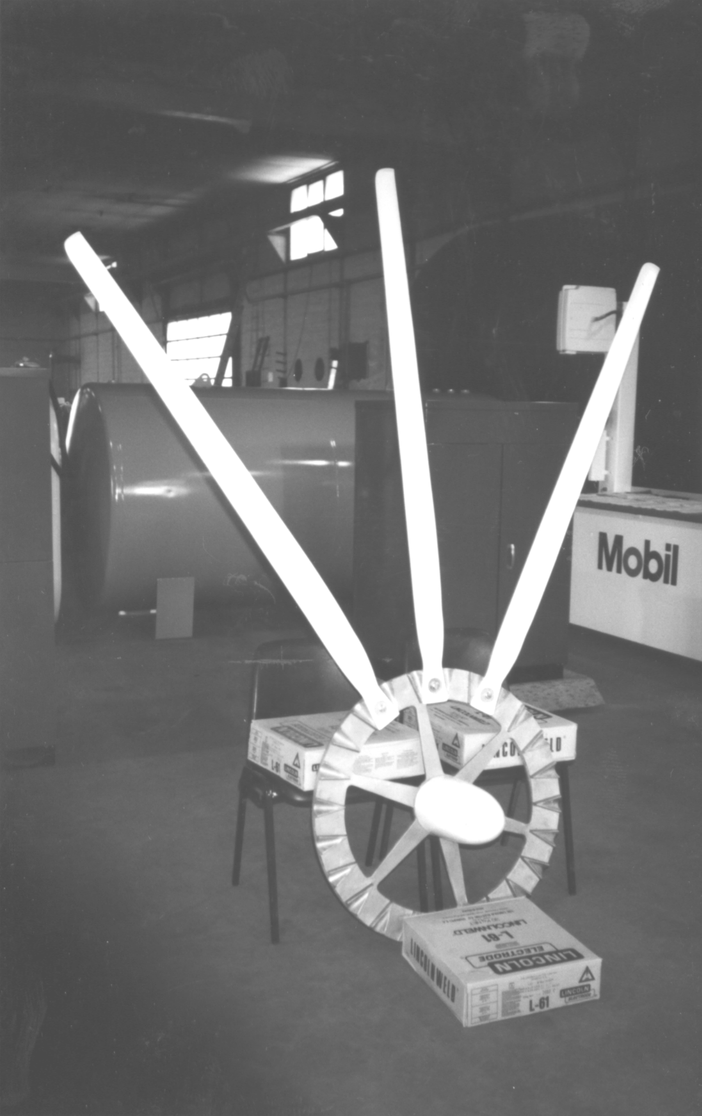


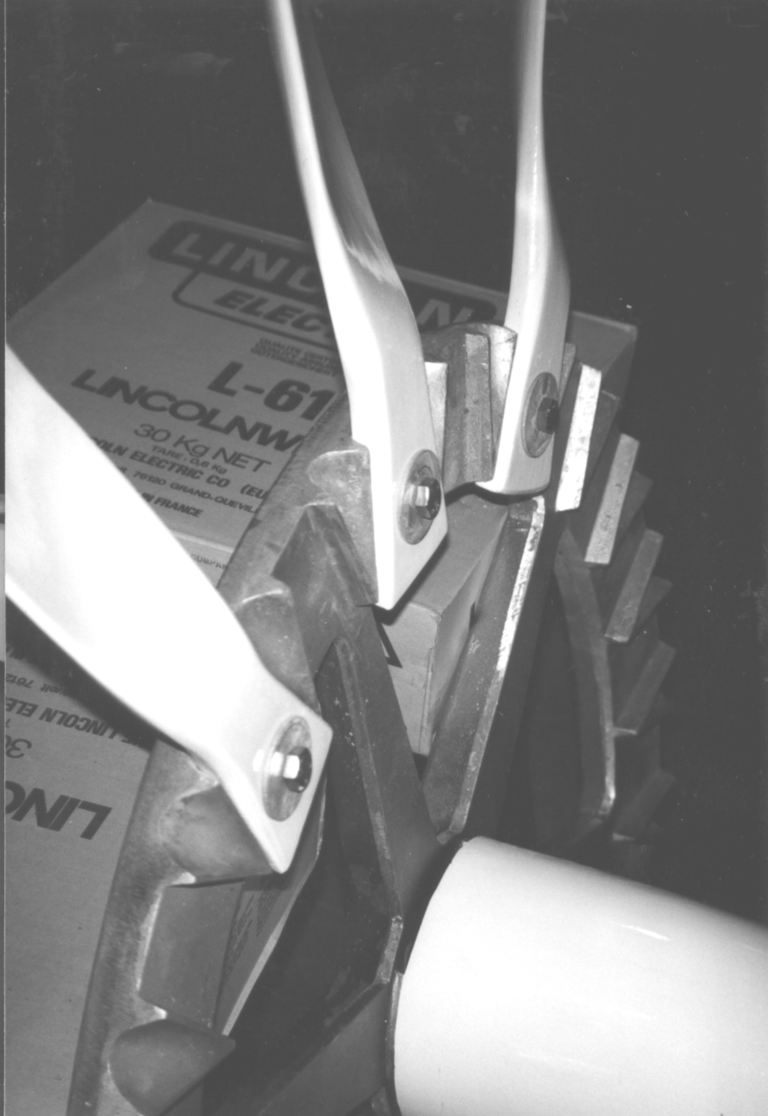


Architect CLAUS NYBROE • Stenbankevej 6 • 5771 Stenstrup • Denmark • Tel/Fax (+45) 62 26 15 55

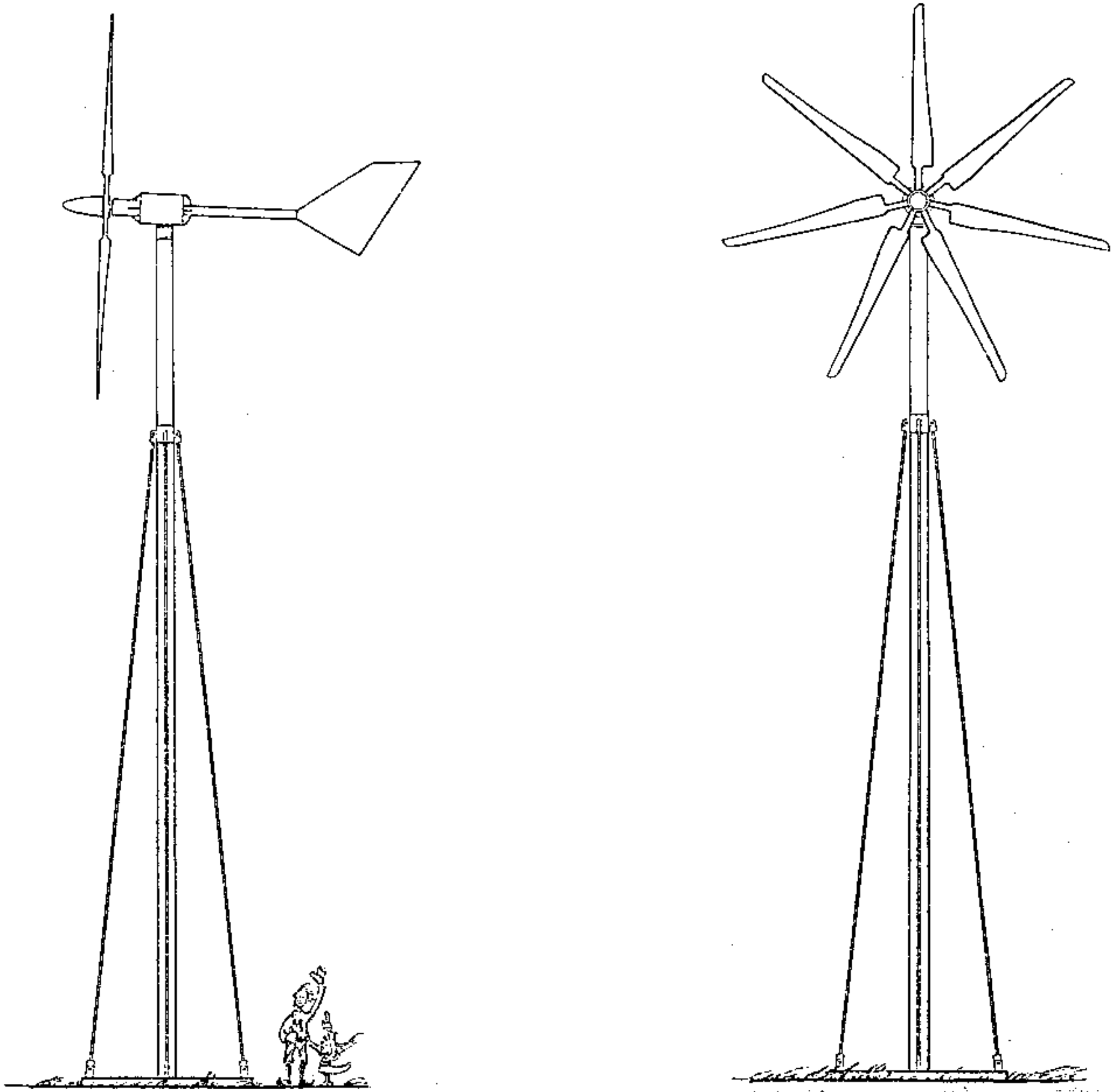
4 kW
Rasmus WINDFLOWER

The new generation • For independent families and groups
Officially approved: The Test Station for Wind Turbines
RISØ National Laboratories, Denmark, 1994


Mobil

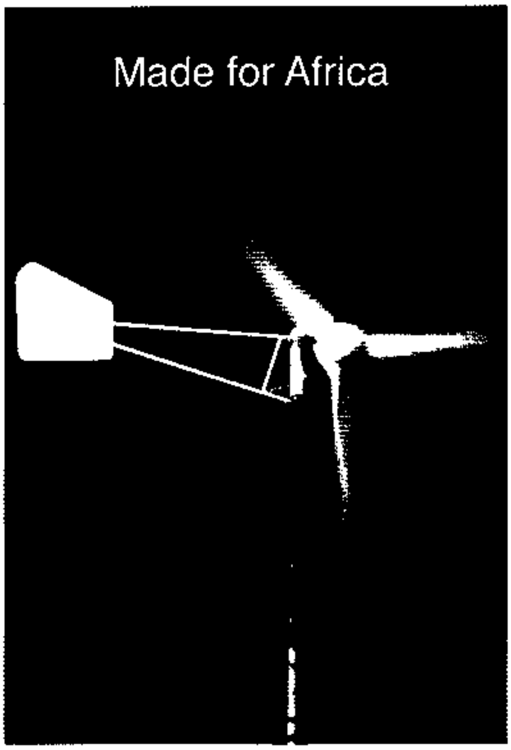

L-61
30 Kg NET


bil
L-61
LINCOLN
ELECTRODE



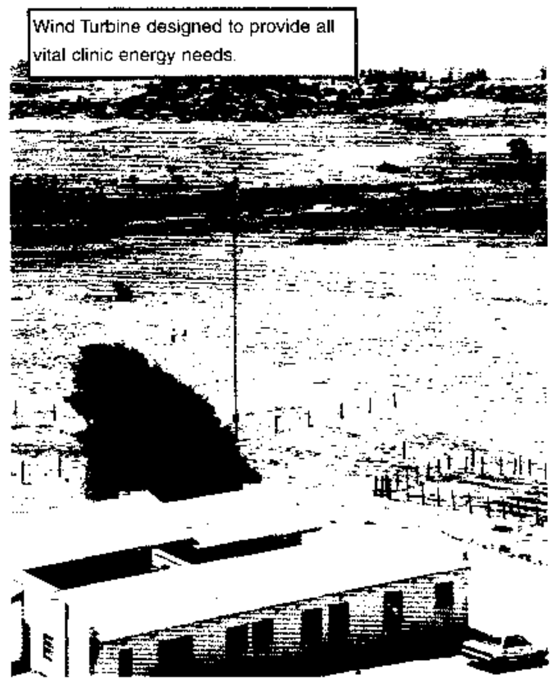
11kW Freja WiNDFLOWER	
Rotordiameter: 7 m	Tårnhøjde: 15 m
DK-årsproduktion:	32.400 kWh i ruhedsklasse 0.5 26.700 kWh i ruhedsklasse 1.0 20.400 kWh i ruhedsklasse 2.0
WINDFLOWER I/S:	Hannebjergvej 24, Langkastrup 8900 Randers, Danmark Tlf 86 49 50 33/Fax 86 49 49 56

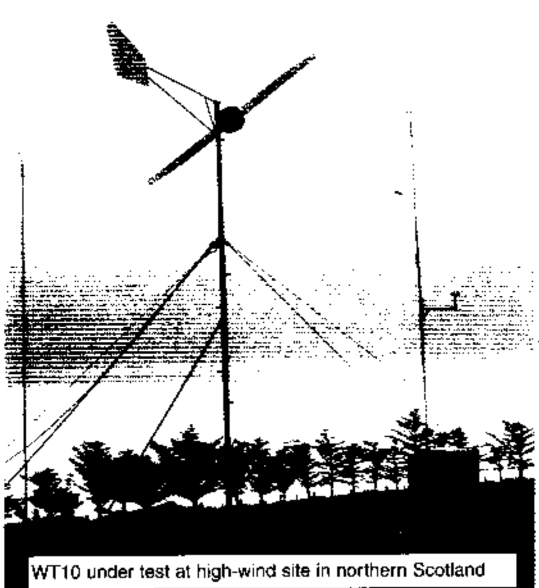
Powertronics
WT10
Wind Turbine

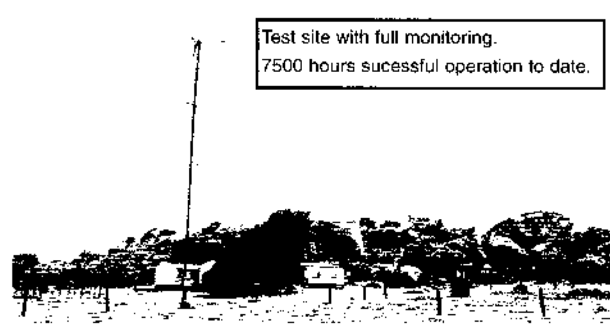


Affordable power from the wind, competitive with multi-panel PV systems in the African wind and sun climate.

Technical Specification
Rotor Diameter: 3.6m
Blade Material: GRP
Speed Regulation: Fixed Pitch
Gravity Yaw tail boom
(Passive mechanism for high reliability)
Generator: Permanent Magnet
3-Phase AC. Rated rpm: 190
Specially manufactured for duty. Brushless.
Gearing: None
Cut-in Wind: 2m/sec
Rated wind: 12m/sec
Design Windspeed: 30m/sec
Rated Output: 1000W
Max Output: 1500W
Annual Production (Rayleigh)
3m/sec 500kWh 42,000Ah@12V
4m/sec 1,800kWh 150,000Ah@12V
7m/sec 3,000kWh 250,000Ah@12V


Wind Turbine designed to provide all vital clinic energy needs.

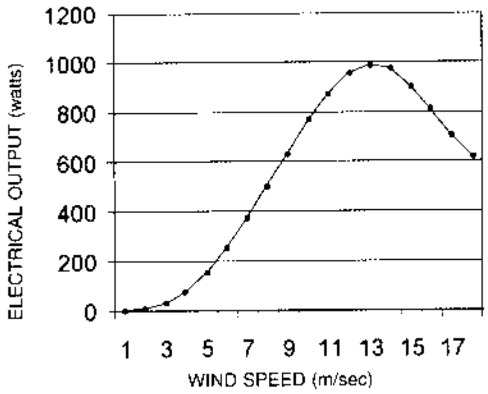

WT10 under test at high-wind site in northern Scotland


Test site with full monitoring.
7500 hours sucessful operation to date.

After an intensive testing and development programme, which included gale-storm testing in the UK, the Powertronics WT10 is avaliable now to meet African remote power needs.

The wind turbine is designed to be competetive in typical African wind conditions wherever there is a need for multi-PV panel installations.

POWERTRONICS
WT10



By incorporating a specially developed low loss generator utilising high Telsa ceramic permanent magnets and "spiral" windings the turbine needs only the lightest of winds to produce energy.

A 3 phase AC output can provide battery charging at 12V, 24V or higher if required. No voltage limitations as with PV.

The controller supplied enables full battery charging with surplus energy avaliable for other uses; heating, pumping etc.

Matched inverters enable the supply of "mains-equivalent" 240V AC current up to 8kVA.

Parts always avaliable. No import delays.

Are you in a fairly windy area?
Is your site open to the winds and not surrounded by high trees?
Have you a power need that will be too expensive with PV?

Then the combination of the latest in wind turbine technology with local manufacturing and full project support capability makes wind a viable option.

The turbine has no gearbox and the minimum of moving parts, all of which are generously over-engineered. It has the reliability of PV, with the advantage of working through the night...

The nature of the wind is that the power produced can increase by up to eight times for a mere doubling of windspeed.

The Power Curve shows output from the wind turbine into a 12V battery bank. In storm winds the "Furlsafe" gravity yaw system, which utilises a minimum of moving parts, allows the turbine rotor to gently feather away from destructive gusts.

The standard turbine is avaliable on a free-standing 12m high mast that hinges at ground level and can be easily raised or lowered by a 4x4 winch.

The rotor blades are fixed, the aerofoil aerodynamics ensuring optimum performance in the lightest of breezes.

When comparing wind turbine power curves, look carefully at the windspeed required for power. The Powertronics WT10 turbine has been built in Africa for best use of the everyday windspeeds of inland Africa. Even on higher windspeed sites it can out-perform other foreign turbines which rely on less frequent, strong winds.

Only once per year maintenance. No gearbox. Low RPM means low noise and low wear.

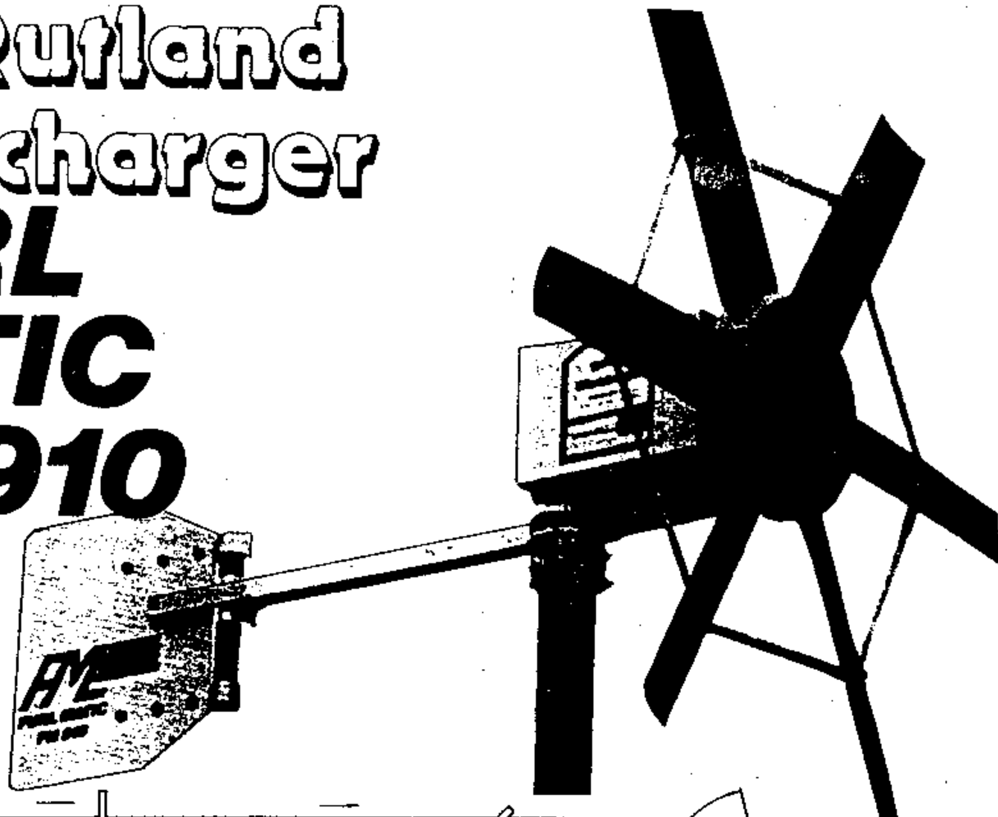
*Clinic supply
*Safari Camps
*Schools
*Telecoms
*Village Mini-Grids
*Refrigeration
*Replace Diesel gensets

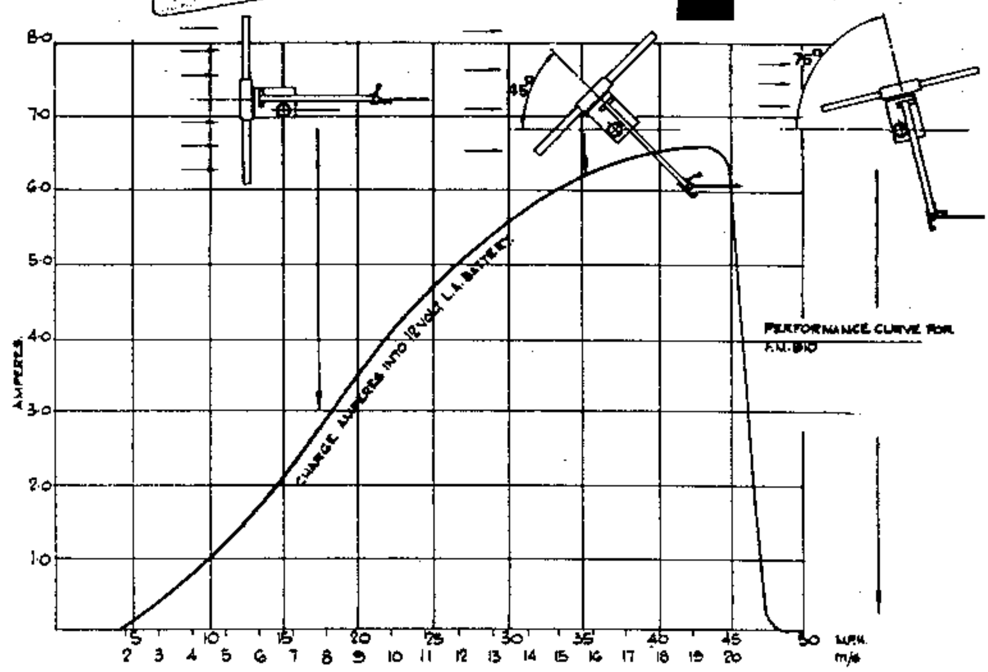
Simple yet sophisticated.
Rugged for Africa.

The 12m tower lifts the wind turbine into the winds above our heads, where the rugged reliability of the Powertronics WT10 provides an economically attractive source of power.

Powertronics
Box 4533 Harare Zimbabwe
Tel. 263-4-771581/4
Fax. 263-4-771580
email- power@harare.iafrica.com
16 Telford Road
Graniteside
Harare

The Rutland Windcharger
FURL MATIC FM 910





The Rutland *Furlmatic*-FM 910

The unique yet simple design of windshaft housing and tail fin assembly enables the unit to "furl" out of the wind at speeds in excess of approx. 65 to 70 kph, (at which speed the 12 volt version will charge at approx. 6.5 amps). This immediately reduces the tip speed of the blades and renders the whole unit safe in potentially dangerous gale force conditions. As soon as the windspeed drops below this level the tail fin assembly containing a torsion spring will return to its normal working position and turn the unit back into the wind to continue charging your battery.

The Rutland Standard Windcharger WG 910

- Commences charging at 6.5 kph (1.8 m/s) wind.
- 12 volt 50 watt output at 35 kph (9.83 m/s) wind.
- Thermostat controlled choke protects against continuous high charge due to strong winds.
- Easily erected on standard 50 mm (2") water pipe.
- Very little maintenance required (check brushes once every three years).

The Rutland Windchargers

Things that Work!
tested by *Home Power*

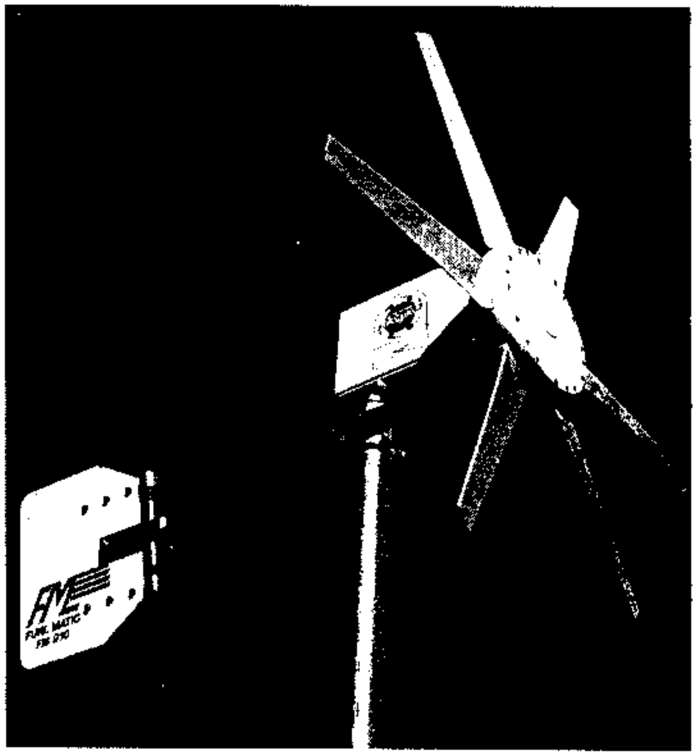
Tested by Mick Sagrillo

Home Power's world of wind generators is host to the introduction of a new breed; the micros. These pint-sized versions of their larger cousins offer sippers of electricity (as opposed to us guzzlers) the same flexibility as incorporating a PV panel or two into one's system. The looming questions are, "Do they work? And will they last?"

To answer these questions, I decided it was time to find a niche for one of the wee ones. I contacted Peter Sanguinetti of Trillium Windmills in Ontario, the North American importer of the Rutland Windchargers. The Rutland Windchargers are manufactured by Marlec Engineering Co. Ltd., in England. Peter arranged for the shipment of a Furlmatic 910, including the import paperwork.

The wind generator arrived via UPS from Canada in two heavy-duty UPS-proof cardboard boxes. One box contained the generator, hardware, controller and instruction manual, while the other contained the blades and tail boom. The instruction manual is brief and to the point. It adequately addresses siting and safety measures for a micro-genny, assembly procedure, possible tower and mounting configurations, installation, plus tools and materials needed. There is even a section detailing a system design integrating PVs. Finally, consideration is given to inspection, maintenance and troubleshooting.

The Furlmatic 910 is Marlec's deluxe micro–genny. It sports a 36 inch six-bladed rotor. Lots of blades means easy start-up in low winds. The blades are made of fiberglass reinforced nylon in an injection mold process. My guess is that, short of vandalism, there is not much



Above: The Marlec Furlmatic 910

that will prevent these blades from going 30 years or so.

The design of the generator itself looks somewhat bulky. The Furlmatic 910 reminds me of a bread box with blades and a tail. That criticism, however, is the only one I can come up with on the unit. The fit and finish of all of the component parts is impressive. All metal is either hot-dipped galvanized or protected with a polyurethane epoxy paint. All fasteners are stainless steel. The unit is advertised as "marine-grade", and I found no components that would not withstand the harshest of environments.

The Marlec specifies a standard 2 inch water pipe for a tower. We constructed a 42 foot guyed tilt-up tower for this and similar wind generators. (Note: this is the maximum height advisable using 2 inch water pipe.) The Furlmatic has a simple clamping system to attach it to the pipe. Wires run through the tower pipe and out the bottom. The Furlmatic alternator is a permanent magnet device with a bridge rectifier attached in its housing. Output is rectified to DC before leaving the unit.

Once the DC enters your power shed, it first travels through the optional Rutland shunt regulator before charging your battery. The shunt regulator monitors battery voltage and dissipates excess power as heat. Rather than purchase Marlec's optional metering, we added our own volt meter and amp meter to monitor output.

The Rutland Windchargers are available in 12 and 24 volt configurations. We chose a 12 VDC system to float various batteries in the shop. The Furlmatic 910 did its job very well. It begins producing perceptible power in a very light wind, about 5 mph (see power curve). Several times we saw it peak at 8.5 amps before governing.

The Furlmatic 910 governs by side-facing the rotor out of the wind. The axis of rotation of the blades is slightly offset from the tower. As wind speed increases, the offset rotor furls itself around the tower and out of the wind.

One pleasant surprises is that this wind generator is remarkably quiet, regardless of the wind speed or load. Loaded or unloaded, the micro-genny's blades emitted a barely audible whirring sound. Under heavy load, we did notice that the unit gave off a resonant humming sound. While I am not positive about this, I believe that the sound actually comes from the electrical harmonic resonance interfacing with our guyed tower configuration. (Note: all electrical generating equipment utilizing rotating parts develops this characteristic hum.)

At one point, we connected the Furlmatic to three hydrogen electrolyzers, a nominal 6 volt load. Rather than stall the blades as I expected, the Furlmatic merrily churned out hydrogen!

Conclusions

At 36 pounds, the Furlmatic 910 is hefty for its output. While it only comes with a one year parts and labor warranty, the Furlmatic 910 is definitely overbuilt and designed to last for decades. I am impressed with the quality materials and construction as well as the performance of this micro-genny. With 20,000 of these little guys sold worldwide over the past 15 years. Marlec Engineering has the design down pat.

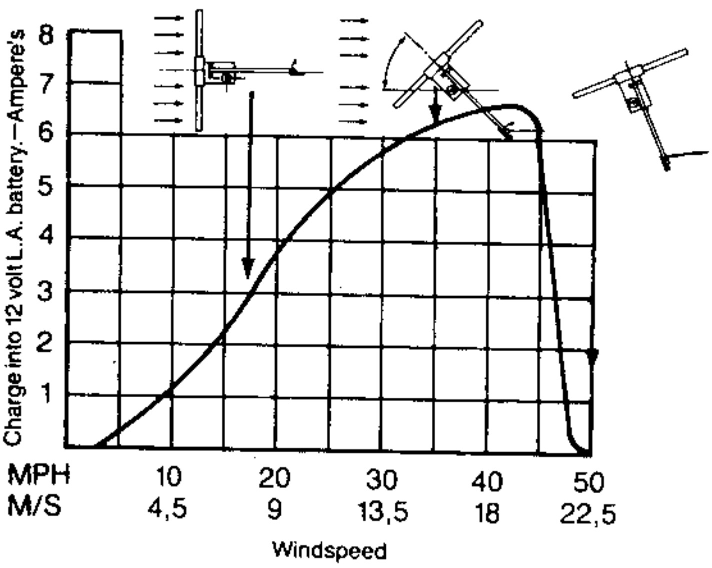
Quality, however, comes at a price. The Furlmatic 910 lists at $850 + UPS. For anyone on a small energy budget looking to hybridize their PV system by incorporating wind, I strongly suggest scoping out the Rutland Windchargers.

Access

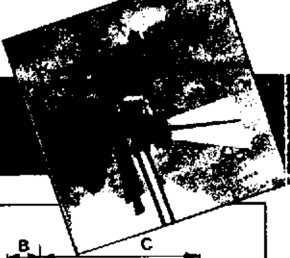
Tested by Mick Sagrillo, Lake Michigan Wind & Sun, E 3971 Bluebird Rd, Forestville, WI 54213 • 414-837-2267

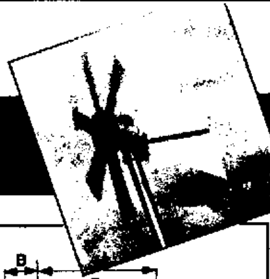
Manufactured by Marlec Engineering Co. Ltd., Rutland House, Trevithech Rd, Corby, Northants, NN17 1XY, UK. Phone (0536) 201558, Fax (0536) 400211

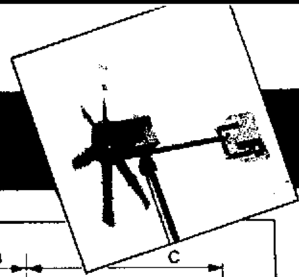
Rutland Windchargers are imported to North America by Trillium Windmills, RR2, Orillia, Ontario, Canada, L3V 6H2 • 705 326-6513 • Fax 705 325-9104

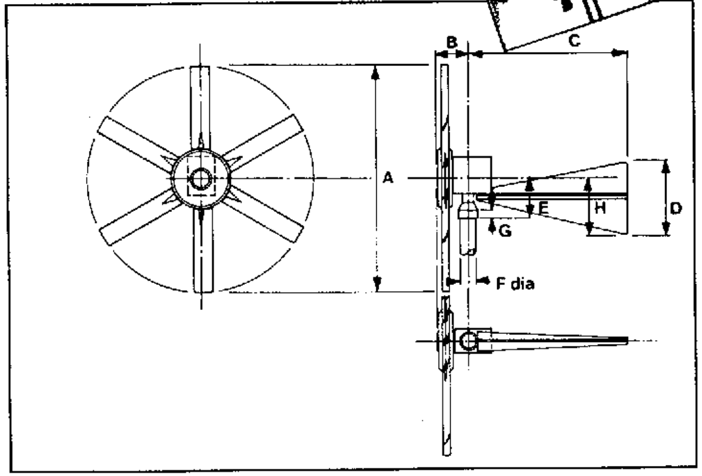


Above: The Furlmatic's output current versus windspeed curve.









TECHNICAL SPECIFICATION: WG910 'STANDARD'

Nett Weight 13.25kg (29.15lbs)

Dimensions	A	B	C	D	E	F	G	H
Inches	35.8	4.7	24.9	11.8	6.8	2.4	1.2	9.1
mm	910	120	632	300	173	61	30	232

Shipping Specification (2 cartons)

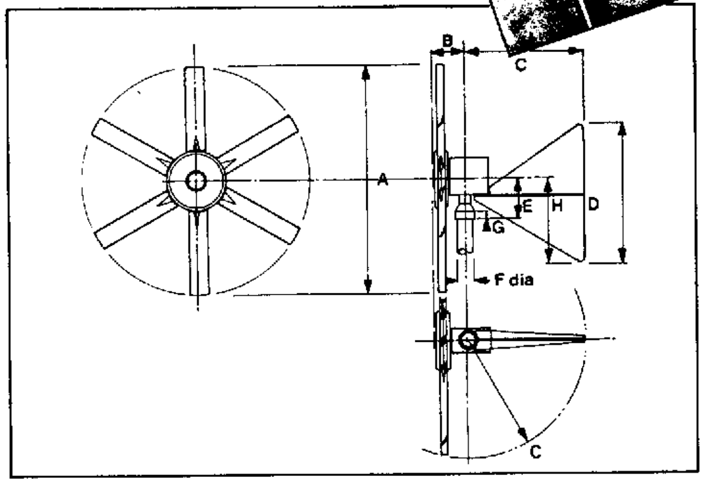
1 Carton	32 × 26 × 25cm	Weight 11.4kg (25.08lbs)
1 Carton	62 × 31 × 9.5cm	Weight 3.4kg (7.48lbs)

The *WG910 STANDARD* is the most widely used model in the Rutland Windcharger range being suitable for most applications.

- It has all the design features shown in the Technical Specification and is designed to be mounted on standard 2″ water pipe (61mm OD) thus alleviating the need for special towers. (FM910 also).
- Like all 3 models it is available in 12 or 24V versions.

Extras for STANDARD, MARINE and FURLMATIC include:

- 12′ Portable Mounting Pole in 4′ sections (Except Marine)
- Shunt Regulator to prevent battery overcharging
- Thorn 2D low voltage fluorescent lights
- Ammeters and Voltmeters
- Tie bar kit for blades (supplied with Furlmatic)



TECHNICAL SPECIFICATION: WG910 'MARINE'

Nett Weight 13.7kg (30.14lbs)

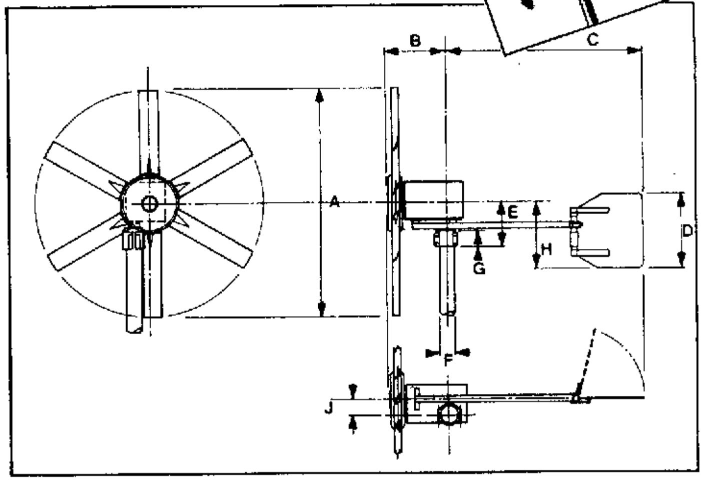
Dimensions	A	B	C	D	E	F	G	H
Inches	35.8	4.7	18.38	23.00	6.8	2.5	1.2	14.25
mm	910	120	470	584	173	64	30	362

Shipping Specification (2 cartons)

1 Carton	32 × 26 × 25cm	Weight 11.4kg (25.08lbs)
1 Carton	49 × 61 × 10cm	Weight 4.1kg (9.02lbs)

The *WG910 MARINE* retains all the features of the *STANDARD* but is specifically designed with the mariner in mind.

- Anti vibration mountings incorporated to prevent transmission of noise to hull of boat.
- Re-designed "short" tail fin reducing turning radius of the windcharger to just 470mm, an asset where deck space is at a premium.
- Designed to be mounted on 2½″ aluminium pipe (64mm OD).



TECHNICAL SPECIFICATION: FM910 'FURLMATIC'

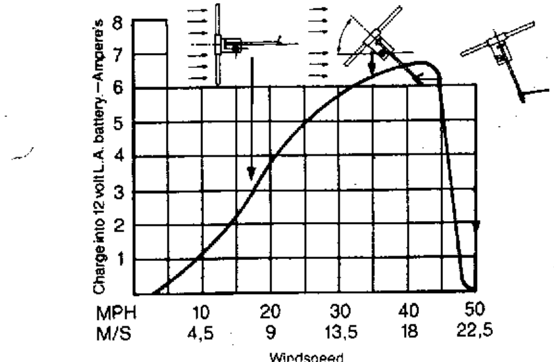
Nett Weight 17.3kg (38.06lbs)

Dimensions	A	B	C	D	E	F	G	H	J
Inches	35.8	9.7	30.25	12	6.9	2.4	2.4	10.63	2.5
mm	910	247	768.3	304	175	61	61	270	64

Shipping Specification (2 cartons)

1 Carton	24 × 31 × 33cm	Weight 14.1kg (31.02lbs)
1 Carton	31 × 10 × 96cm	Weight 5.2kg (11.44lbs)

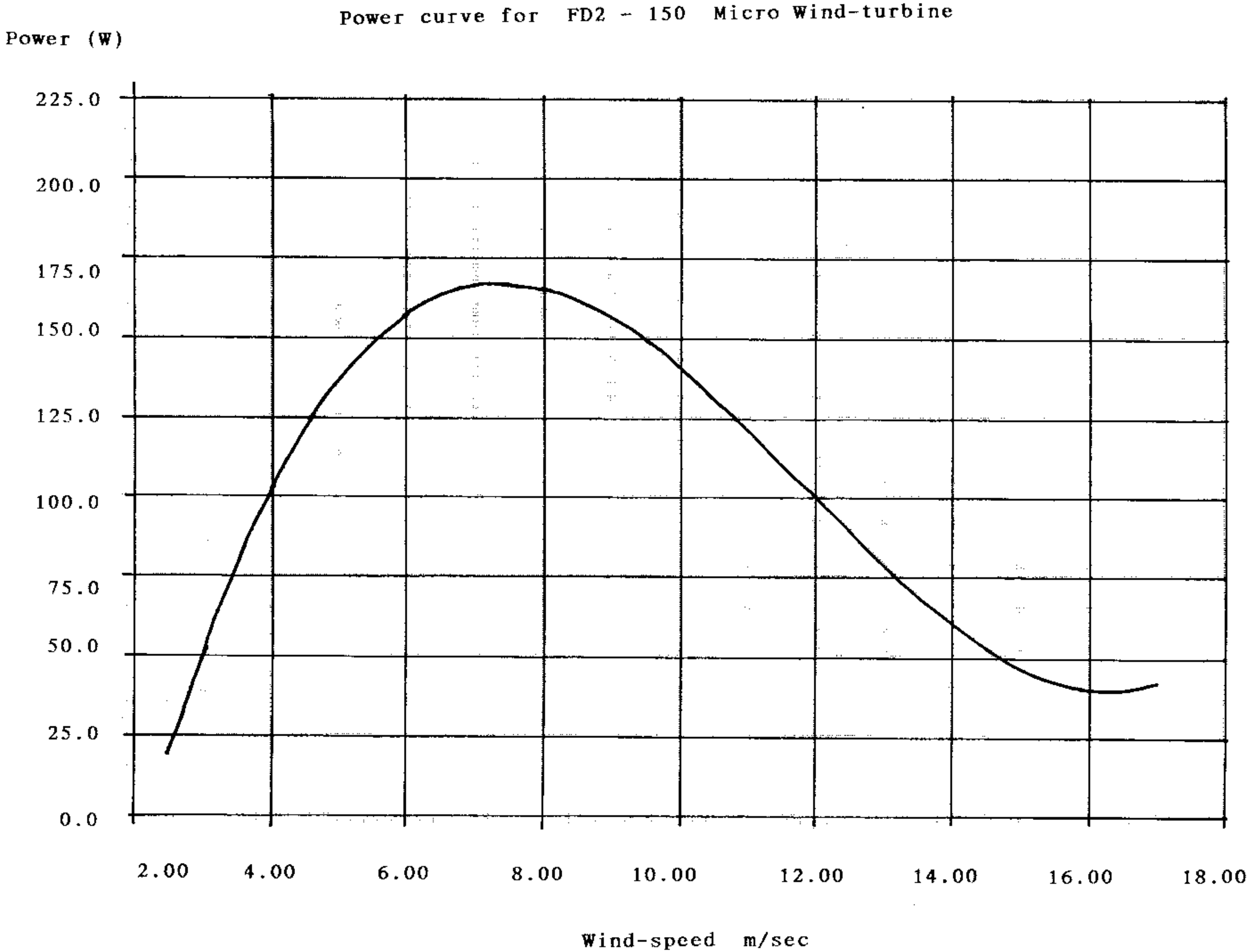
The *FM910 FURLMATIC* is a development from the highly successful *STANDARD* specially for areas of extremely high wind conditions where regular supervision is not available or possible. It retains all the features of the *STANDARD* (generator hub and choke control are identical). However, unique yet simple design enables the unit to 'furl' out of the wind in very high winds. *(See diagram below)*.



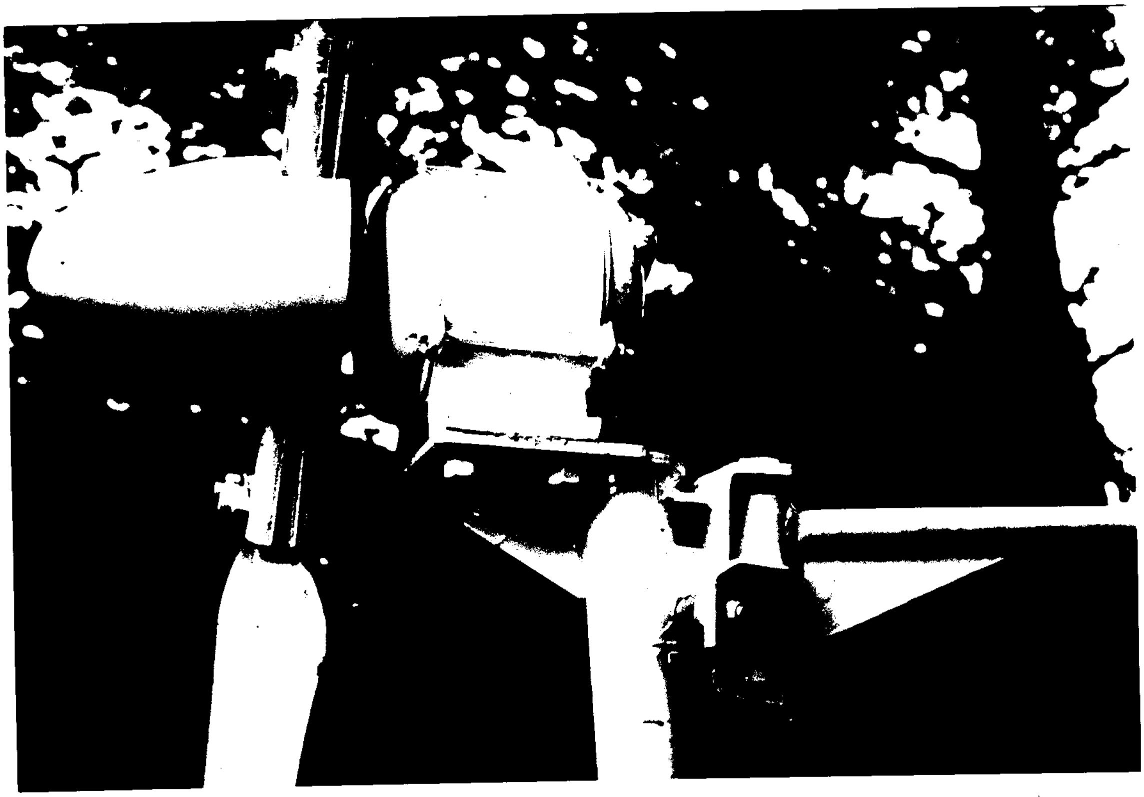
FD2- 150 MICRO WIND-TURBINE

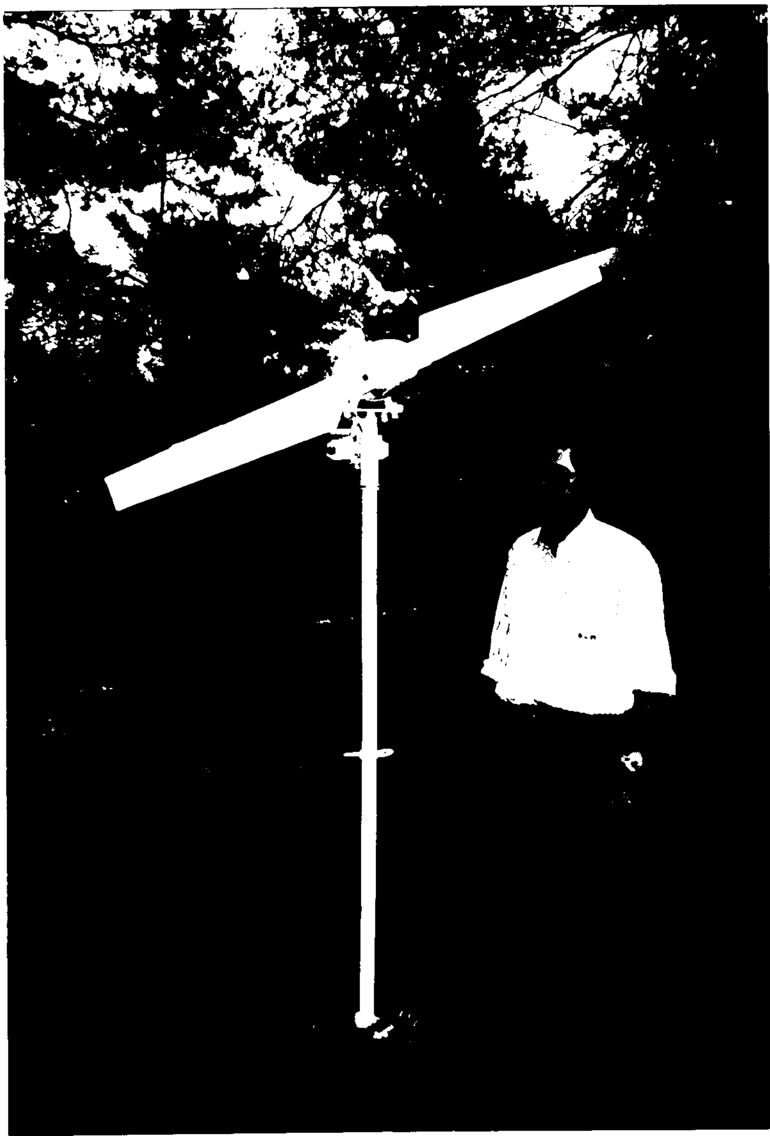
HANDBOOK

INSTALLATION AND MAINTAINENCE


Power curve for FD2 - 150 Micro Wind-turbine
Power (W)
225.0
200.0
175.0
150.0
125.0
100.0
75.0
50.0
25.0
0.0
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
Wind-speed m/sec

Chinese 200 watts micro wind-turbine
(wind-generator)





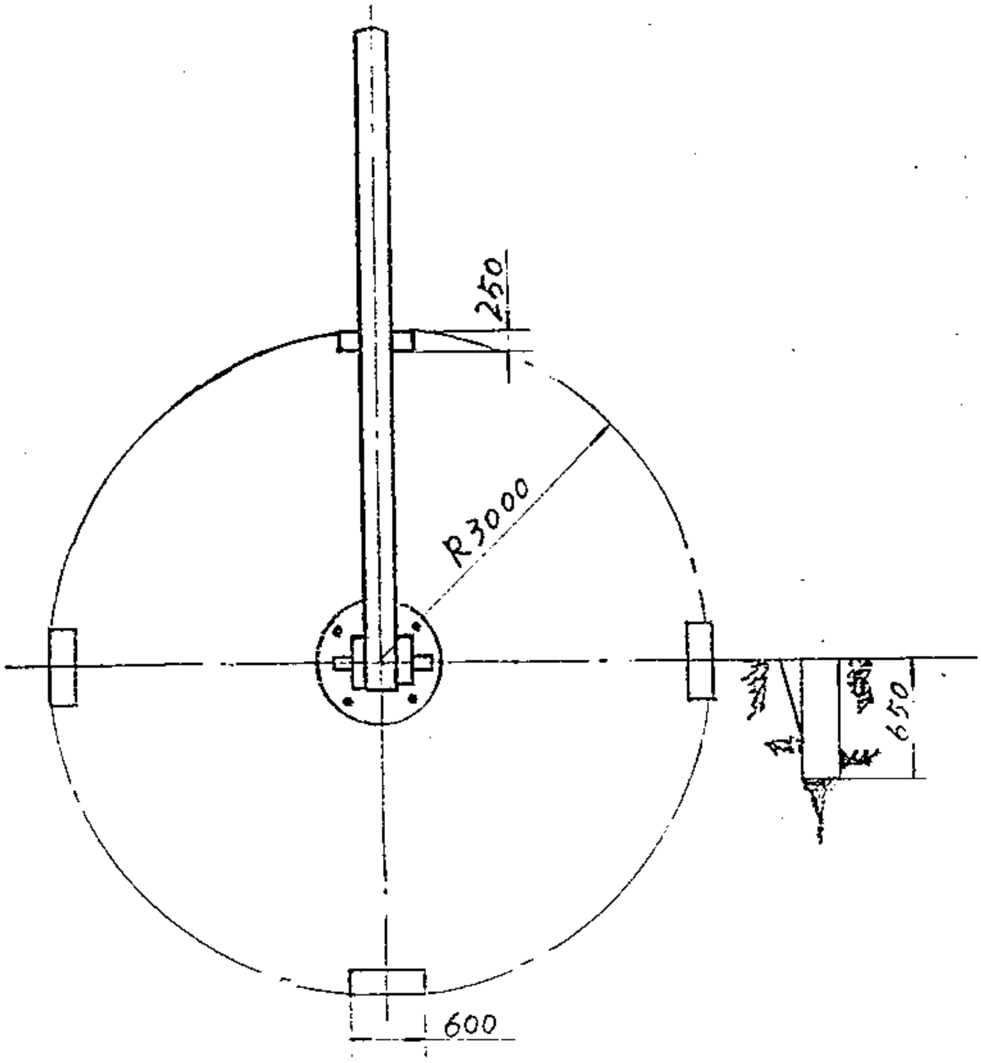


Figure 2. Installation Diagram

CONTENTS

1: Unpacking and control of components. ----------------

2: Assembly of mast, baseplate, and the steel-cable guy wires. --------------
- 2.1 Assembly of mast. ----------------
- 2.2 Assembly of baseplate to the mast. ------------
- 2.3 Assembly of the guy wires. ----------------

3: Assembly of the generator platform and tail-vane. ----
- 3.1 Assembly of tail-vane. ------------------------
- 3.2 Assembly of plastic sleeve linings. -----------
- 3.3 Assembly of the generator platform. ------------
- 3.4 Assembly of anti-vibration pads. --------------

4: Placement of ground anchors. ----------------------
- 4.1 Placement of mast. -----------------------------
- 4.2 Reinforced ground anchors. --------------------
- 4.3 Mounting the mast on the baseplate. -----------

5: Mounting the generator platform on the mast. ---------
- 5.1 Fastening the generator on the generator platform. ----------------
- 5.2 Installation of the electric cable. ------------
- 5.3 Placement of ball-bearing. --------------------
- 5.4 Mounting the generator platform on the mast. ---

6: Assembly of the blades. ----------------
- 6.1 Assembly of the 2 blades. ---------------------
- 6.2 Tightening procedure for the blade-bolts. ------

7: Mounting of blades, nacelle and nose cone spinner. ---
- 7.1 Placement of the assembled blades on the generator. ----------------
- 7.2 Fastening the nacelle and nose cone spinner. ---
- 7.3 Painting the wind-turbine. --------------------
- 7.4 Take-down and disassembly of wind-turbine blades. ---------------

8: Erection of mast. ----------------
- 8.1 Erection of assembled and complete wind-turbine. ----------------
- 8.2 Fastening of guy wires to ground anchors. ------

9: Electrical wiring and sub-assemblies. ---------------
9.1 Assembly of generator cable to control-box. ----
9.2 Installation of batteries. -------------------
9.3 Installation of cable to user. ----------------
9.4 Function of the control-box. -----------------

10: Safety precautions. ----------------
10.1 Tightening of nuts and bolts. -----------------
10.2 Tightening of electrical connections. ----------
10.3 Tightening of guy wires and ground anchors. ----

11: Maintainence. ----------------
11.1 Maintainence of the mast. --------------------
11.2 Blade maintainence. -----------------
11.3 Maintainence of generator platform. ------------
11.4 Maintainence of the generator. ----------------
11.5 Maintainence of the battery / batteries. -------
11.6 Maintainence of the electrical systems. --------
11.7 General maintenence. -----------------

12: Trouble-shooting. -----------------
12.1 Non-rotation of blades. -----------------
12.2 Vibration of wind-turbine. -----------------
12.3 Failure to function. -----------------

13: Technical specifications. -----------------

14: Power curve. -----------------

15: Installation diagram. -----------------

16: Packing list, and description of components. -------

1: Unpacking and control of components.

Unpack all pieces and check that the description and the number of components agree with the supplied list of parts. Check that all pieces are in good and undamaged condition.

Identify all parts and pieces by name, in the following instructions, these will be refered to by name only.

2: Assembly of mast, baseplate, and steel-cable guy wires.

2.1 Assembly of Mast.

The top half and the bottom half are joined together, by sliding the one into the other. The join is first given a heavy coating of chassis grease.

2.2 Assembly of baseplate to the mast.

The baseplate is fastened to the mast with the baseplate bolt. At the foot of the mast are 2 holes. The baseplate bolt is removed from the baseplate, and the mast is placed so that the holes in the baseplate are in line with the holes in the mast. The baseplate bolt is pushed through the holes, and is tightened with a nut and washer, and then secured with a split pin.

2.3 Assembly of the guy wires.

The 4 guy wires are unrolled carefully, so that there are no kinks, or sharp bends in the wires. The wires are fastened to the 4 eyes on the top section of the mast. Each wire is secured with a wire cable clamp or locking bolt.

3: Assembly of generator platform and tail-vane.

3.1 Assembly of tail-vane.

The tail-vane is fastened to the tail with the accompanying nuts and bolts.

3.2 Assembly of the plastic sleeve linings.

The 2 plastic sleeve linings are placed in the tail-vane axle sleeve.

3.3 Assembly of the generator platform.

The tail-vane is fastened to the generator platform, by bringing the tail-vane axle sleeve in line with the 2 holes in the generator platform, and then mounting the tail-vane's vertical axle through these holes, and the plastic sleeves. The axle is fastened with a washer and nut and secured with a split pin. The nut is not tightened more than the tail-vane can freely turn in relation to the generator platform.

3.4 Assembly of anti-vibration pads.

The 2 rubber pads, to absorb vibration, are fastened with washers and nuts, to the metal angles on the generator platform.

4: Placement of ground anchors.

4.1 Placement of mast.

Mark the place on the ground where the mast will stand. With a cord or rope, trace a circle with a diameter of 6 meters. On the circumference of this circle, set out 4 pins at:

1. 90 degrees
2. 180 degrees
3. 270 degrees
4. 360 degrees

At each of these 4 pins, using a heavy hammer or sledge hammer, hit down an ground anchor. The ground anchors must be placed at an angle of about 30 degrees from the vertical, the top of the ground anchor pointing away from the center of the circle.

4.2 Reinforced ground anchors.

In areas with soft or loose earth, proper anchor plates should be dug, as the forces on the guy wires in the event of high winds, can up-root the ground anchors supplied .

4.3 Mounting the mast on the baseplate.

The mast is mounted on the baseplate by the baseplate bolt passing through the holes in the baseplate and the bottom section of the mast. The bolt is fastened with a washer and nut and secured with a split pin. The mast should be temporary supported about 1 meter above the ground on a saw-horse or tresle.

5: Mounting the generator platform on the mast.

5.1 Fastening the generator onto the generator platform

Bolt the generator onto the generator platform, with the supplied 4 sets of nuts, bolts and washers.

5.2 Installation of the electric cable.

The supplied electric cable is installed in the generator connection box. The assembly is made with the supplied connectors. Remember to prevent any possible strain on the cable. The cable must not hang inside the box.

5.3 Placement of the ball bearing.

Install the supplied ball bearing on the mast bearing ring. If necessary place a cover over the bearing to protect it from rain and/or dust.

5.4 Mounting the generator platform on the mast.

The generator platform is positioned on the mast, by placing the hollow sleeve of the platform, down over the sleeve bearing on the mast.

6: Assembly of the blades.

6.1 Assembly of the 2 blades.

The 2 blades are joined together with a metal junction unit, and the supplied nuts, bolts, and washers.

Note that the blades are joined together in such a way that the marked arrows are facing each other on the metal junction unit.

6.2 Tightening procedure for the blade bolts.

The blade bolts are tightened, then re-tightened, and then finally re-tightened and re-checked immediately before erecting the wind-turbine.

7: Mounting of blades, nacelle and nose cone spinner.

7.1 Placement of the assembled blades on the generator.

The blade assembly is fastened to the generator and secured with a nut and washer. Note that the metal blade junction unit is equiped with a conisk hole, that fits the generator axle. The blades therefore cannot be incorrectly fitted on the axle.

7.2 Fastening the nose cone spinner, and nacelle.

Fasten the supplied plastic nose cone spinner, on the blade junction unit, with the suplied screws. Fasten the supplied nacelle, with the supplied screws.

7.3 Painting the wind-turbine.

Paint the assembled wind-turbine, a final time, before erecting the finished and completed unit.

7.4 Take-down and disassembly of wind-turbine blades.

The blades can be disassembled from the generator with the use of the supplied puller. The puller can be temporary fastened to the threaded holes on the blade junction unit.

8: Erection of mast.

8.1 Erection of assembled and complete wind-turbine.

The assembled and complete wind-turbine, is pulled into the vertical position with the aid of the guy wires and eventually with the assistance of a pole, or another mast or crane. It is an advantage to have a couple of assistants, as it is a hard task.

8.2 Fastening of guy wires to the ground anchors.

When the mast is in a vertical position, the wires are fastened to the hammered-down and buried ground anchors. The wires are tightened, (perhaps by using wire pullers) the wires are then secured and locked by using wire clamps.

9: Electrical wiring and electrical sub-assemblies.

9.1 Assembly of generator cable to control box.

The supplied electric cable is first connected to the 3 generator wires in the generator connection box. The other end of the cable is then connected to the terminals in the control box, that are clearly marked " GENERATOR ". It is vital that all connections are carefully and solidly made.

9.2 Installation of batteries.

The wind turbine batteries, are conected to the conections in the control box, that are clearly marked, " BATTERY ".

There is available a pre-assembled cable set.
For 24 volts output, 12 volt batteries are connected in series.

9.3 Installation of cable to user.

The cable to the user can either be connected direct to the batteries, or to the connection, clearly marked, " LIGHT ", routed through the " ON - OFF " switch on the control box, and including a fuse, if so desired.

9.4 Function of the control box.

The wind-turbine is supplied, with different types of control box, according to the individual requirement of the purchaser. Common for all the different types, is that the control box rectifies the AC current from the generator to 12 volt or 24 volt DC, in addition to giving the possibility to brake the wind-turbine, from the control box.

There is also available , as extra equipment :

1. Voltmeter
2. Amperemeter
3. Voltage supervision
4. Provision for co-generation with a solar-cell panel.

10: Safety instructions and precautions.

For the wind-turbine to function corectly, and without risk for people or the surroundings, it is vital that it is assembled correctly, and that all parts, and all nuts, bolts and screws are checked for tightness from time to time.

10.1 Tightening of nuts and bolts.

All bolts, and nuts, must be re-tightened, just before the wind turbine is erected. Split-pins and washers are checked for corect assembly.

10.2 Tightening of electrical connections.

All electrical connections, must be re-tightened, just before the the wind turbine is erected. It is important that the wind turbine is always connected to at least 1 battery.

10.3 Tightening and control of steel guy wires.

The guy wires and the ground anchors must be regularly controlled. Wire clamps, or wire pullers, (if used) must be controlled and re-tightened.

11: Maintainence.

To enable the wind-turbine to give many years of reliable service, it is vital that it must be regularly checked and serviced. We recomend that the wind-turbine should be lowered at least once a year for maintainence. In exposed areas, it may be necessary with half-yearly maintainence schedules.

11.1 Maintainence of the mast.

The mast must be checked for rust. Possible rust patches must be sanded down to the bare metal, and then painted with anti-rust paint, followed by a covering layer of paint.

11.2 Blade maintainence.

The blades must be cleaned and the fastening bolts checked. The blades must be checked for cracks, or other defects. Small cracks can be repaired with glass-fibre. Possible larger cracks can result in replacing either one, or both blades. Do not install blades without a balance test, ---- to prevent serious vibration.

11.3 Maintainence of generator platform.

The generator platform must be checked for rust. Possible rust patches must be sanded down to the bare metal, and painted with anti-rust paint, followed by a covering layer of paint. All bolts and nuts must be re-tightened. Bearings must be cleaned, and greased with chassis grease.

11.4 Maintainence of generator.

The generator must be checked for rust. Possible rust patches must be sanded down to the bare metal, and painted with anti-rust paint, followed by a covering layer of paint. All nuts and bolts must be re-tightened. The generator axle must be cleaned, and greased with chassis grease.

11.5 Maintainence of the battery / batteries.

Disconnect the battery connections, clean the terminals. Grease the terminals in acid-free petroleum jelly / vaseline. The level of electrolyte in the battery is controled, and if necessary, distilled water is added. The battery is then re-connected, and the bolts are re-tightened.

11.6 Maintainence of the electrical system.

The control box is checked for damage. The electric cable must be checked for abrasions or cuts, cracks, or other damage. A damaged cable must be replaced. The connections in the control box must be checked, and re-tightened.

11.7 General Maintainence.

Clean and lubricate the tail pin and the rotating joint in the connector, once a year.

Replace the generator shaft, every 5 years.

12: Trouble-shooting.

12.1 Non-rotation of blades.

a. Generator-winding short-circuited: --- Investigate which part is responsible for the short-circuit.

b. Generator shaft damaged, stator and rotor worn out: --- Replace damaged or worn parts.

12.2 Serious vibration of wind-turbine.

a. Rotor staticly un-balanced: --- Made a static balance test, so as to ensure that the un-balance moment is less than, 3g*m.

b. Shaft distortion: --- The correct distortion must not exceed 5mm.

c. Difference of pitch angle exceeded: --- Adjust pitch angle 1.5, and tolerance 0.5.

d. Generator shaft bent: --- Replace.

e. Too frequent changes of wind direction, with resultating serious wind turbulence: --- Find another site with a more stable wind direction.

12.3 Failure to function, (does not produce power).

a. The winding's lead-cable circuit broken or a bad connection: --- Investigate, and connect the circuit.

b. Dis-connection of circuit to the rectifier and storage battery: --- Check controller and storage battery and connect the circuit.

c. Controller socket without power and fuse burn-out: --- Change fuse.

d. Controller switch disconnection: --- Change switch.

13: Technical specifications.

The FD2-150 micro wind-turbine, can supply 24V DC power for lighting, radio, etc. in remote areas.

a.	Rotor:	diameter:	2 meters.
		number of blades:	2 NACA 23015 - 23018.
		rated rotational speed:	460 rpm.
b.	Generator:	type:	magneto, 3 phase, AC
		rated rotational speed:	460 rpm.
		rated value:	28V. 150W.
		efficiency:	0.6
c.	Rated wind speed and power:		7m/s 150W
d.	Max output:		300W
e.	Start-up wind-speed:		3m/s
f.	Wind-speed range:		3m/s - 40m/s
g.	Survival wind-speed:		40m/s
h.	Output in different wind-speeds:		see power curve.
i.	Speed regulating method:		deflecting rotor

j. Storage battery: 24V 60Ah-135Ah.

k. Installation height and weight: 5.1 meters, 70 kgs.

16: Packing/Shipping List, for 2 Micro wind-turbine units.

No.	Quantity	Colli nr.	Description
1.	2	B002	150W magneto generator (24V AC)
2.	3	A001	Rotor
3.	2	B002	Rotating frame
4.	2	B002	Tail rod
5.	2	B002	Tail vane
6.	8	B002	Guy wires
7.	16	B002	Cable clamps
8.	8	B002	Turnbuckle screw
9.	8	B002	Ground/soil anchors
10.	2	B002	Base Pad
11.	4	B002	Base pad anchor
12.	2	B002	Front spinner/nose cone
13.	2	B002	Rear nacelle
14.	2 sets	A001	Cable
15.	2 sets	B002	Bolts
16.	2 (4 sections)	A001	Tower
17.	2	B002	Tower pin

Chronology of Wind-turbine Development.

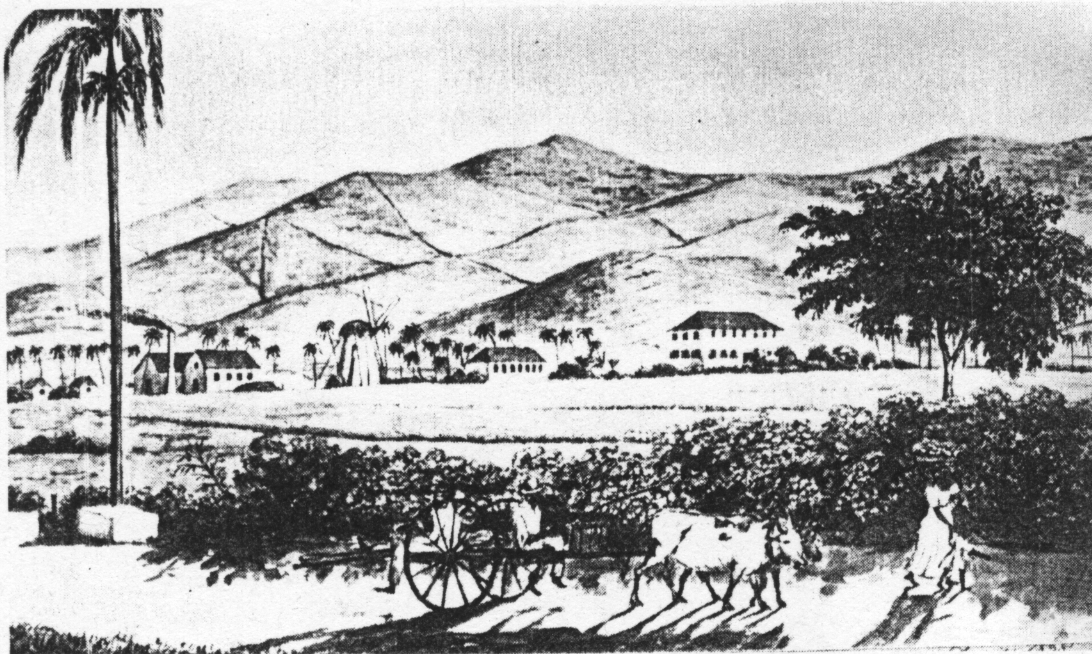
Period nr. 0	Dutch type, F. Nansen, USA 1894
Period nr. 1	La Cour, Denmark 1890 - 1925. La Cour from Askov in Denmark, was the pioneer of modern large-scale wind electrical power generation. - 3kW.- 30 kW. [co-generation systems].
Period nr. 1.5	Lykkegaard, Denmark 30 - 75 kW. 1920 - 1945. Series-production period.
Period nr. 2	F.L. Smidth, Denmark [60 - 70 kW. with effective gear-box developed from cement-ovens], Hütter in Germany, Darrieus in France, Putnam in USA, and especially, very large-scale mass-production in the USSR. 1930 - 1945. [small wind-generators for battery charging, mass-produced in USA].
Period nr. 2.5	J. Juul, Denmark 1950, 13kW.- 45 kW.
Period nr. 3	J. Juul, 200 kW. Gedser wind-turbine, 1955 - 1967, and from 1977 [operated under Danish and USA-NASA research contract]. Plus UK and West-Germany. [Gedser was the first modern, reliable wind-turbine].
Period nr. 4	Re-discovery phase, 1968 - 1978, USA and Denmark. This phase results in 2 different development strategies: - Top-down, and Bottom-up.
a:	Mega turbines; Tvind-college in Denmark & official Danish state research program, West-Germany, USA. - [Development of glass-fiber Tvind-wing].
b:	The Riisager wind-turbines from Denmark, 10kW.- 30kW. These pioneered the development of the cost-effective wind-turbine
Period nr. 5	Large-scale Danish commercial development and production; - 55kW.- 100 kW. 1978 - 1985.
Period nr. 6	150kW.- 225 kW. 1985.
Period nr. 6.5	300 kW. 1991.
Period nr. 7	Large-scale production of cost-effective 500 kW. units, Denmark and Germany. 1993. Development of wind-turbines without gear-box, [Ring-generator -- Enercon, Germany]

There is at the present time [1997] small-scale production in Denmark of Mega-sized wind-turbines, [between 800 kW. and 1.7 MW.]. However great consideration, must be paid to eventual dis-economies of scale, maintenance, siteing, etc. etc.

Windmills of Period Type 0, as used in sugar plantations in the Virgin Islands.

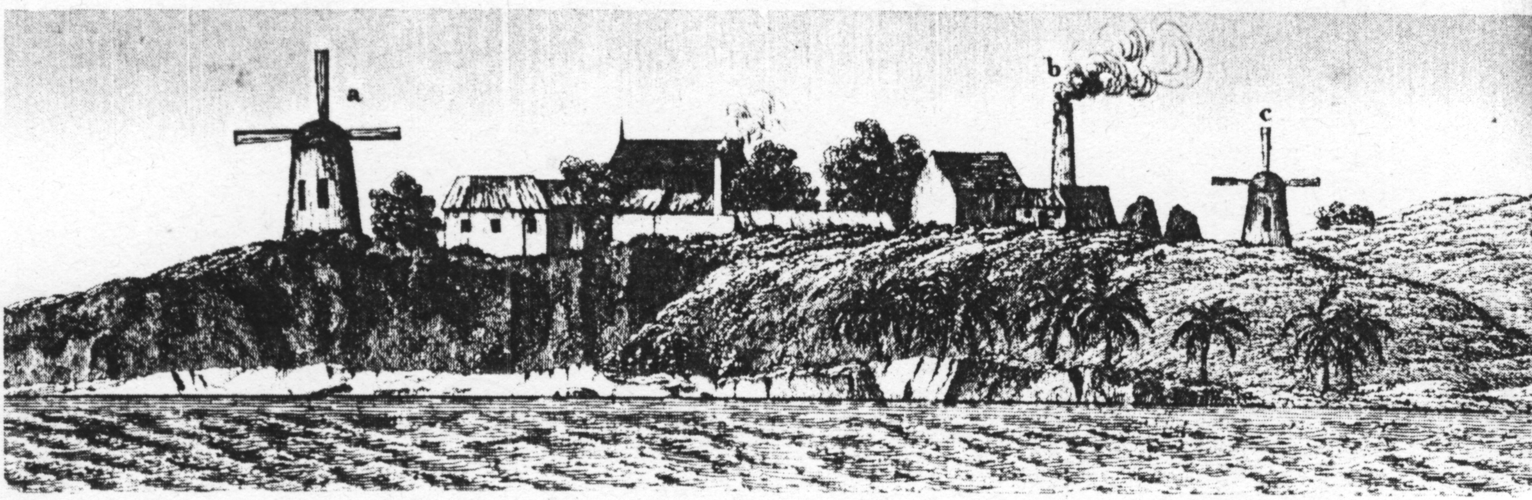
Prosperity on St. Croix. Coloured drawing by Frederik v. Scholten 1833. H. & S.

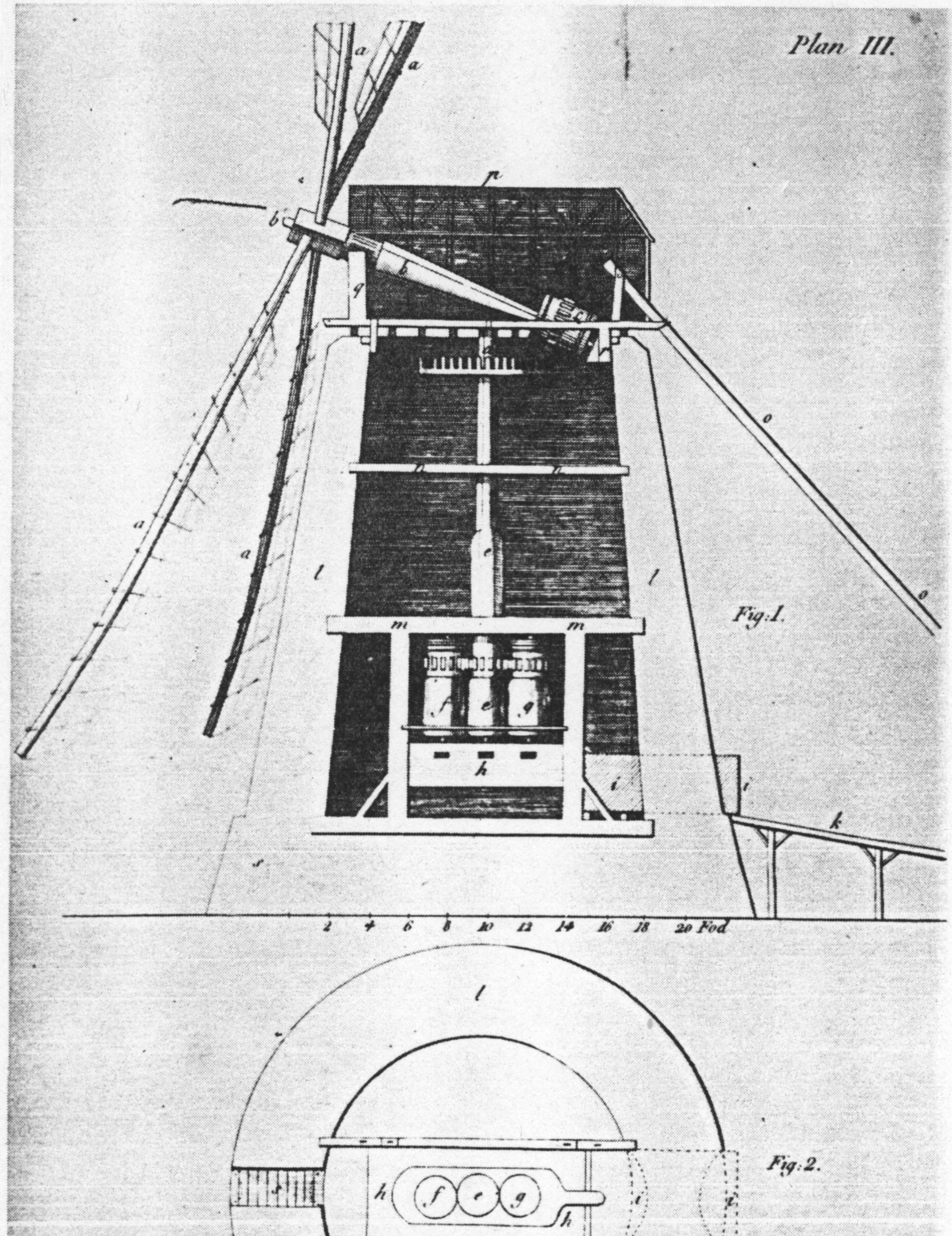
Plantagen Prosperity på St. Croix. Farvelagt tegning af Frederik v. Scholten 1833. H. & S.



Shoys near Christiansted. Coast profile c. 1860. KB.

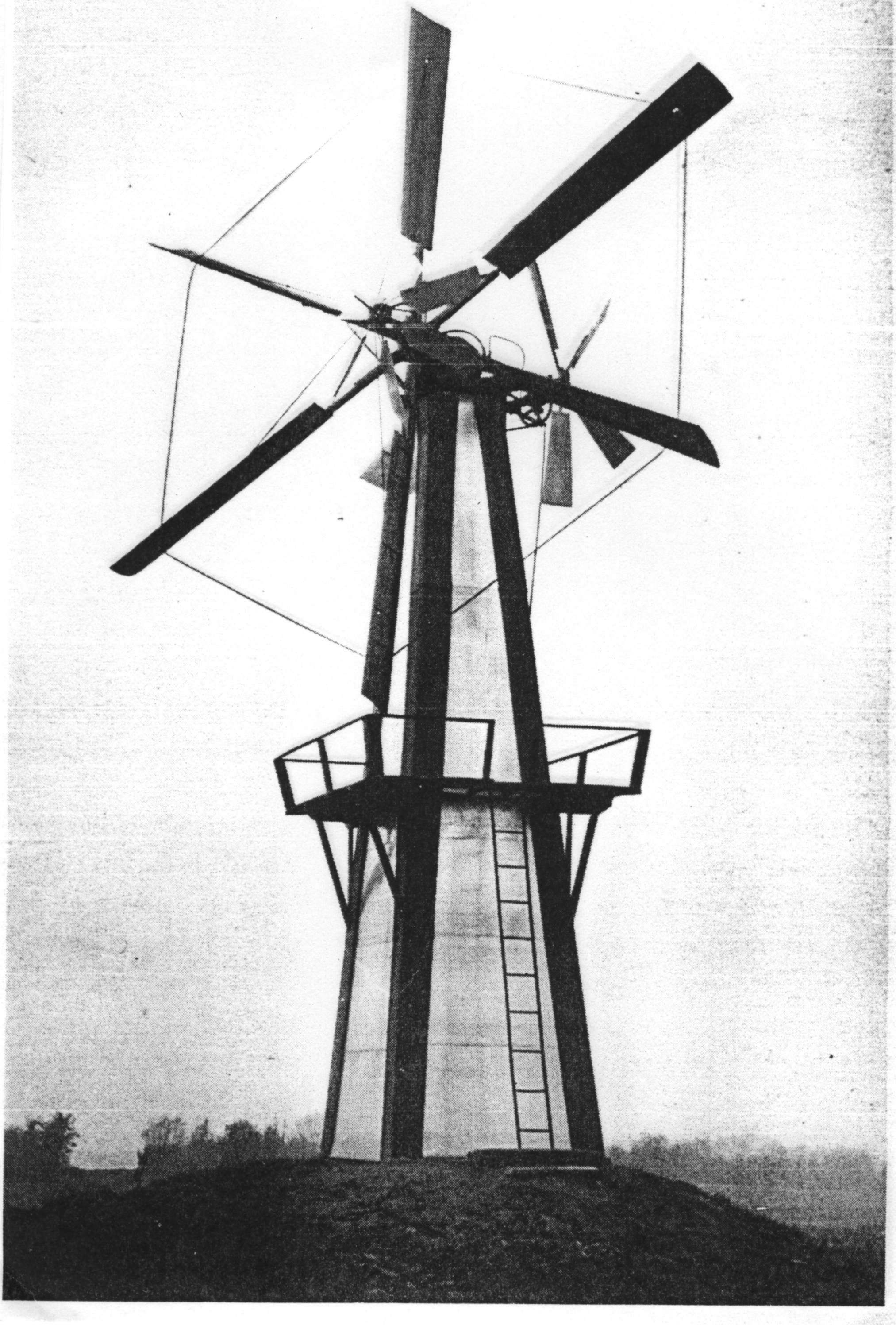
Shoys ved Christiansted. Landtoning ca. 1860. KB.





Sugar mill.
Engraving from
P. L. Oxholm: St. Croix,
Kbh. 1797. KB.

Sukkermølle.
Stik i
P. L. Oxholm: St. Croix,
Kbh. 1797. KB.



Modern re-construction of Type 0, for electrical power generation.
Wooden blades, radius 4 m.

La Cour-type Windmill for Electricty Production:
Lykkegård model Denmark 1928.

Danske elproducerende vindmøller 1892 -1962:
Jytte Thorndahl. Elmuseet. DK. 1996.
87-89292-36-7.

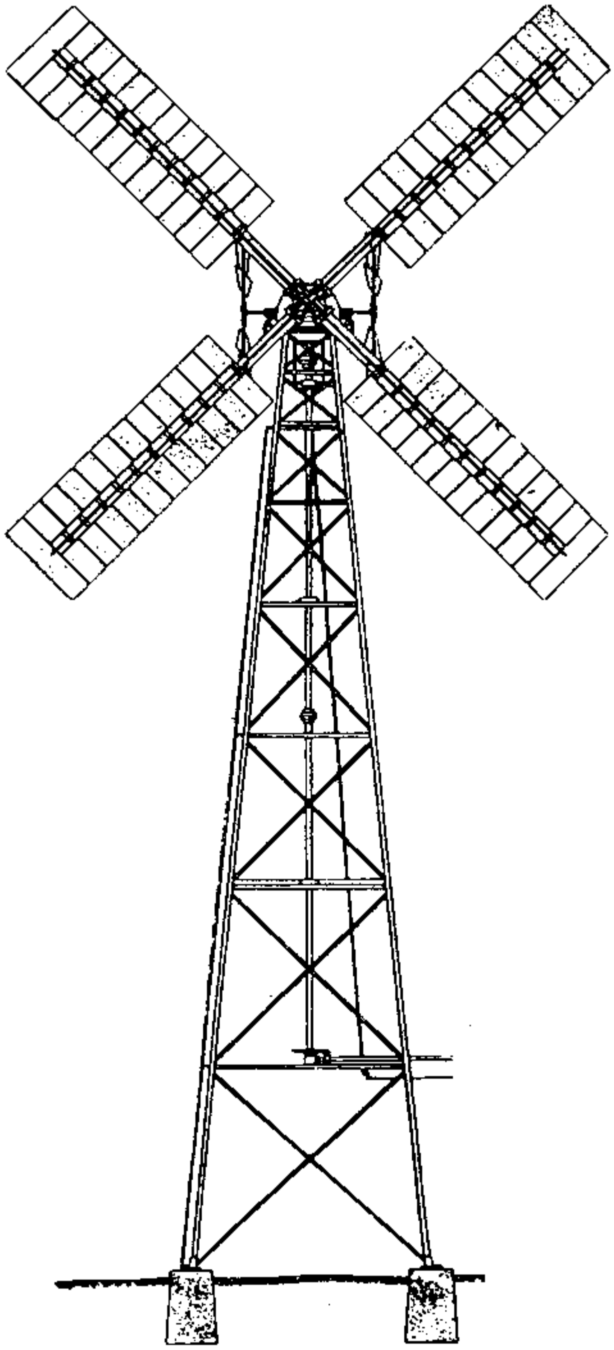


Fig. I

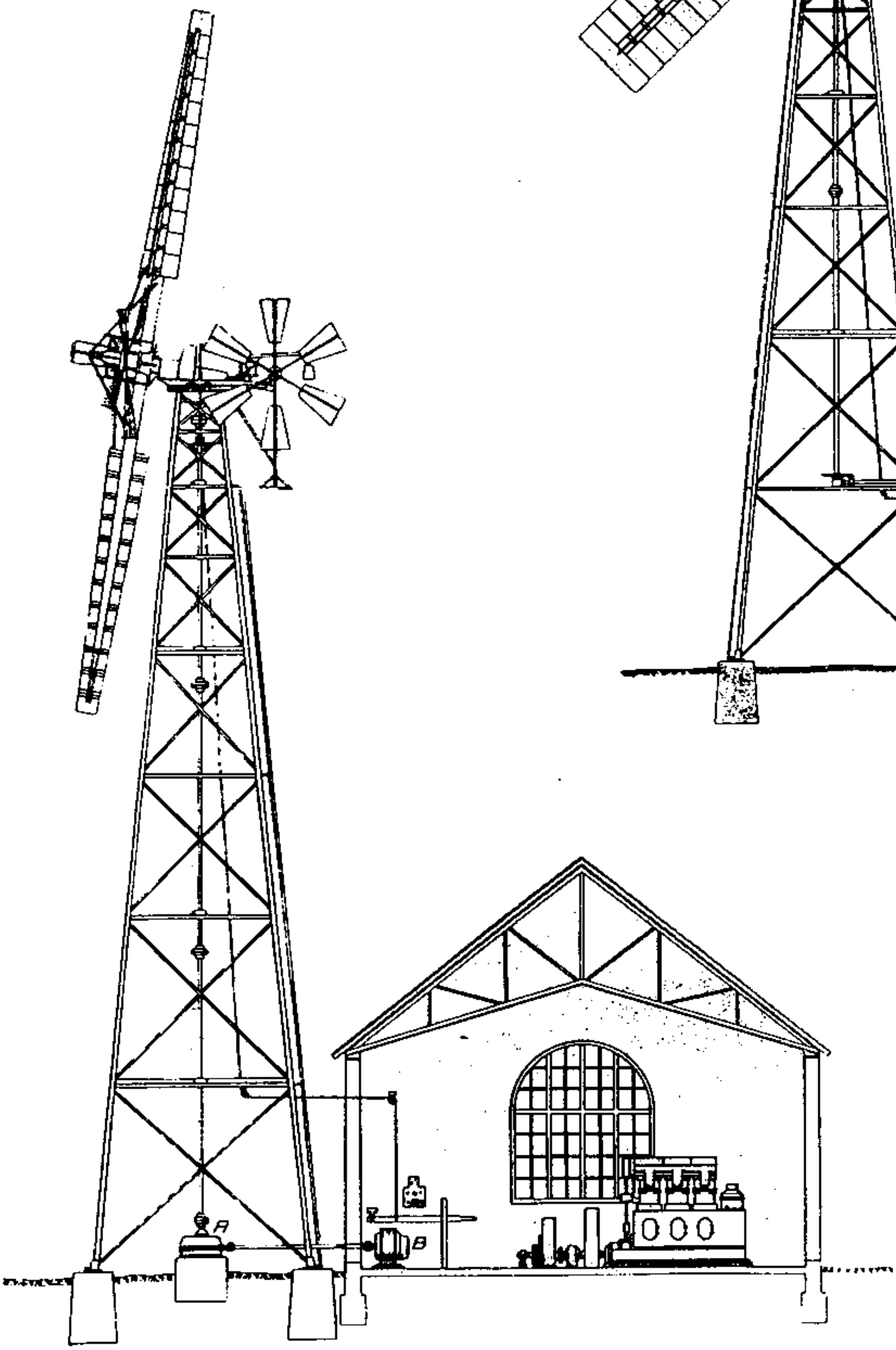
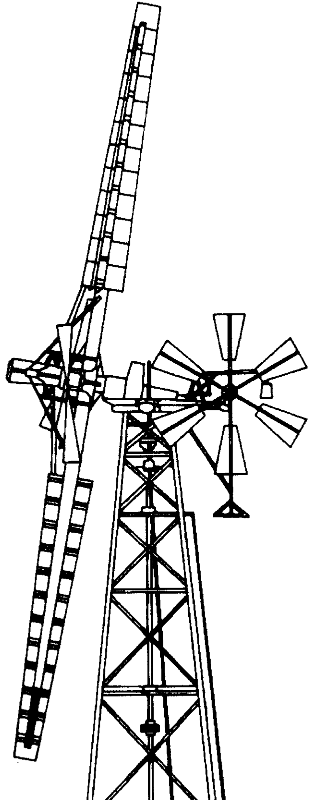
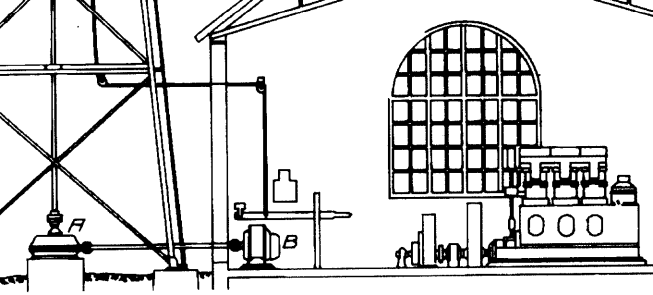


Fig. II




A
B

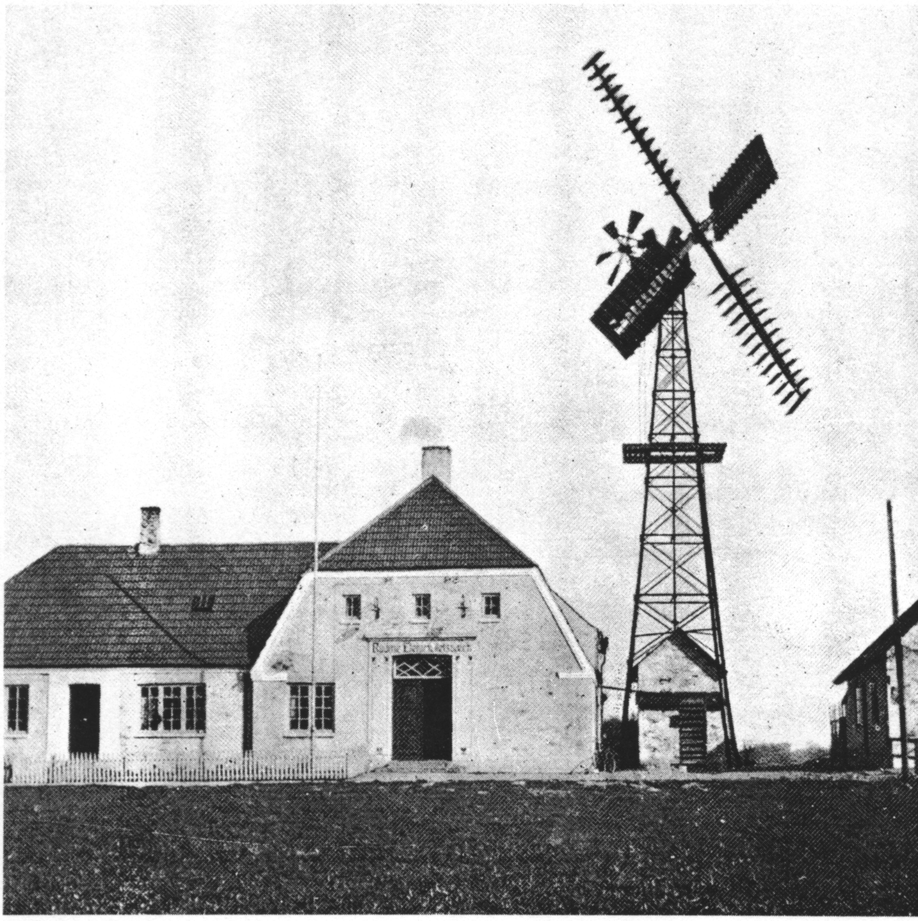
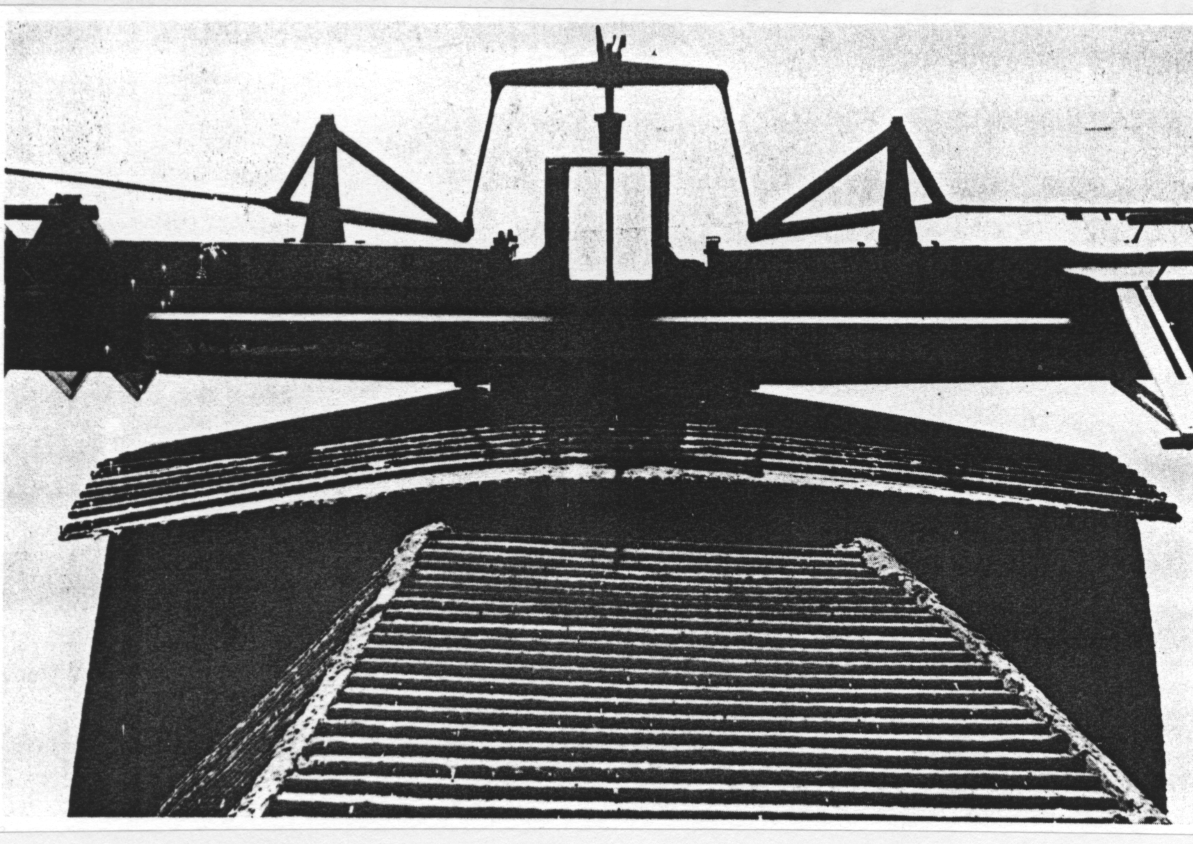
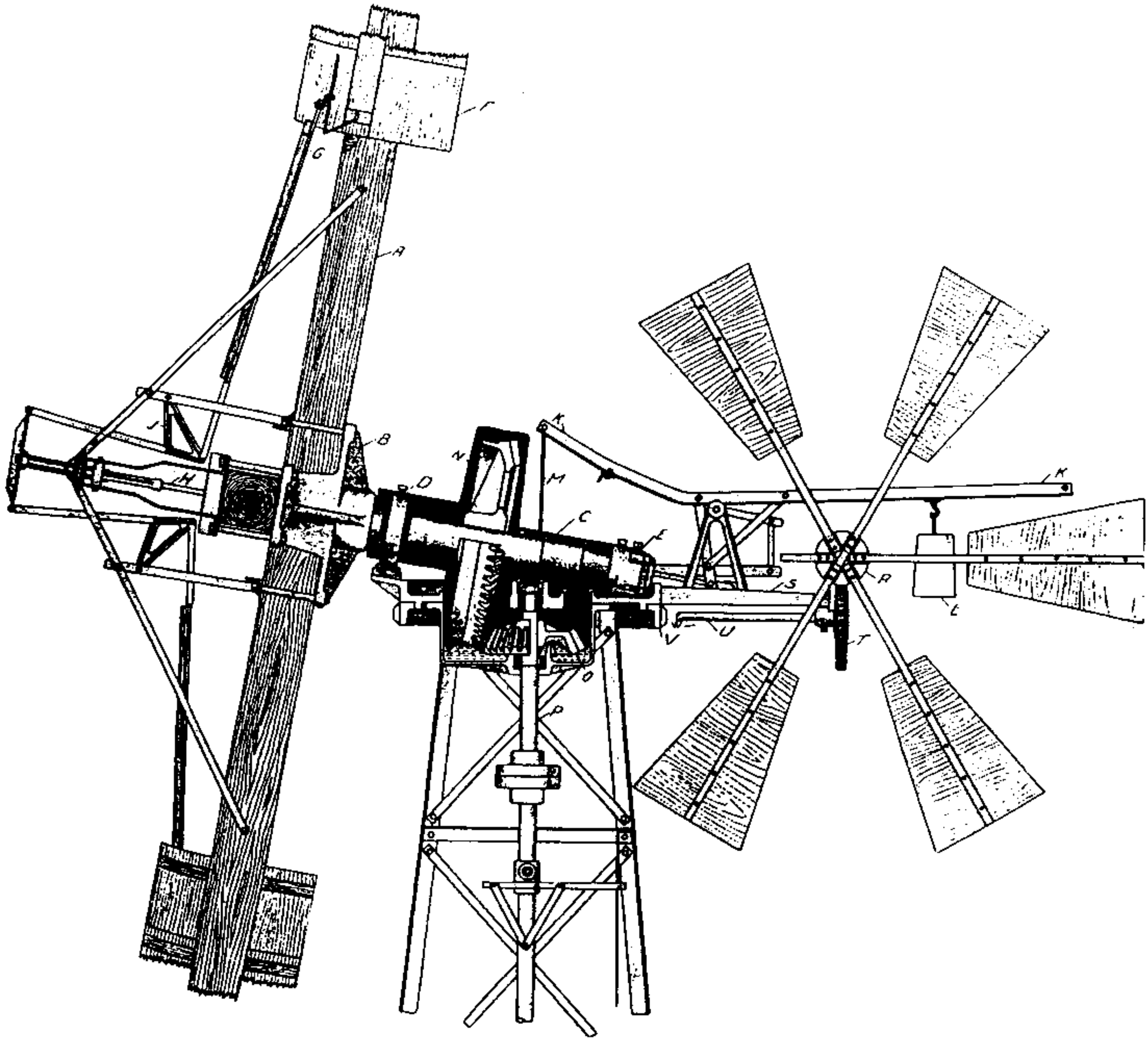
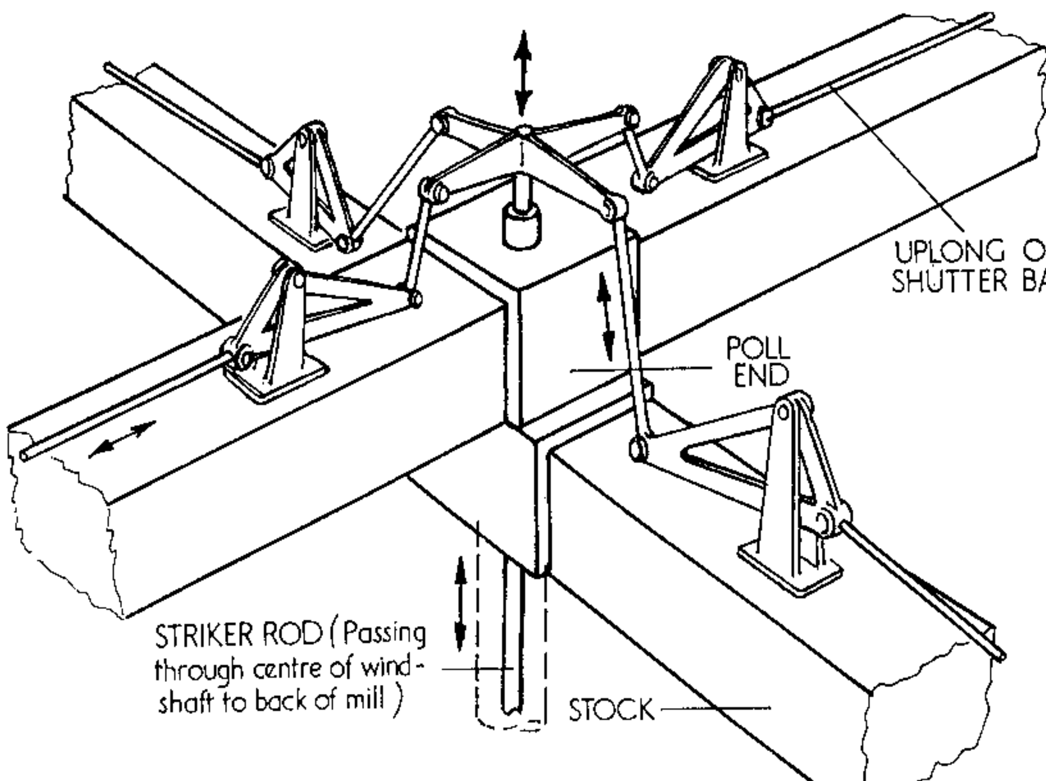


Figure 4. Rudme power plant.



Windmills: Suzanne Beedell. David & Charles Publ. Newton Abbot, London UK. 1975. 0-7153-6811-7
Stelling Minnis Windmill, Kent UK.
Looking up from the bottom and showing the spider striking gear. Stelling Minnis - is a 4-bladed windmill. In this photograph only the horizontal blades are in place. The striking rod can be clearly seen passing through the empty section of the canister, into the windshaft.





Striking mechanism.

Combined Windmill and Fuel-oil
Electrical Power Generating Station.

Period Type 1.5 Lykkegård model 1928.
18 m. rotor diameter. 30 kW DC - Dynamo.
[These models were in series production for 50 years].

The blades are made from wood. The blade stocks **A** are held in place by a cast-iron cross-type canister **B** fastened on the main windshaft **C** which runs in two sets of ball bearings, - one at the front and one at the rear end of the windshaft.

The blade shutters **F** are all connected by a steel shutter bar or rod **G** which runs the length of each blade. The four steel rods meet in the center of the blade rotor, where they are joined together with the control or striker rod **H** - through a system of counter-balanced rods, where the control striker rod is joined to the lever arm **K** . The counter-weight **L** maintains the shutters in a closed or shut position.

When the pressure from the wind increases, the shutters will tend to gradually be pressed open. With increased wind speeds that could possibly endanger the safe operation of the windmill itself, or of the machinery that the windmill is driving, - the shutters will further open. The blades and rotor will thereby be maintained at a, more or less, constant speed of rotation.

If the shutters are completely opened, - the windmill will come to a standstill. The windmill can be stopped at will by pressing down on a shutter-release lever arm placed at the foot of the tower. Likewise the windmill can be re-started by raising the same lever arm.

The main windshaft drives the main gear wheel, - the so-called "brake wheel" **N** - that engages the horizontal wallower gear wheel, **O** on top of the long vertical shaft **P** that transmits the wind energy down to the bottom of the tower. The power from the vertical shaft is transmitted to the dynamo through a right-angled gearbox, as shown from **A** - **B**.

The windmill powered dynamo generates electrical energy for a battery bank or for direct use in a local grid, with a back-up petroleum, diesel or fuel-oil engine driving another dynamo.

The following suggestions are based entirely on the excellent work recently done and published by Prof. P. la Cour in Denmark on behalf of that Government, which has in that particular placed itself ahead of other countries—considerably to the advantage of many of its villages and isolated dwellings. The reader must be prepared to experiment a little—not indeed in principles but in details of apparatus to suit his own case—but may rest absolutely assured that the method is quite practical and satisfactory.

There are two main difficulties in applying a power so variable and intermittent as wind to the production and supply of electricity. There must, first, be a means of automatically switching on the dynamo to a set of accumulators whenever the former is in a position to deliver current, the same apparatus cutting it out when the power falls away. Secondly, means must be adopted whereby an increase of wind-power beyond the normal amount required to just work the dynamo shall not affect the output by increasing either voltage or current. Both these ends have been attained by La Cour with the simplest apparatus imaginable.

A consideration of the second question raised will show why it is necessary to decide on a definite wind-velocity as being that at which any given windmill shall supply its "normal" output. By rating it low, say a wind of 9 miles per hour, it is possible to keep a dynamo working nearly every day in the year and for twelve hours out of the twenty-four. But the power of the wind at 9 miles an hour is only a quarter of that at 15 miles an hour, and although the latter only blows about half the total number of days in a year, and then for only about nine or ten hours a day, its total output is greater than the other. Another point to be considered is that a very small dynamo is much less efficient, so that a double loss is experienced if too much constancy of work is aimed at. Of course, in a large installation these points have less emphasis, and it becomes desirable to run the plant at a lower wind-rating (in other words, use a comparatively large mill), the only limiting factor being the initial cost of the plant.

In a wind-driven generating plant the following points should be noted. The windmill itself should be self-regulating (as, for example, that described in Chap. V.), and fitted with tail so as to turn to face all possible winds. The dynamo should be shunt-wound, so that an increase in the external resistance tends to raise the terminal voltage. If necessary, this tendency may be increased by having one or two resistance coils in series with the shunt-winding, these coils being automatically cut out as the external resistance rises and current falls. A low-speed machine is certainly preferable, the speed of a windmill being rather low itself. The accumulator is a vital point: it should have a large capacity, as on this depends its ability to maintain a supply over a longer period of calm; yet as it is undesirable for any accumulator to remain long at a low state of charging, care must be taken to avoid draining it—especially if a spell of calm weather seems likely.

The whole of the electrical apparatus is shown diagrammatically in fig. 73, the only part needing much description being the automatic switch, further illustrated in three views in fig. 74. This consists of two electro-magnets, EM, each like an ordinary bell-magnet, and wound with fine wire, but with an extra winding of a few turns of thick wire, exactly like a compound-wound dynamo field magnet. A horse-shoe permanent magnet, PM, is suspended so that its poles lie opposite and near to the poles of the electro-magnets, and swings by means of the pivot screws which work in a *brass* (or non-magnetic) block, B. This block also carries the copper rod CR, each end of which turns downward into the wooden cups 1 and 2, containing mercury, matters being so arranged, however, that the end 1 is always in the mercury whichever way PM is swung, while 2 only touches the mercury when that end of CR is drawn downwards.

The switchboards present no special features. By following out the connections it will be seen that any agreed number of cells can be switched on to the dynamo, while any independent number can be caused to supply the lamps. This latter arrangement is desirable to allow for drop of voltage during discharge, also to provide for losses in mains and for an extra cell or two in case of accident to others.

The action of the automatic switch is as follows: Assuming the dynamo to be still, or running at too low a speed to furnish current, it will be seen that the battery is energising the electro-magnets EM through the fine wire-coils, the current passing also through the armature of the dynamo. The winding of EM is such that the current in this direction attracts the poles of PM to the right and so raises the end, 2, of CR out of the mercury. Only a very small current is required, or allowed, to be thus wasted. Supposing now the wind to increase sufficiently to raise the speed of dynamo so much as to be able to supply current, the first effect will be to reduce the current in EM to nil and then to reverse it, altering the polarity of the electro-magnets and throwing the lower end of magnet PM over to the right. This, by dipping the end 2 of CR into the mercury, makes connection between the dynamo and accumulator, the charging of which at once begins. The effect of the thick-wire coils on EM is to hold the magnet switch more securely during charging. The opposite action—that of throwing out the dynamo when the speed fails—is obvious on inspection.

There would be twelve accumulator cells, each of from 150 to 200 ampere-hour capacity, which would be easily capable of dealing with the full current for twenty-four hours' continuous charging. The capacity mentioned is the maximum suitable for the given plant, but the minimum may be anything down to twelve pocket-batteries, if so desired. Within the limits given, the greater the capacity the more the independence of conditions of wind.

With regard to the automatic switch, a little experimenting and adjusting will be needed to ensure its correct working. The electro-magnets may be two ordinary bell-magnets, wound with No. 36 wire, the bobbins being about 1¼ inches long and 1 inch diameter outside. A resistance may be needed in series with this winding, or the effect may be tried of connecting up only six of the cells to these coils, the six on the left-hand side in fig. 73 being, of course, selected. All four bobbins will be joined in series. Over the fine wire on each bobbin will be wound from six to twelve turns (to be determined by experiment) of No. 16 or 14 gauge cotton-covered wire, the winding being in same direction as the fine wire in each case, so that the current is a reinforcing one when being supplied from the dynamo. The balance of the permanent magnet can be adjusted by moving the copper rod CR either to right or left.

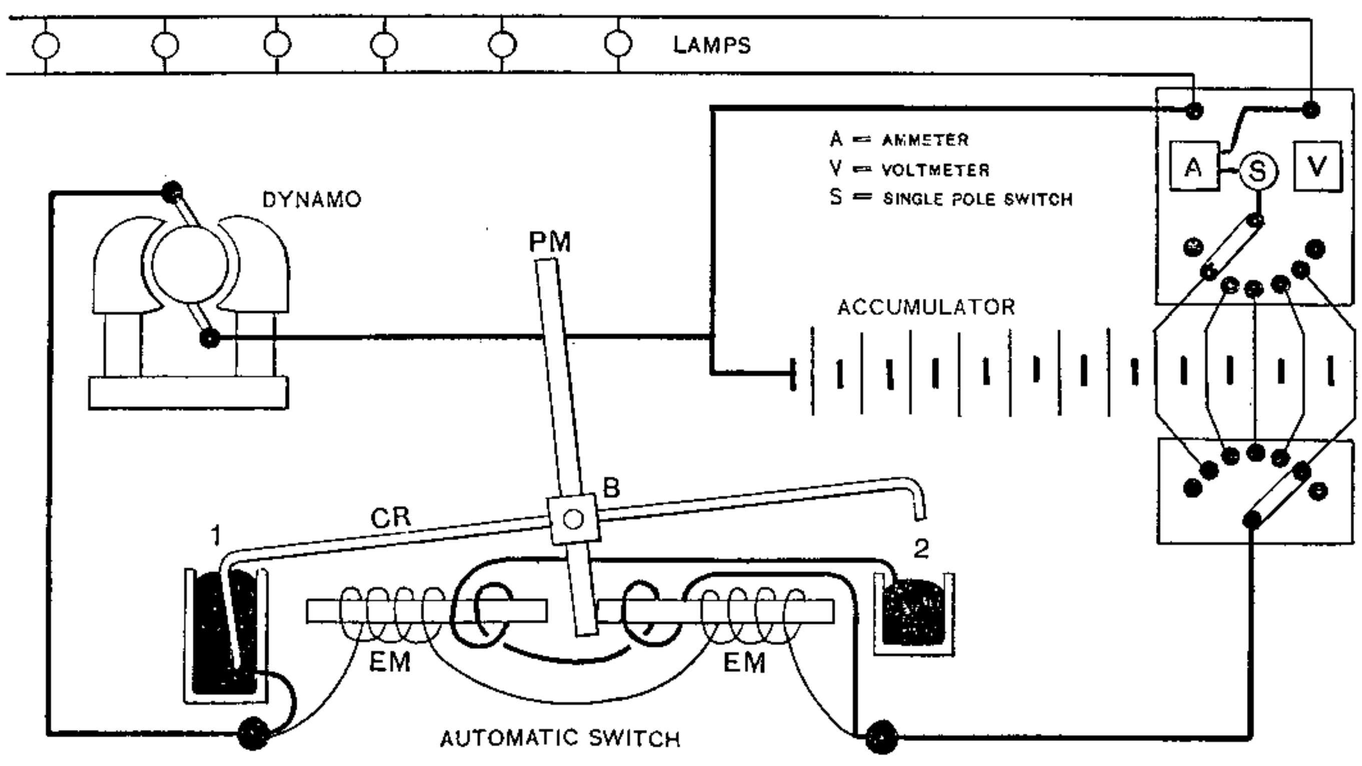


Fig. 73.—Diagram of Connections for a Wind-driven Electrical Installation.

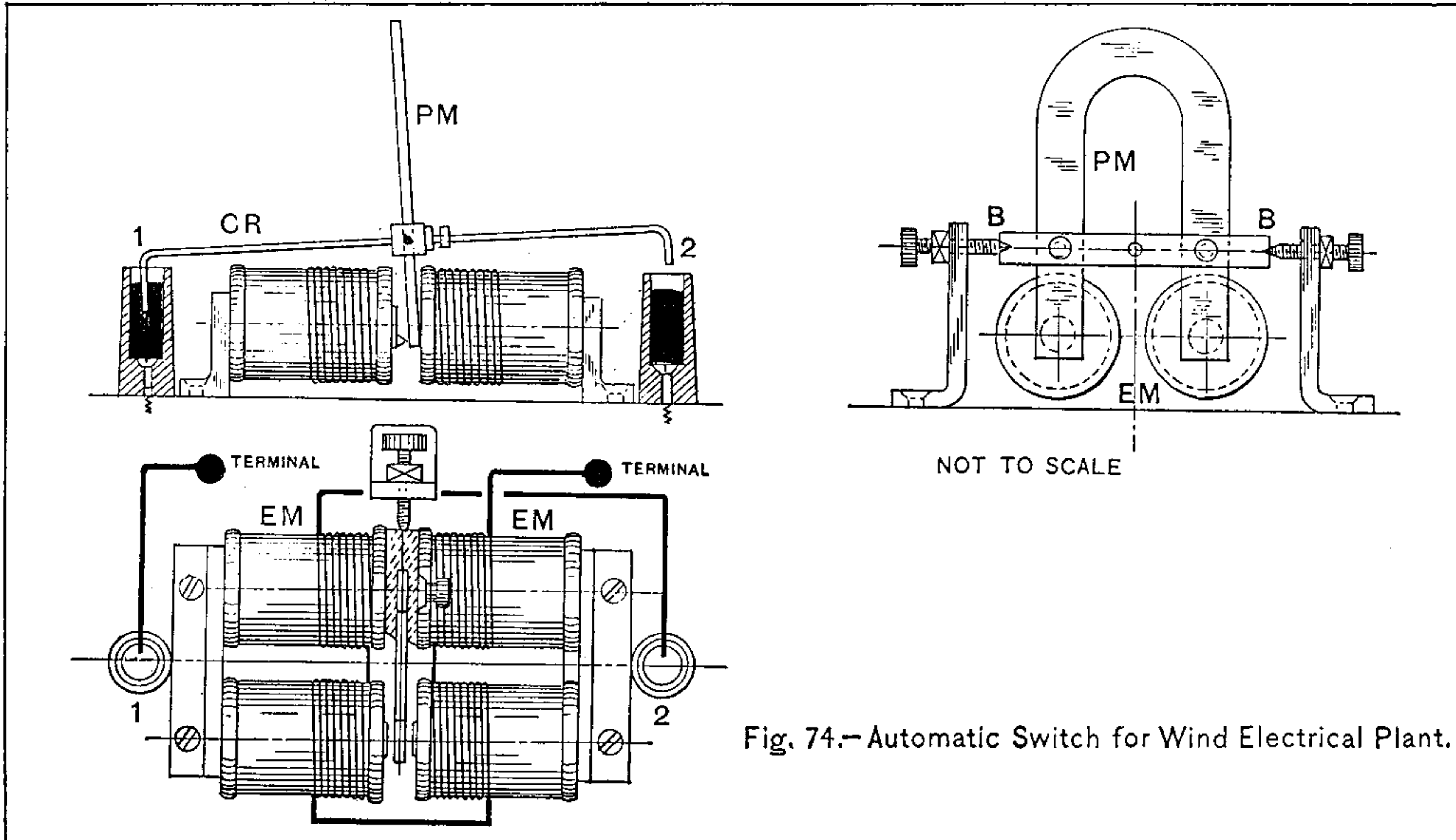


Fig. 74.—Automatic Switch for Wind Electrical Plant.

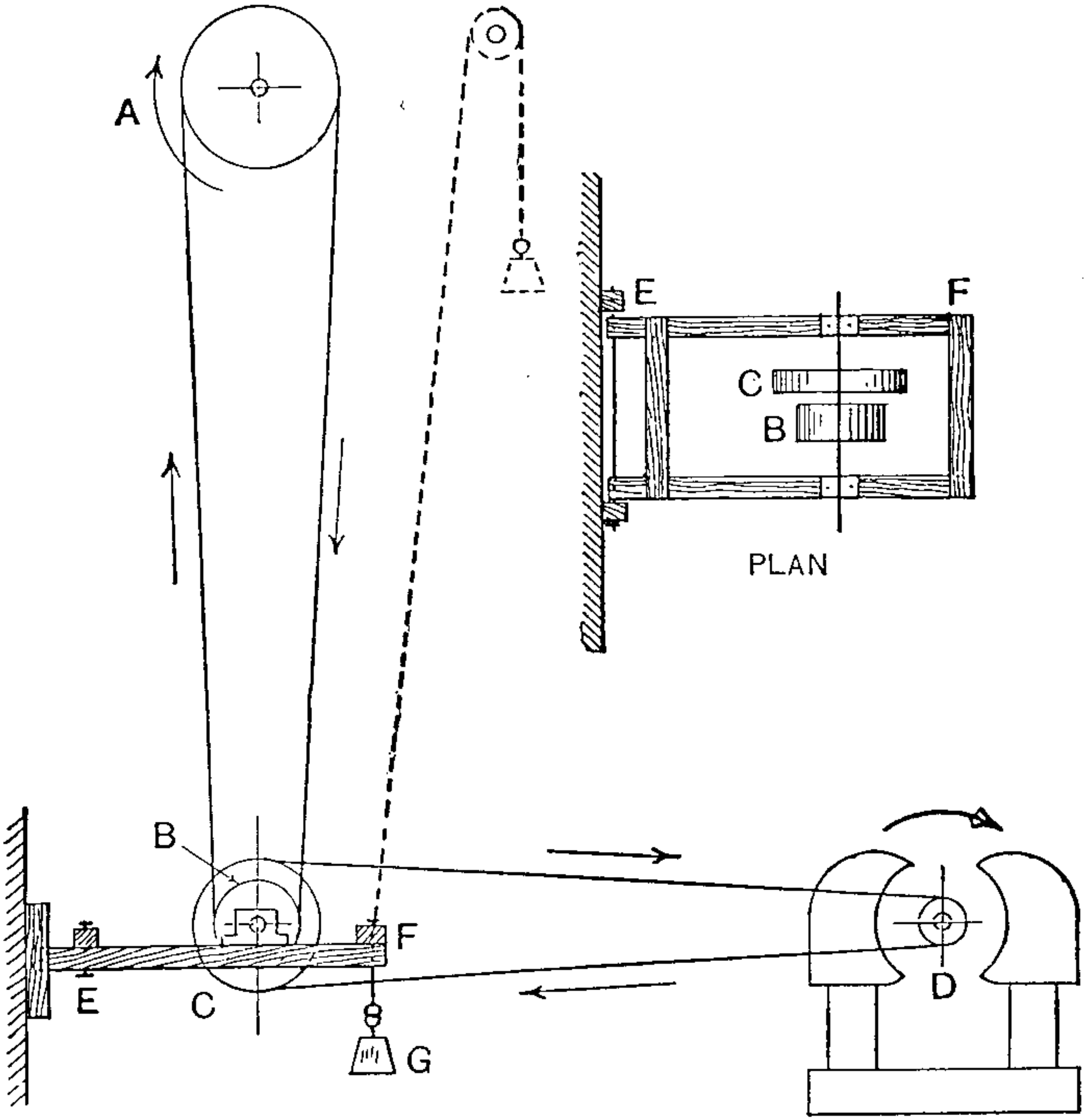


FIG. 75.—Driving Belt Arrangement for Wind Electrical Plant.

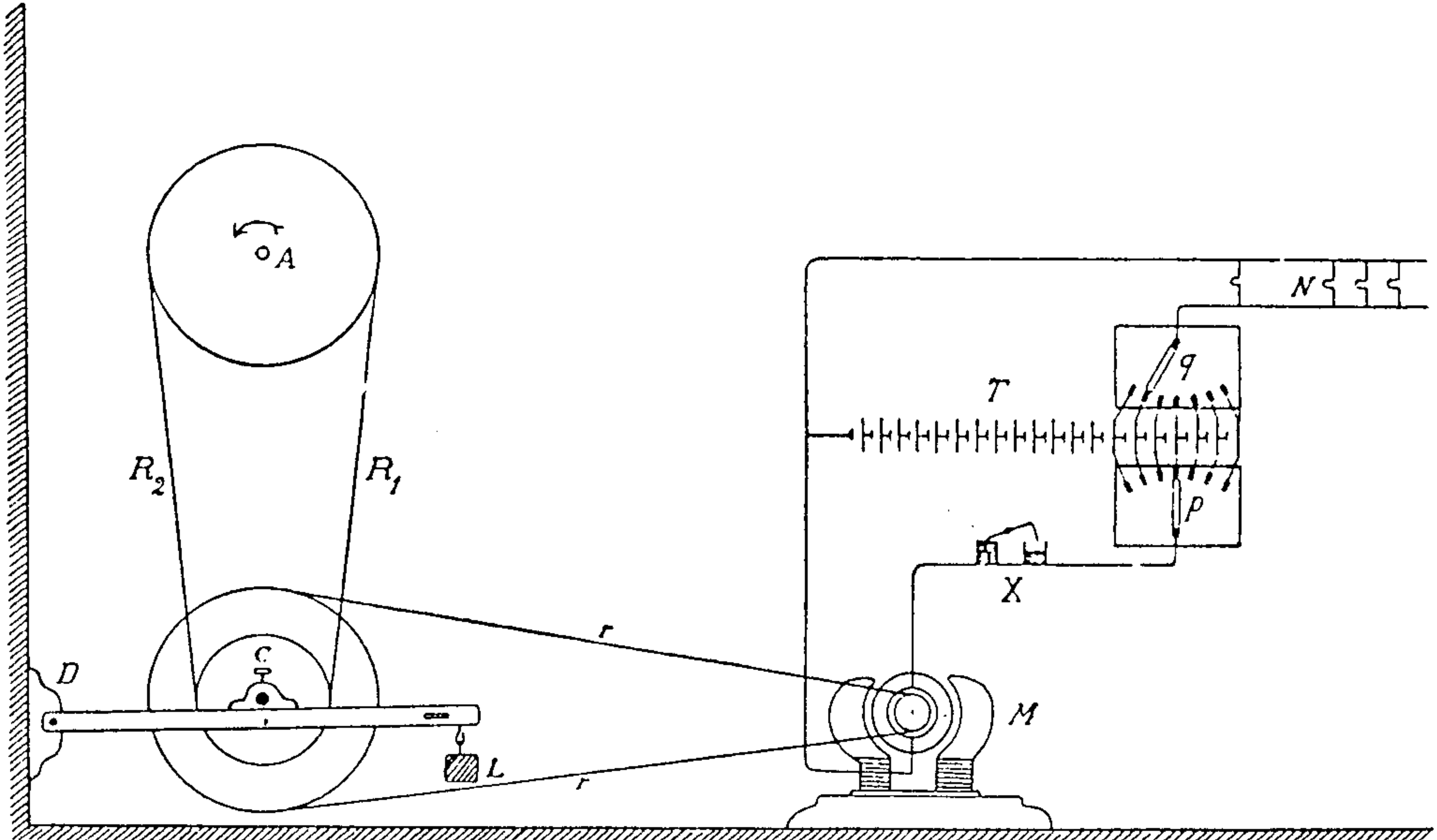
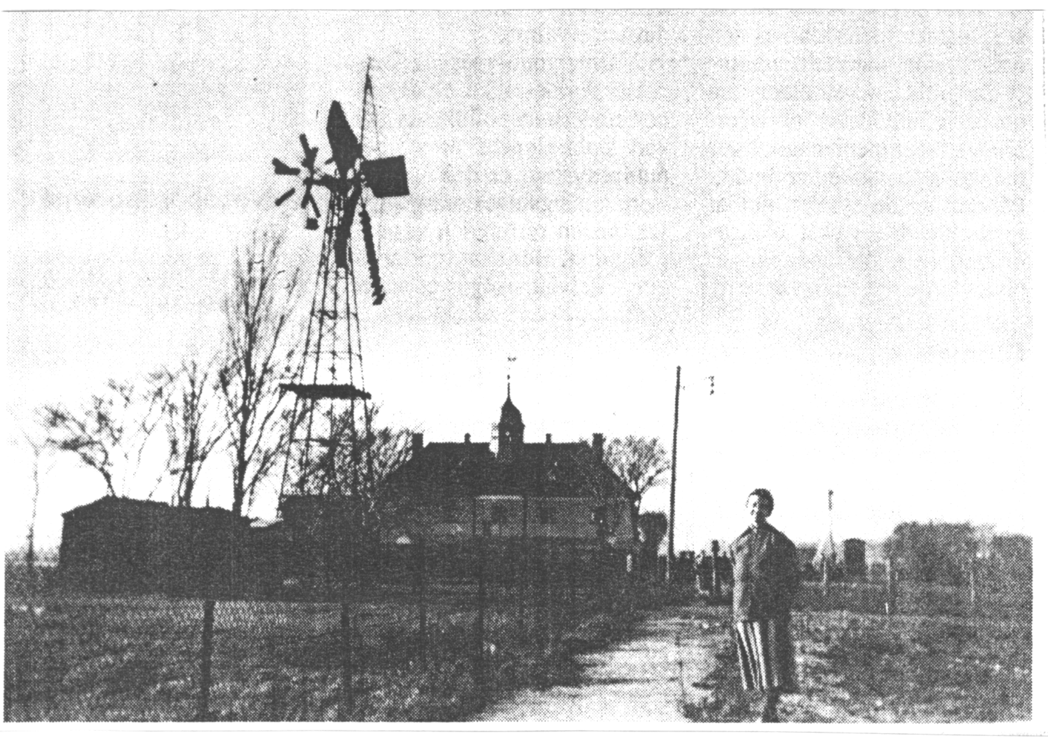


Fig. 5. Konstant elektrisk Strøm.

Wind machine for mechanical power, for farm or small factory use. Photographed in March 1994.



Wind-turbine of Type 1 - 1.5 built 1904. 10 kW DC Generator
Tower height 17 m. Blade diameter 16 m.
Sited in Copenhagen Harbour, in operation until 1957.
This was a combined wind-turbine - petroleum spark ignition motor generator.

Agricco wind turbine - designed by Vinding and Jensen - Denmark 1918
5 - 12.5 meter rotor-diameter. 40 kW asynchronous induction generator
In production from 1918 - 1926.
For further details:
www.vindhistorie.dk
Danske Elproducerende Vindmøller 1892 - 1962 - Elmuseet DK 1996
Lærebog i Maskinlære - 2nd edition, P. Schrøder Copenhagen 1924

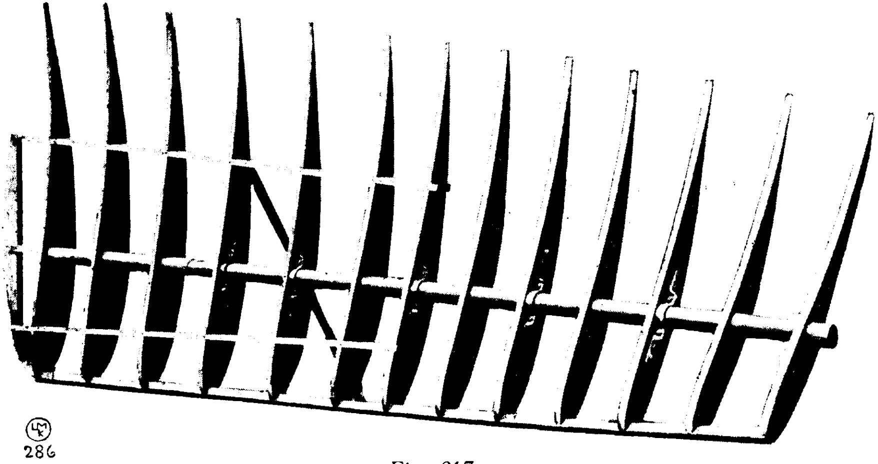


Fig. 617.

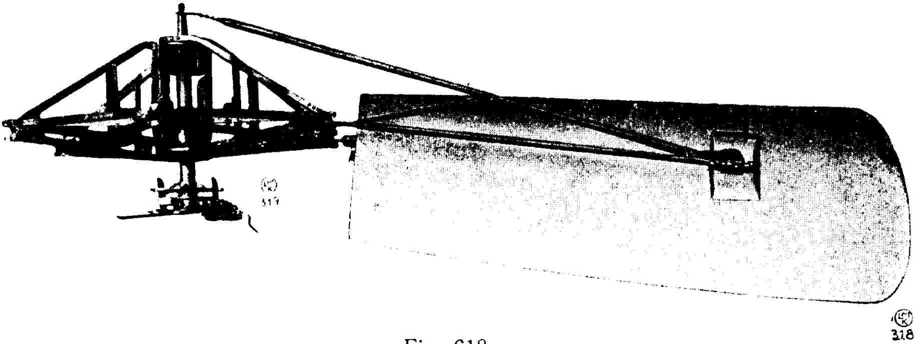


Fig. 618 a.

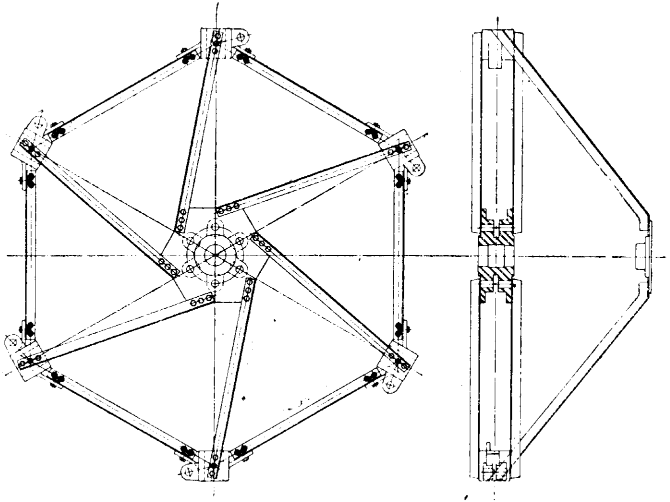


Fig. 618 b.

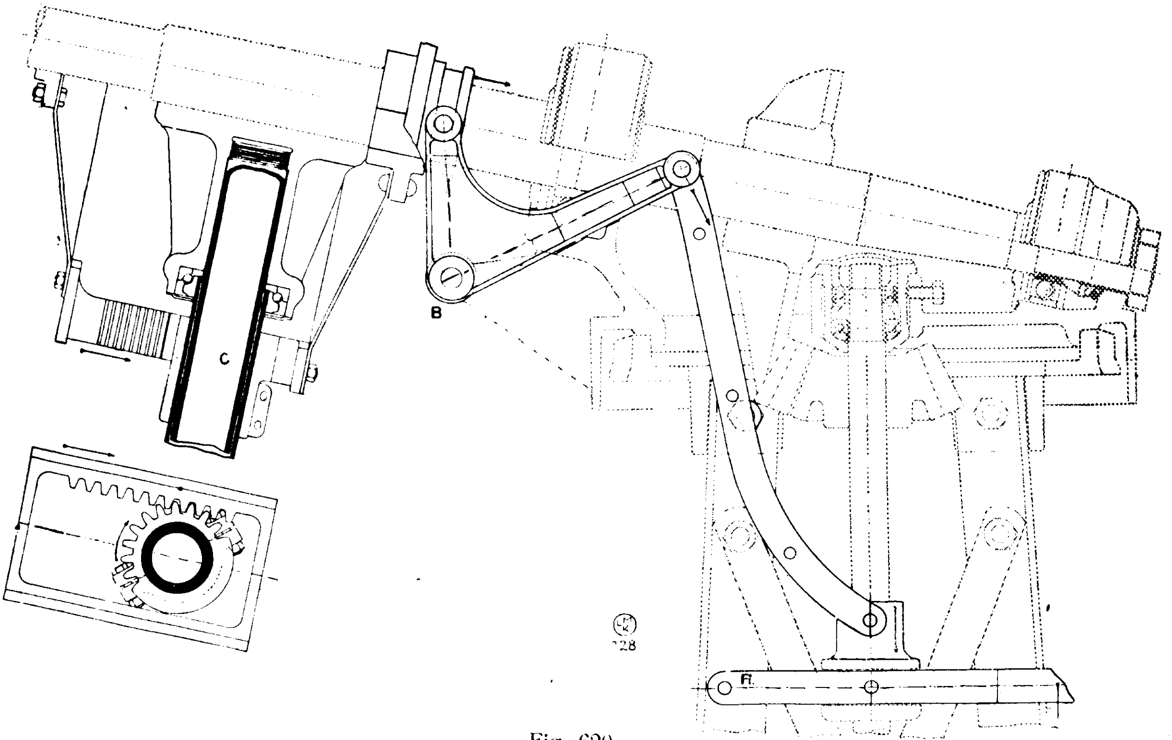


Fig. 620.

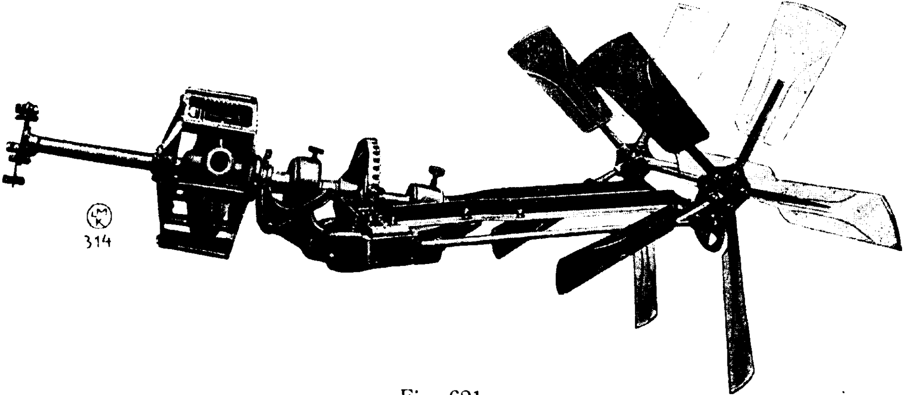
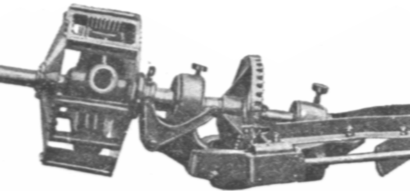
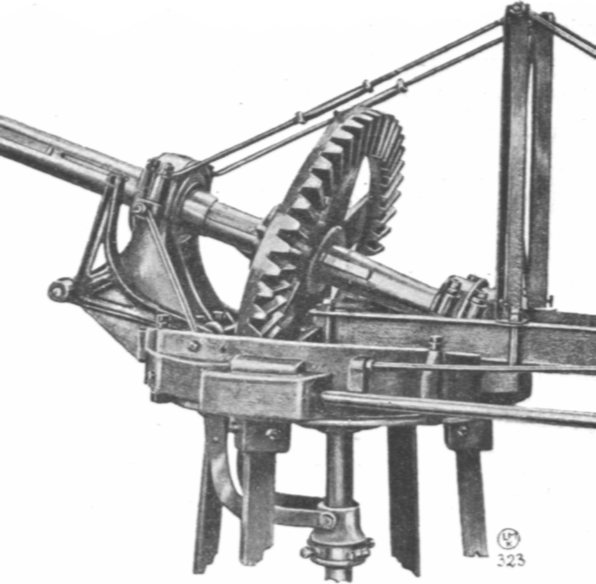
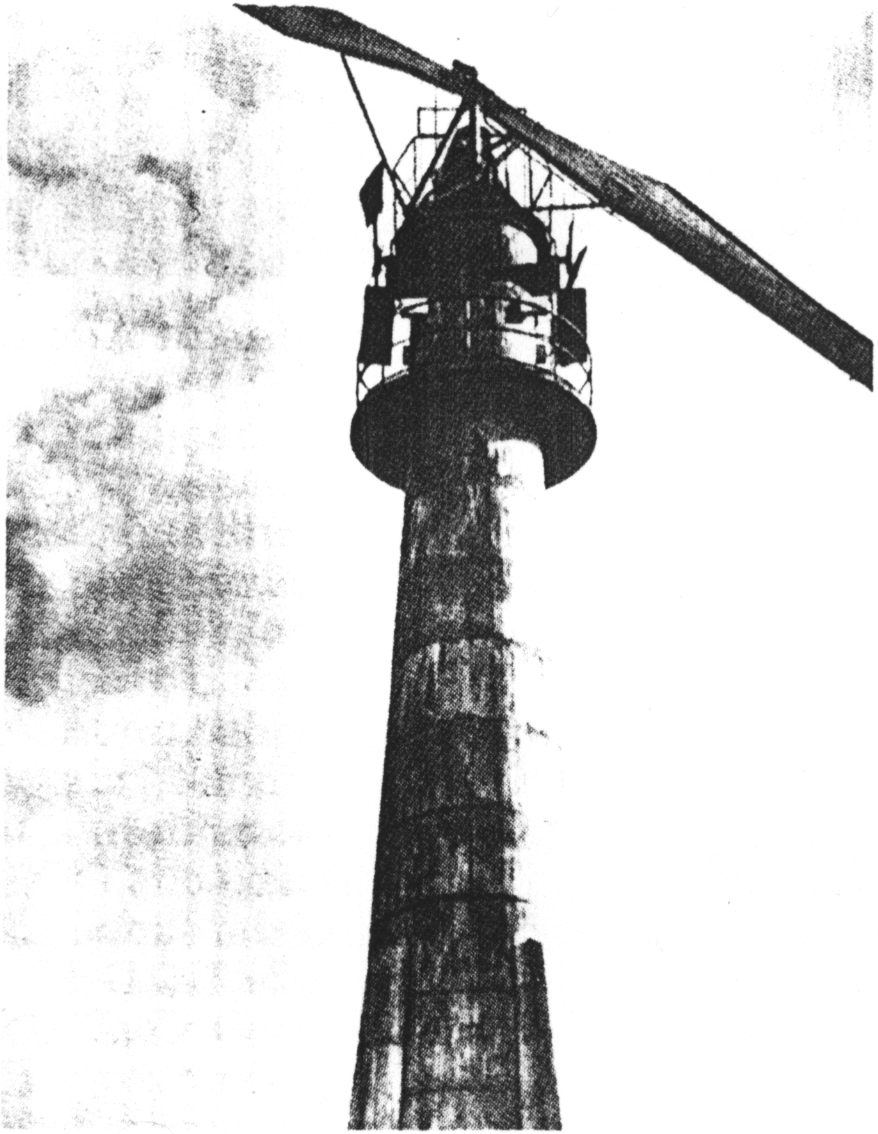


Fig. 621.



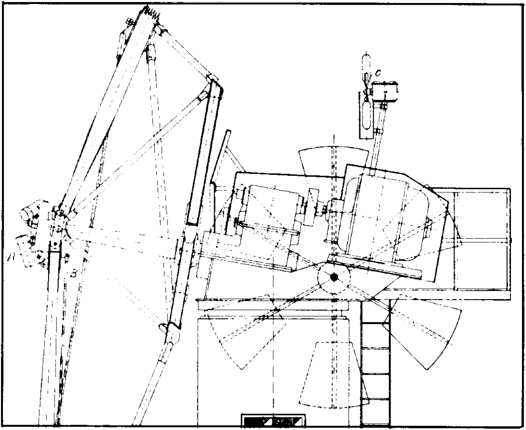


323



F.L. Smidth "Aeromotors". 1941-43 the company erected 12 2-bladed and 7 3-bladed DC wind turbines with generators of about 60-70 kW.

Period Type 2 : Designed for low wind speeds
2-bladed 17.5 m. diameter. 70 kW 3-bladed 24 m. diameter.
Spar of laminated wood, 2-stage gear.



C
A
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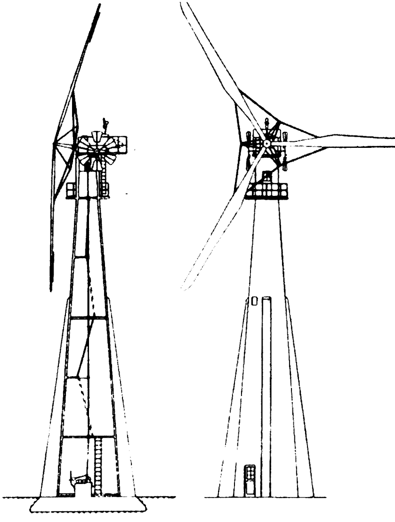
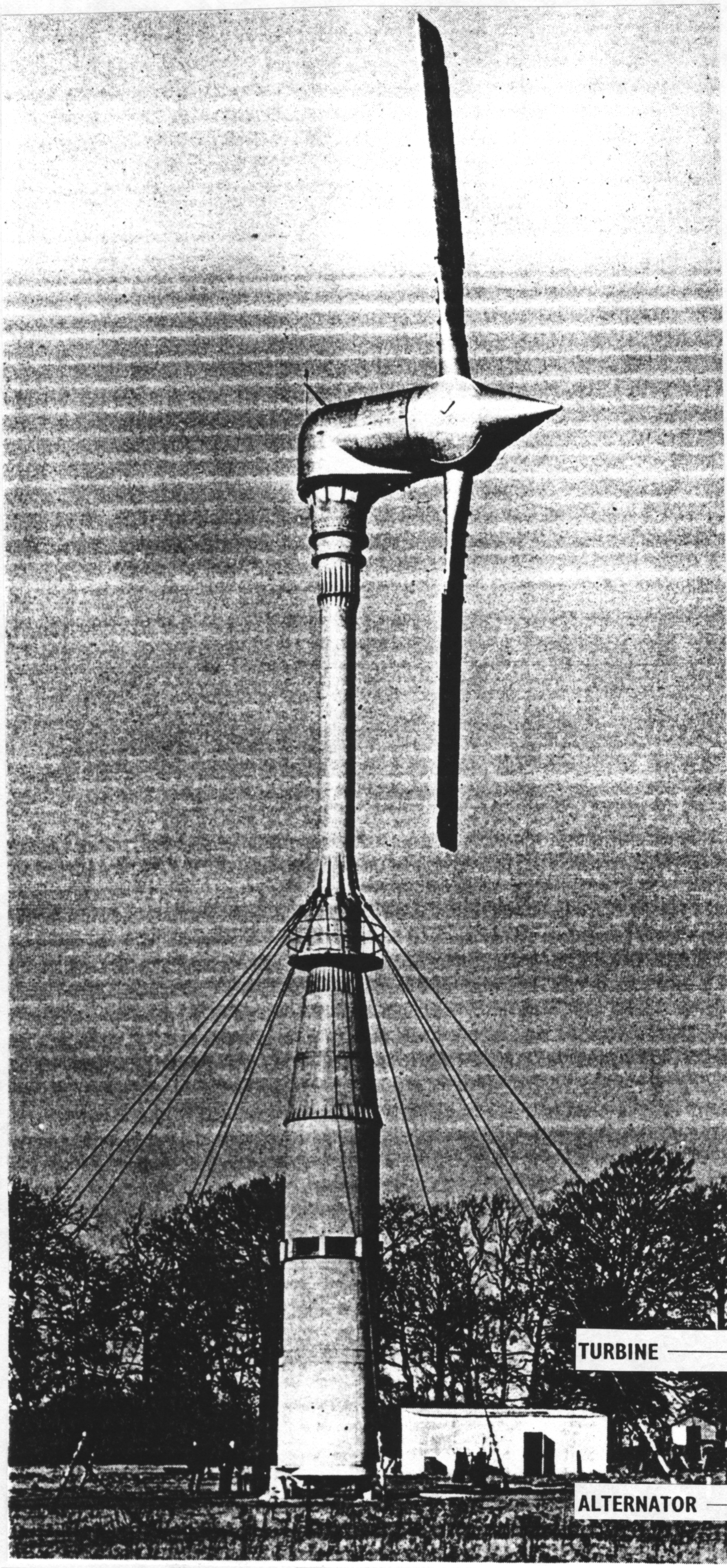
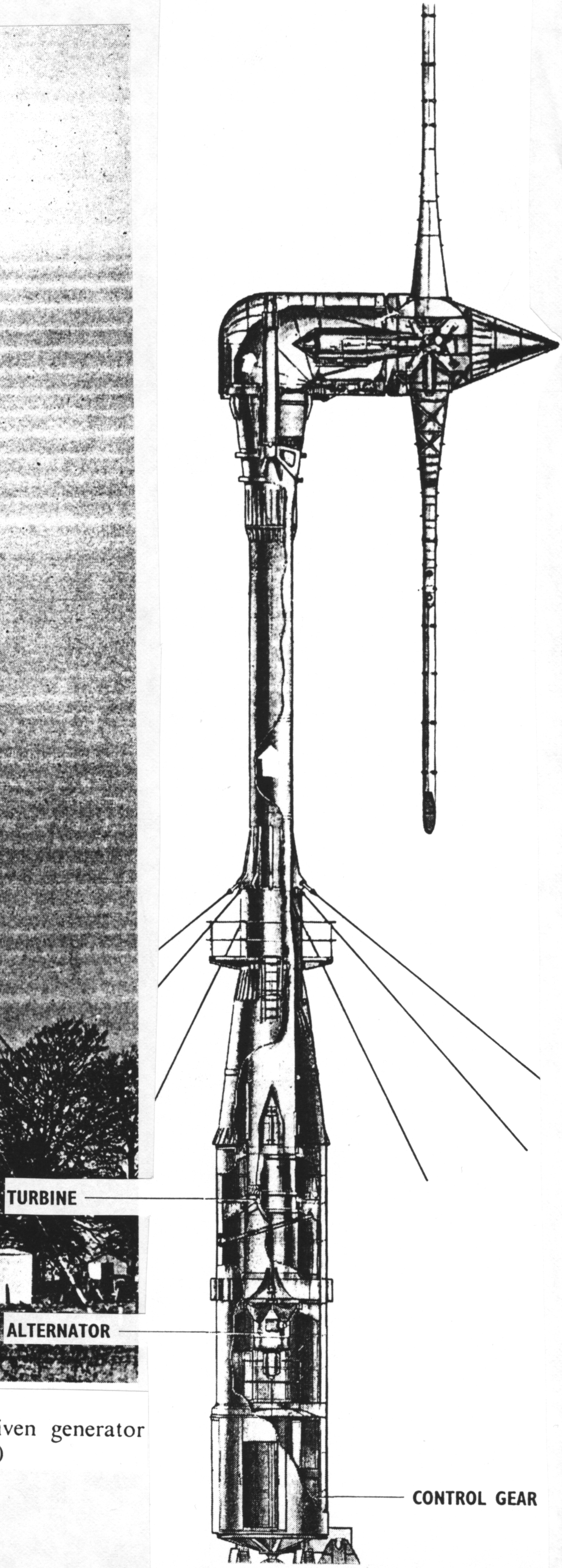


Figure 6. Research windmill of J. Juul, utility company SEAS, at the island Bogø. Early 50s, 45 kW AC.



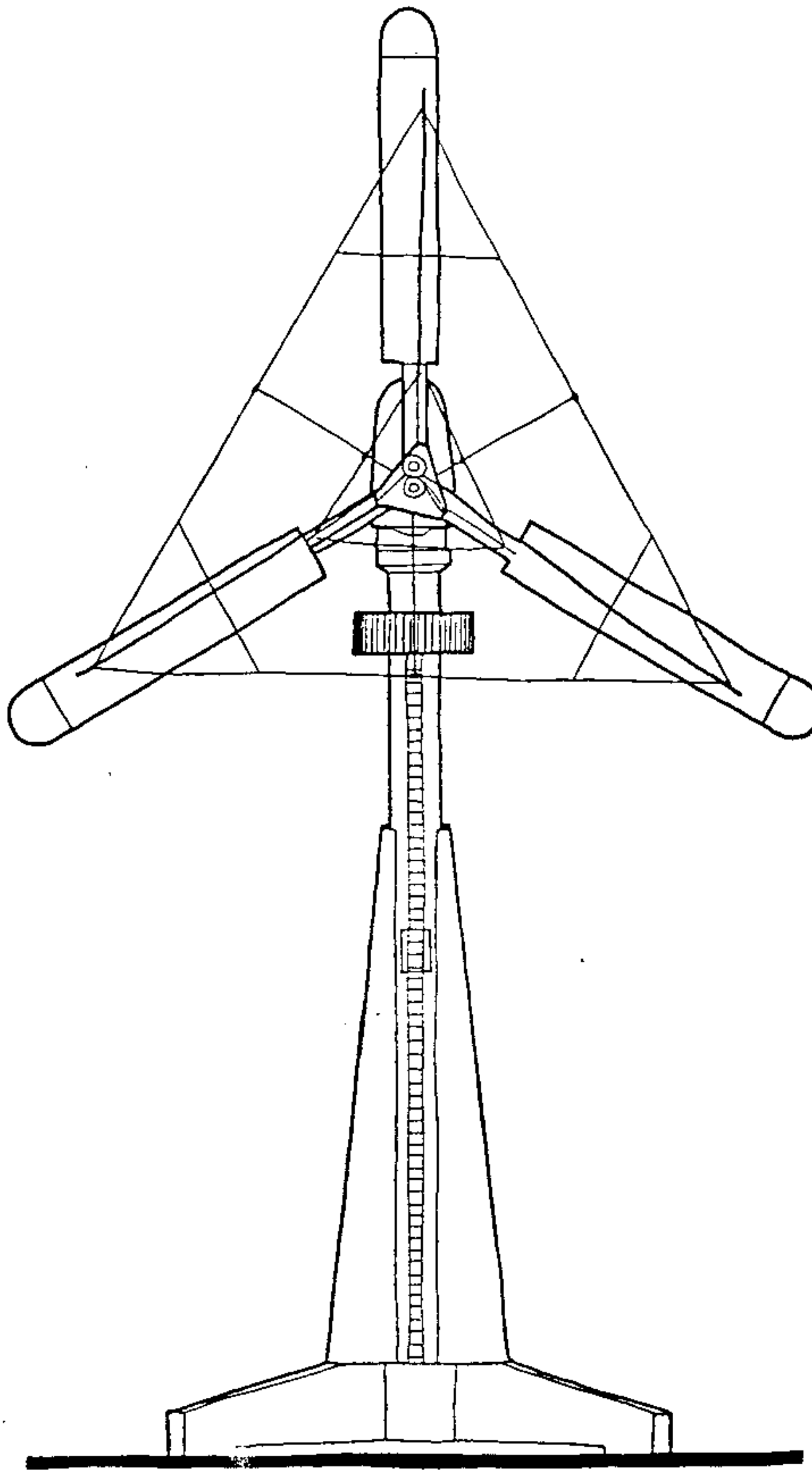
Showing the 100 kW Enfield-Andreau wind-driven generator on St. Albans test site. (*Enfield Cables Ltd.*)



The 200 kW Gedser wind turbine.

Period Type 3   1955 - 1967, and from 1977.
This machine, was the first modern reliable wind-turbine, now at the Danish electrical museum.

75 ft wind turbine at Gedser, Denmark, in operation since 1957. The 200 kW machine generates about 400,000 kWh/year, roughly one third of the output of the Smith-Putnam turbine. From J. McCaull, 'Windmills', Environment, Jan/Feb 1973 p. 8



Energy Environment and Building Philip Steadman
Cambridge Uni. Press UK / USA 1975 ISBN 0-521-09926-9

Freja 1974 , Architect School Copenhagen Denmark 1974 p. 44

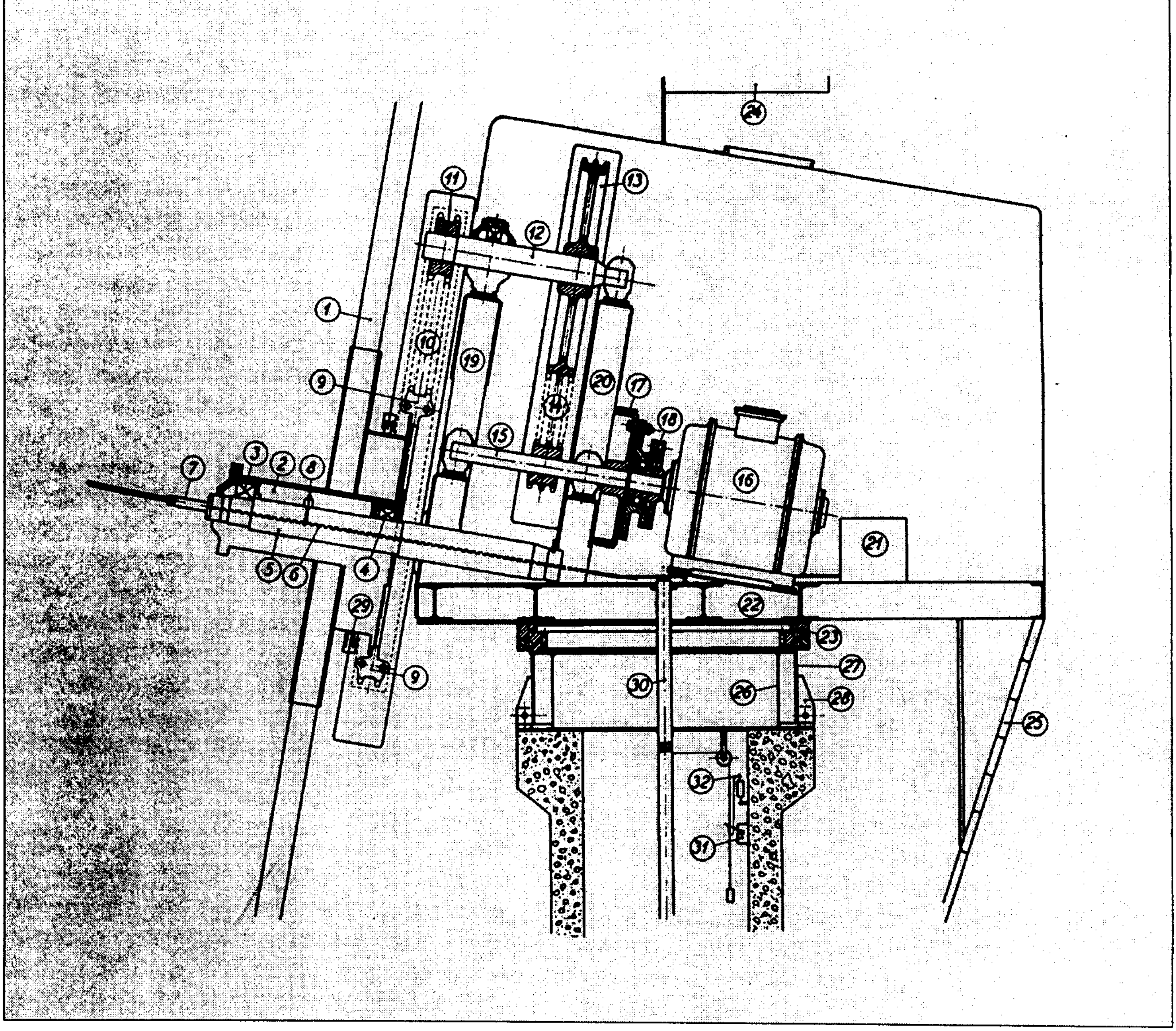
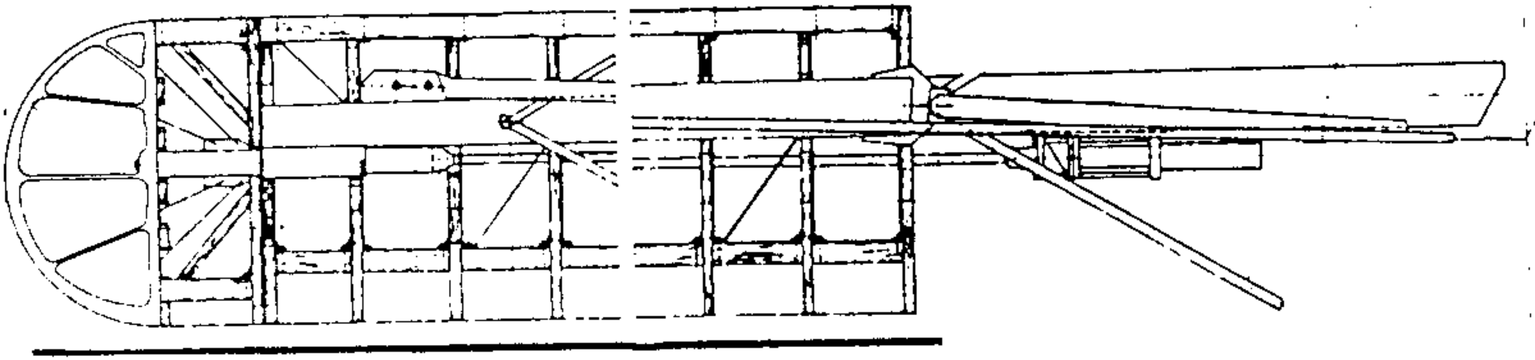


Fig. XVIII. Konstruktion af Gedsermøllens hat. (Fra Vindkraftudvalgets Betænkning, 1962)
1) vinger 2) nav 3-4) hovedlejer 5) dorn 6) hydraulikforbindelse til vinger 7) drejeunion 8) sikkerhedsventil 9-11) langtsomgående geartrin 12) mellemaksel 13-14) hurtigtgående geartrin 15) hurtigtgående aksel 16) generator 17) håndbremse 18) elastisk kobling og brudkobling 19- 20) lejebukke 21) hydraulikstation 22) bundramme 23) krøjeleje 24) vindfløj 25) stige til hat 26-28) målecylindre og lasker 29) tætning 30) gummirør til kabler 31-32) vipperelæ.

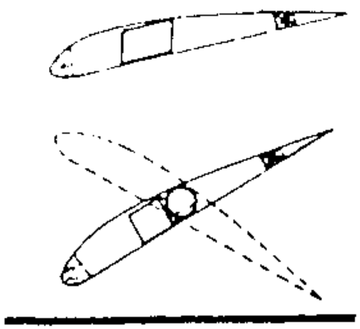
Wing for Gedser Wind Turbine: Angle in relation to the plane of rotation:

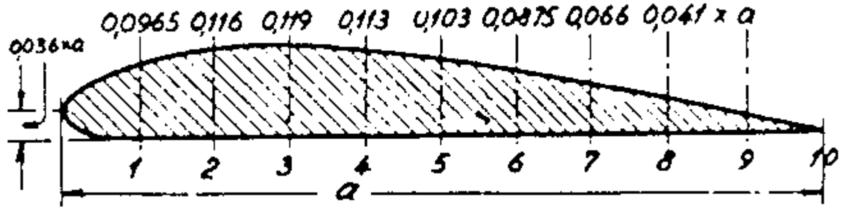
16° at the Axle

4° at the wing tip



GEDSER WIND TURBINE WING





Gedsermøllens vingeprofil

GEDSER WIND TURBINE WING PROFILE

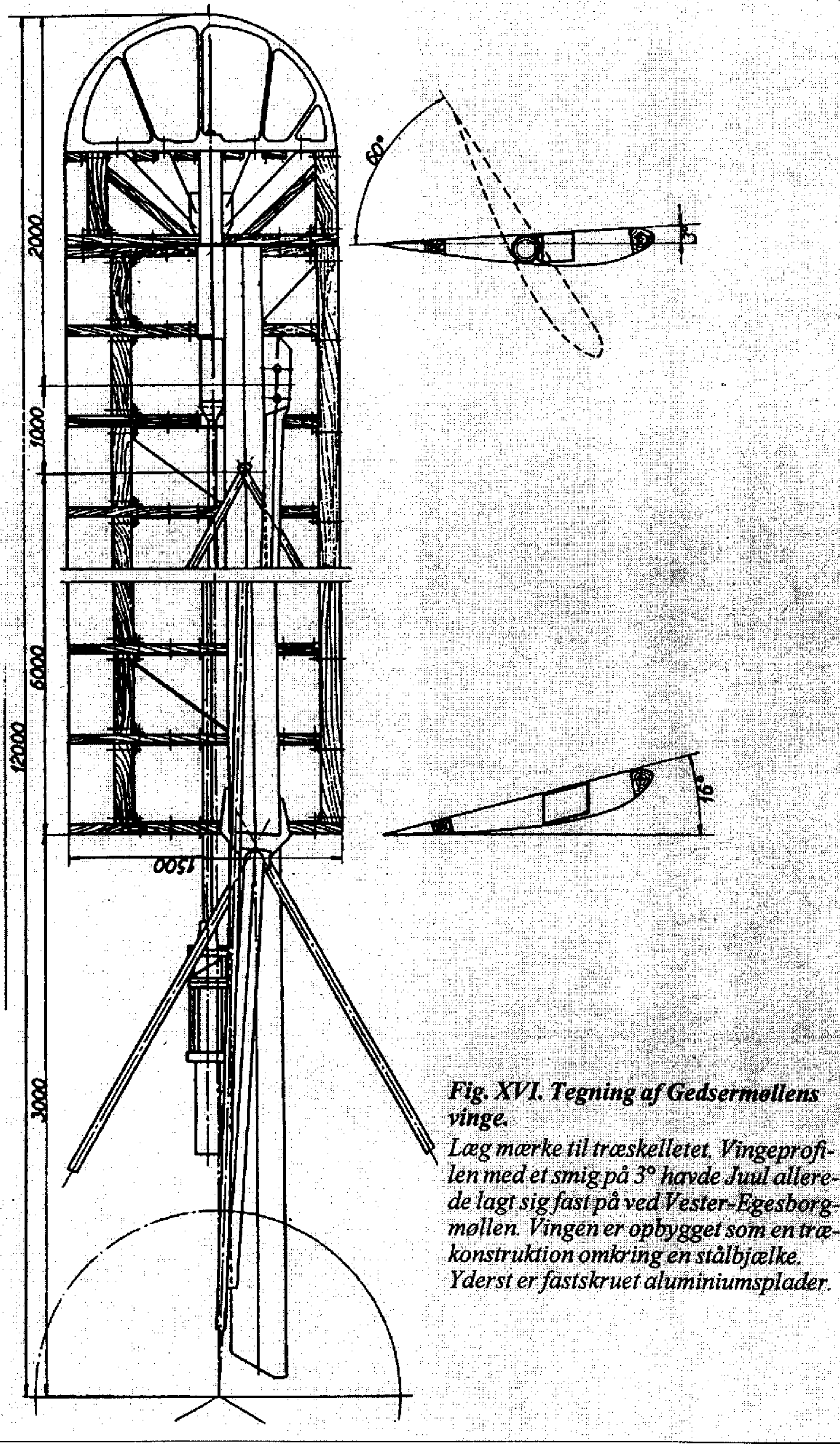
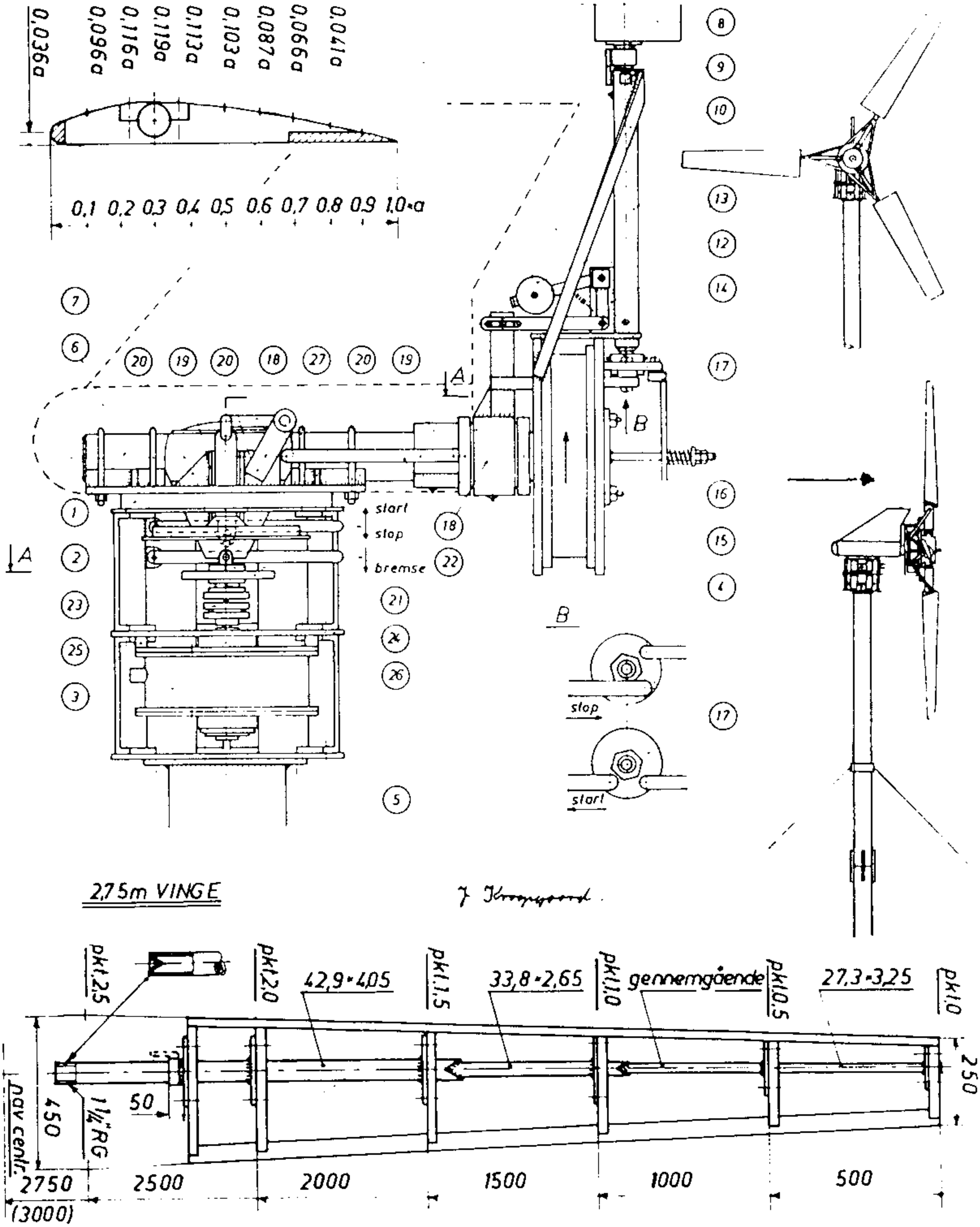


Fig. XVI. Tegning af Gedsermøllens vinge.

Læg mærke til træskelletet. Vingeprofilen med et smig på 3° havde Juul allerede lagt sig fast på ved Vester-Egesborgmøllen. Vingen er opbygget som en trækonstruktion omkring en stålbjælke. Yderst er fastskruet aluminiumsplader.



Wing based on Gedser-type, Denmark 1975.
Designed by mechanic G.Broe, and engineers Krogsgaard and Ottesen

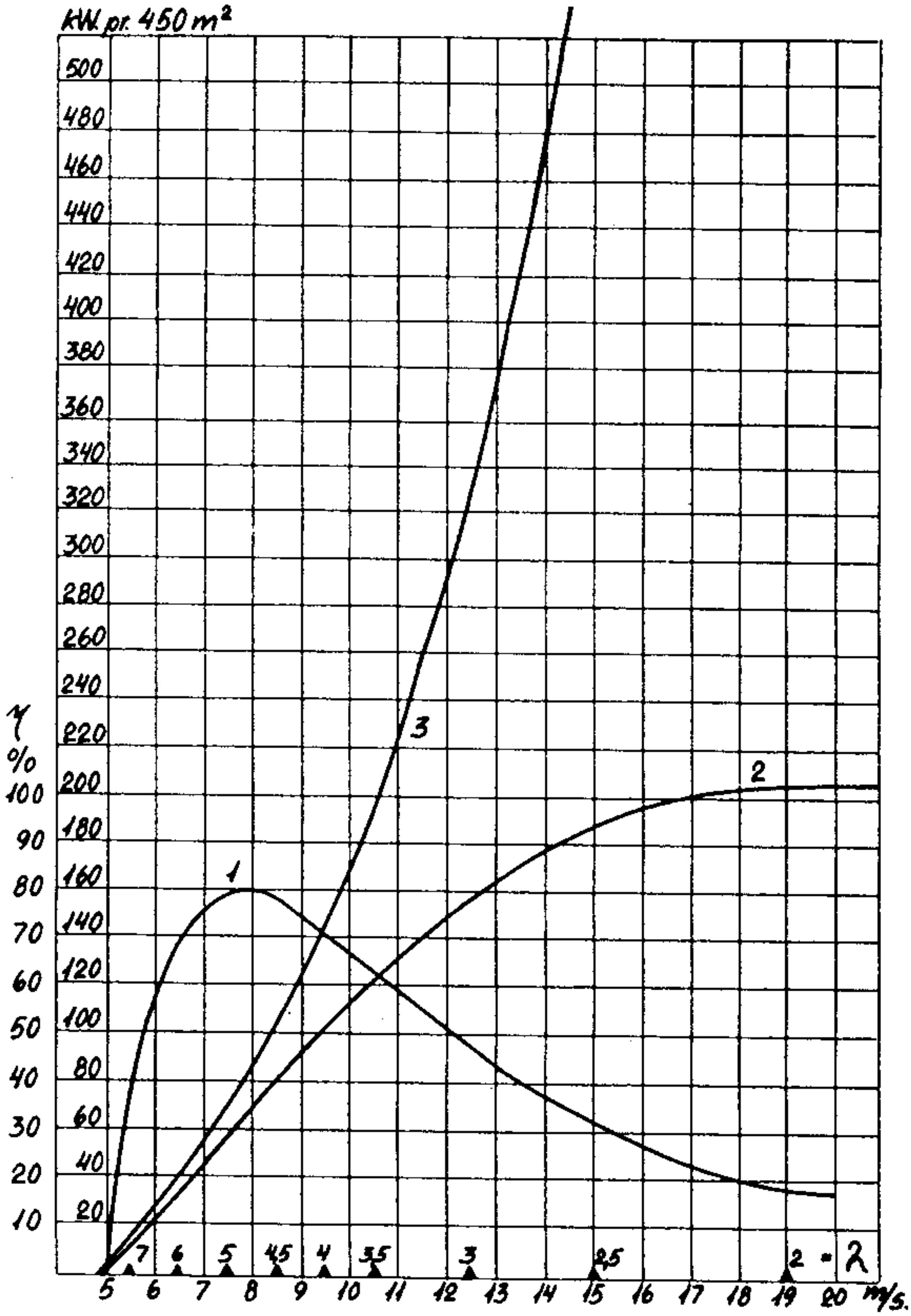
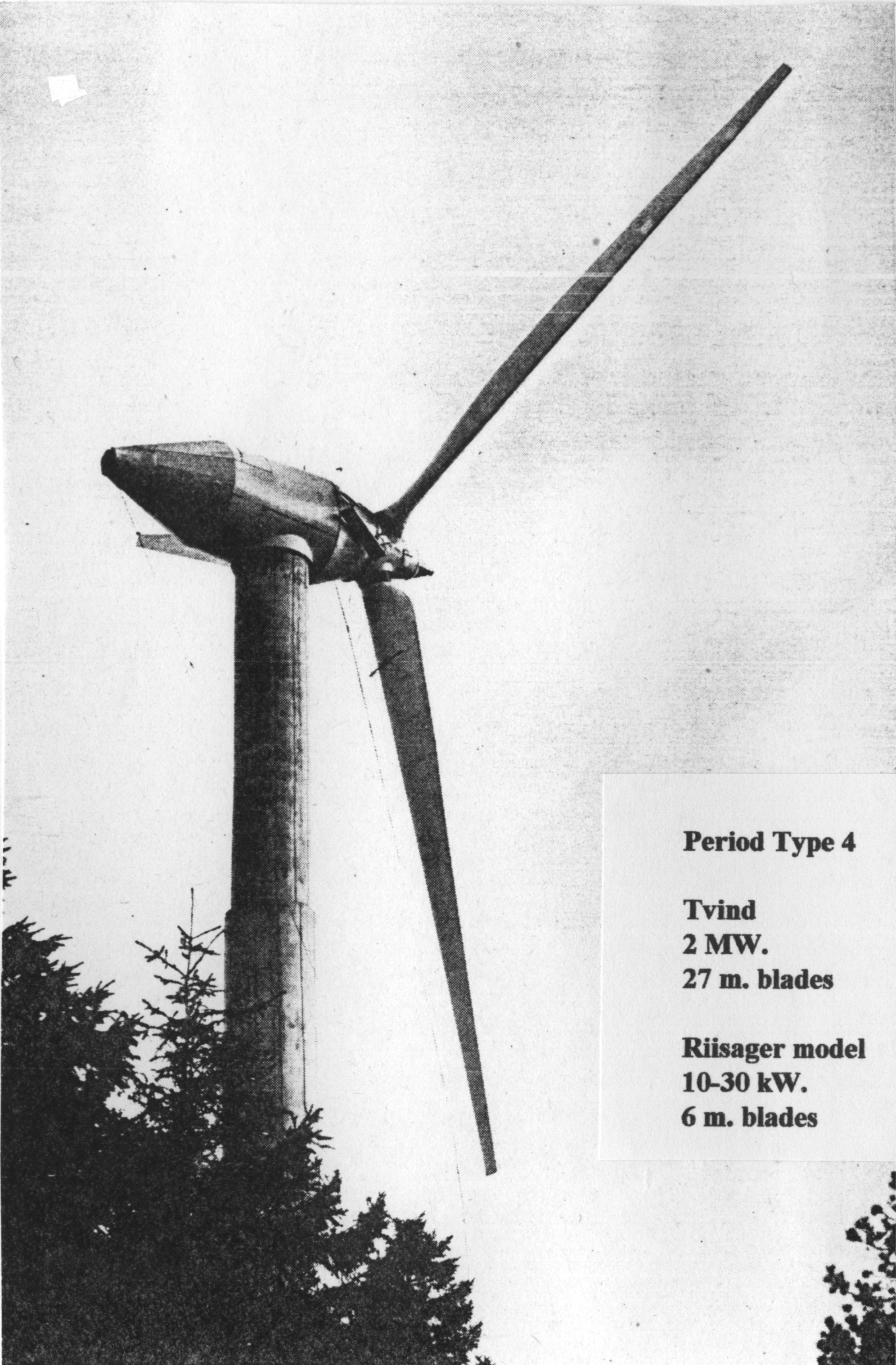
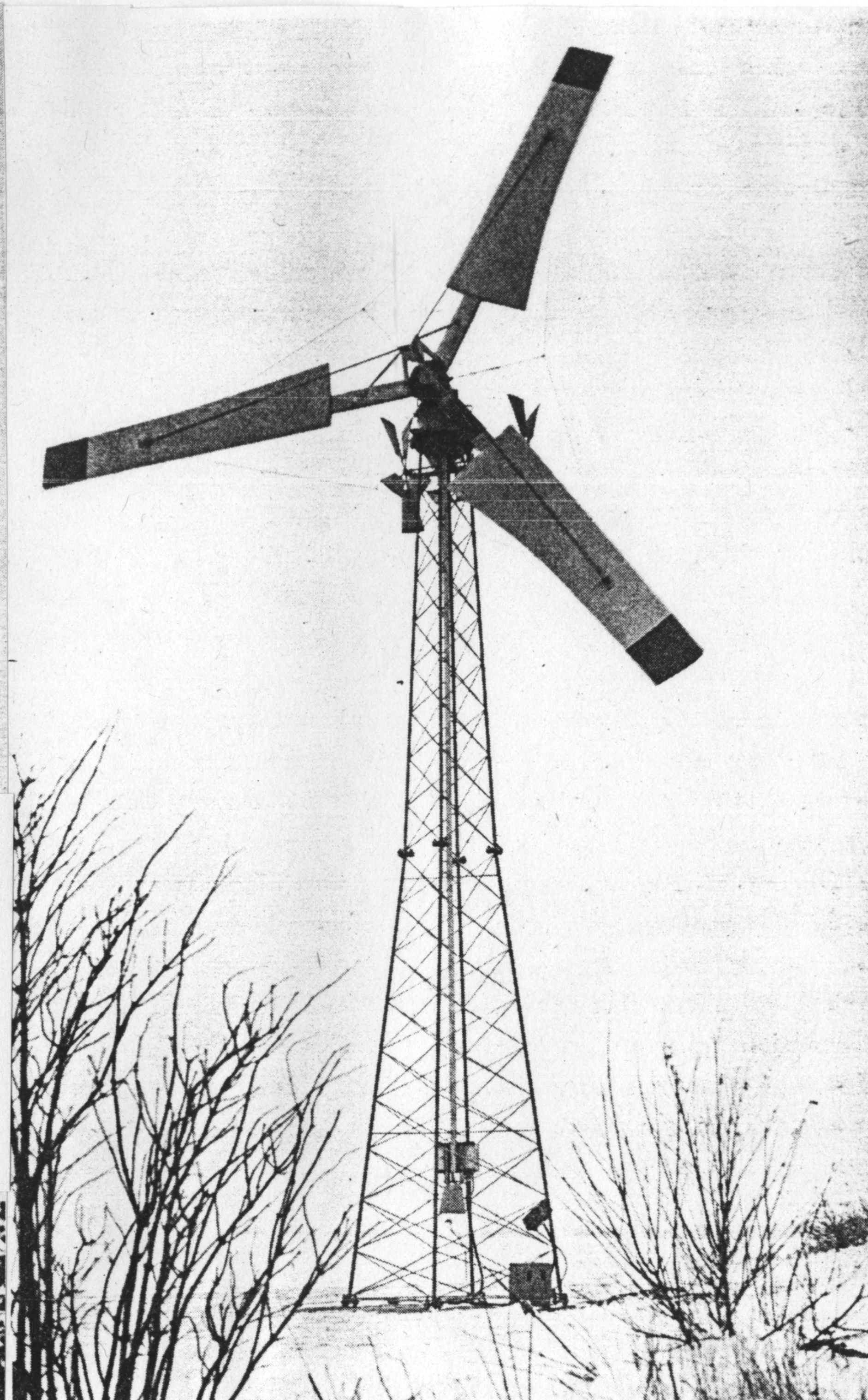


Fig. XV. Effektkurve og virkningsgrad for Gedsermøllen. (Fra Vindkraftudvalgets Betænkning, 1962)

Kurve 1. Gedsermøllens virkningsgrad.
Kurve 2. Gedsermøllens effekt.
Kurve 3. Vindenergi beregnet efter formlen $D^2 \cdot V^3 \cdot 0{,}000285$.
Med $D = 24$ m

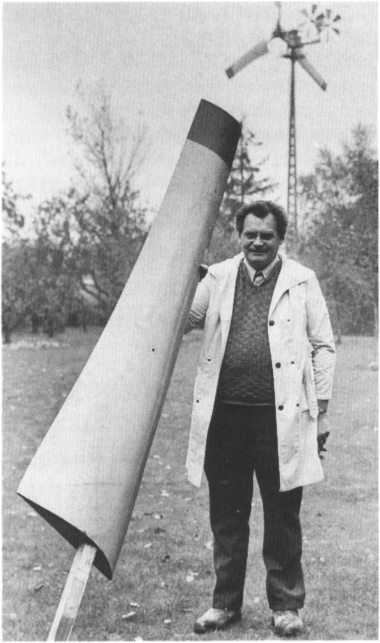




Period Type 4

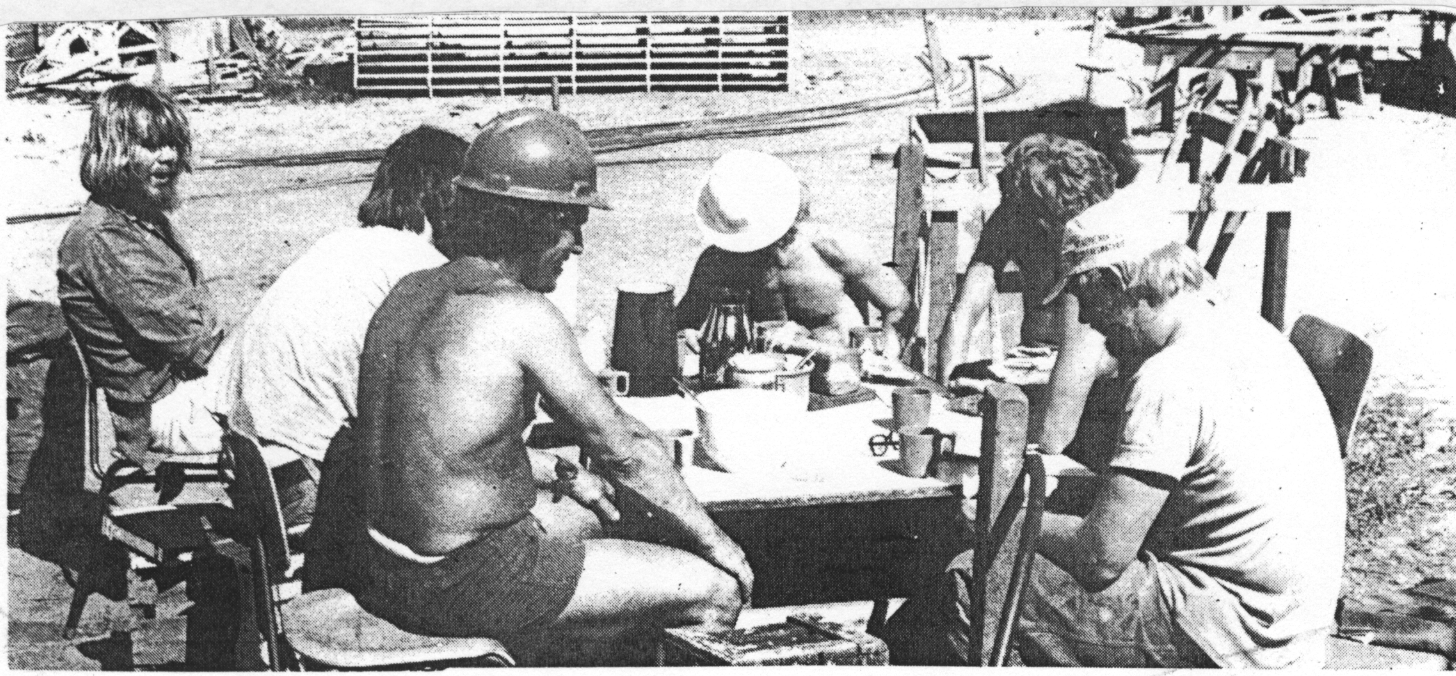
Tvind
2 MW.
27 m. blades

Riisager model
10-30 kW.
6 m. blades

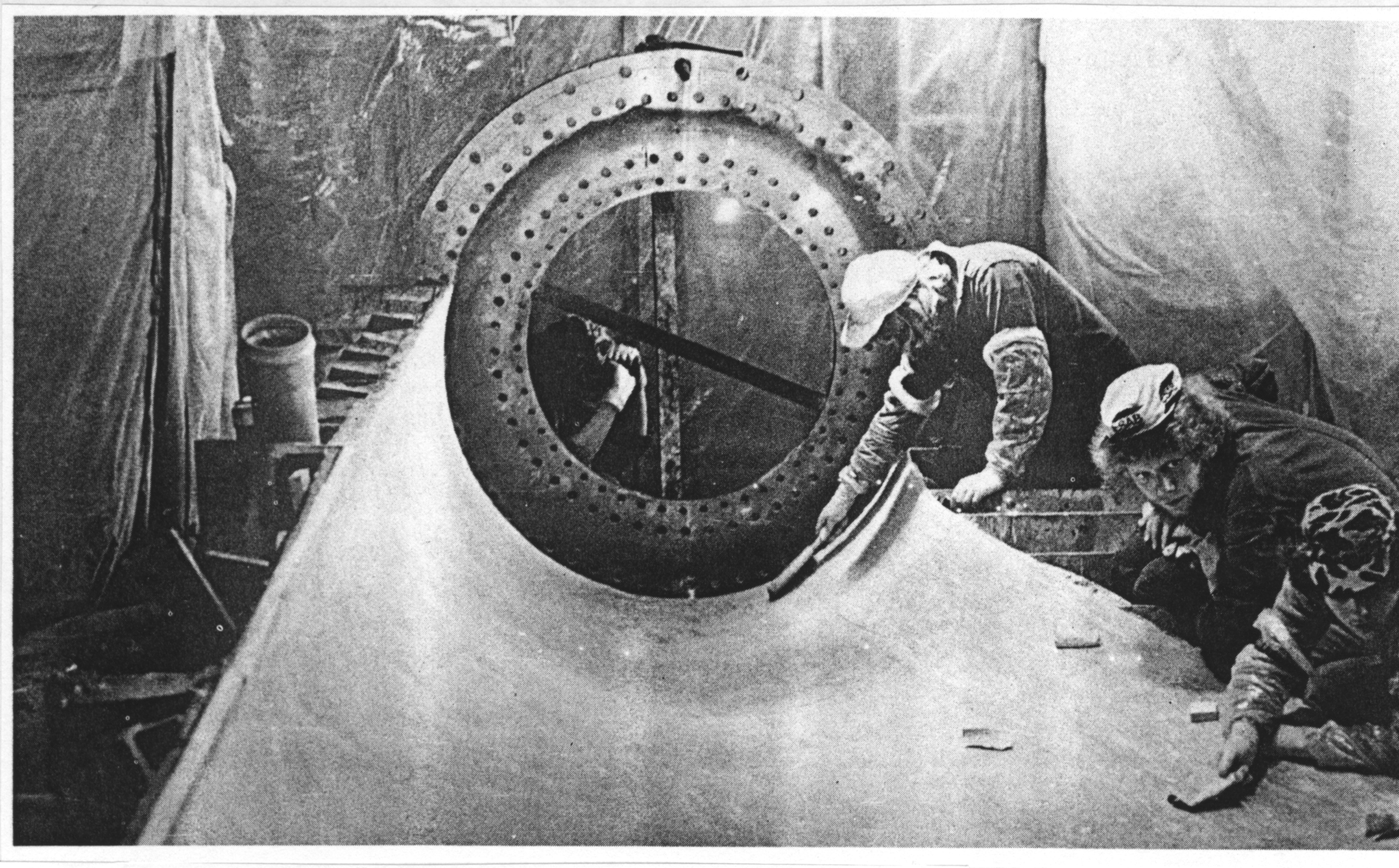


Christian Riisager med sin hjemmelavede vinge og med sin private vindmølle i baghaven. Foto: Chr. Riisager.


ELMER

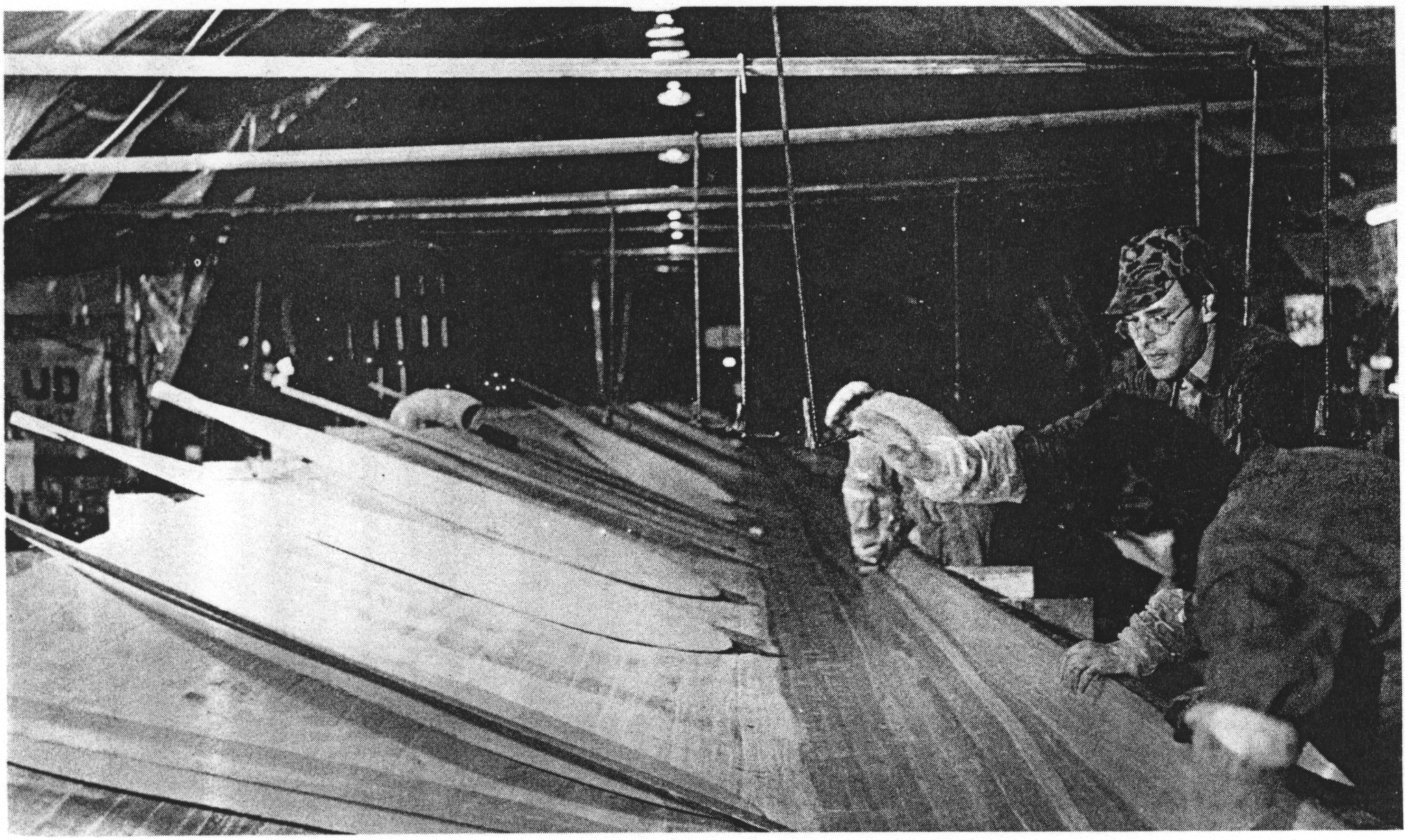


Tower-construction crew - Tvind Wind-Turbine - Summer 1975.

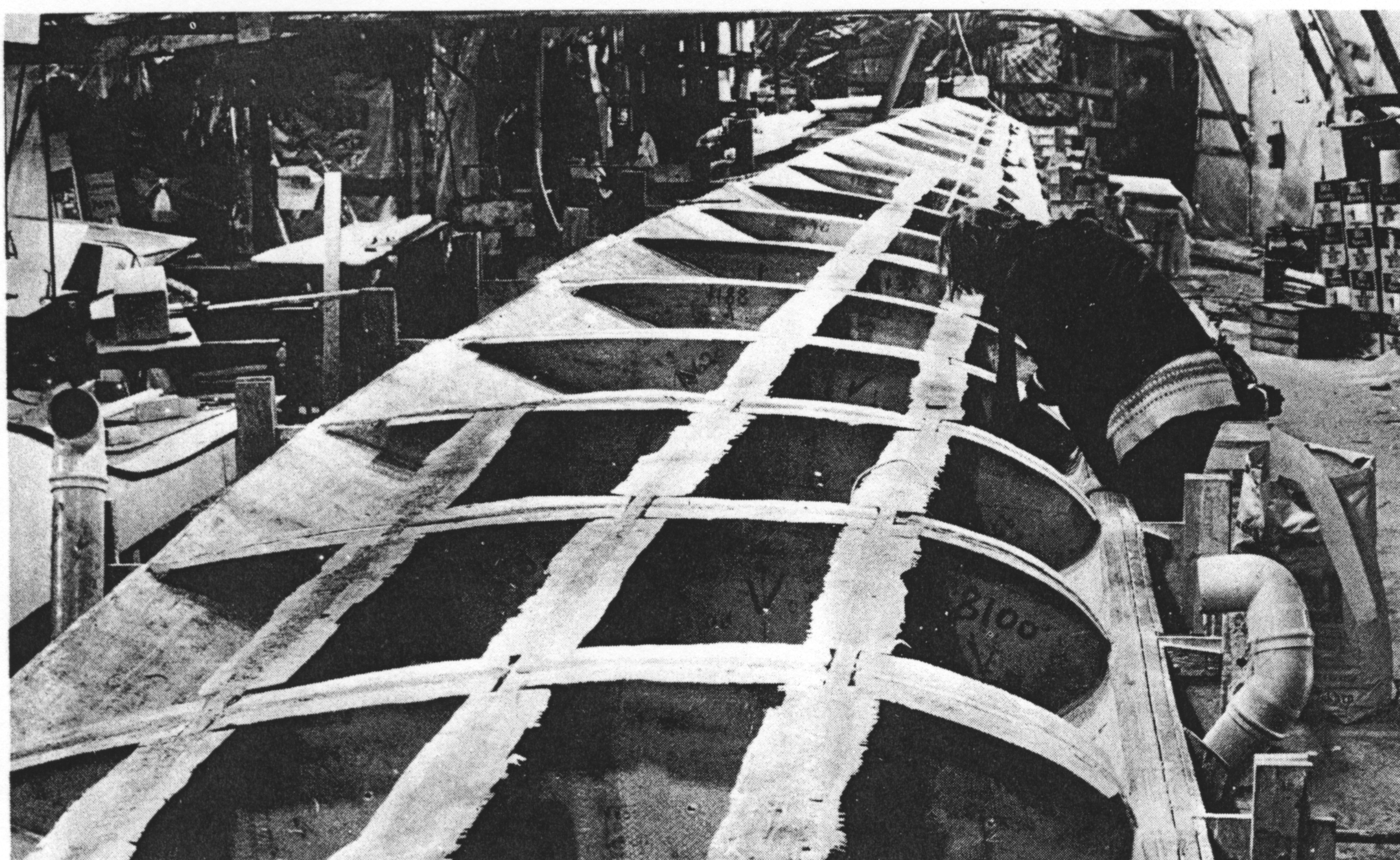


Blade-root construction - Tvind Wind-Turbine - Summer/Autumn 1977.

Glass-Fiber "sausage-roll" production for blades.



Glass-Fiber rolls being pressed down onto the mold - using a metal straight-edge.



Wing-Sections with sawn-out "Flamingo"- Polystyrol blocks.

Fiberglass (glass-reinforced polyester, or GRP to Europeans) has grown increasingly popular (see Figure 6-13). Like wood, fiberglass is strong, relatively inexpensive, and has good fatigue characteristics. It also lends itself to a variety of designs and manufacturing processes. Fiberglass can be pultruded, for example. Instead of pushing the material through a die, as in extrusion, fiberglass cloth (like the cloth used in fiberglass auto body kits) is pulled through a vat of resin and then through a die. Pultrusion produces the side rails for fiberglass ladders and other consumer products. The pultruded blades on Bergey Windpower's turbines can be easily identified by their constant width and thickness. Pultrusion gives Bergey's single-surface airfoil a strength and torsional flexibility not found in other constructions.

For pleasure boaters fiberglass has become the material of choice. In fact, the techniques used to build fiberglass boats have been successfully adapted by Danish, Dutch, and American companies to build wind turbine blades. These manufacturers place layer after layer of fiberglass cloth in half-shell molds of the blades. As they add each additional layer, they coat the cloth with a polyester or epoxy resin. When the shells are complete they

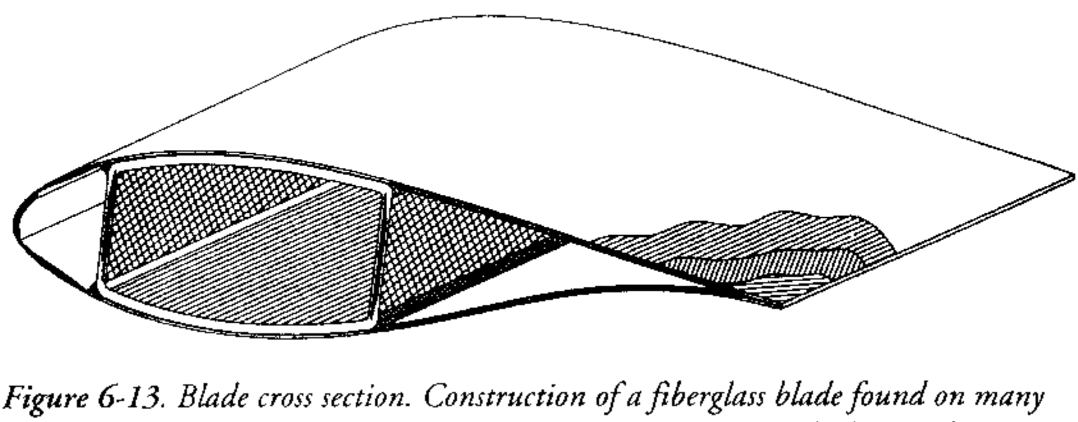


Figure 6-13. Blade cross section. Construction of a fiberglass blade found on many medium-sized wind machines. The central section is the spar, which provides the blade's principal structural support. (Vestas DWT)

literally glue them together to form the complete blade. Nearly all medium-sized European wind turbine blades are made with this technique.

Filament winding is another process where fiberglass strands are pulled through a vat of resin and wound around a mandrel. The mandrel can be a simple shape like a tube, or a more complex shape like that of an airfoil. Originally developed for spinning missile cases, filament winding delivers high strength and flexibility. Though some blades have been made entirely from filament winding, the process is often used only to produce the blade's main structural spar. The blade is then assembled in a mold with a smooth fiberglass shell using the boat-building technique.

Wind machines larger than 10 meters in diameter use induction generators almost exclusively. If you want a slow-speed, permanent-magnet alternator on a wind machine larger than 10 meters (33 feet) in diameter, you're simply out of luck. Mid-sized wind turbines typically are much more complex than their smaller counterparts. Nearly all use transmissions, and many use two generators.

Dual Generators

As mentioned elsewhere, don't be swayed by the size of the generator alone. It's only an indication of how much power the generator is capable of producing, not how much it will generate. Ask Danish manufacturers what size generator they have in their machine and they'll look at you quizzically and ask, "Which one?" Danish wind machines often use two induction generators, one for low winds and another, much larger, generator for higher winds.

Induction generators operate inefficiently at partial loads. For a wind machine with a generator designed to reach its rated output in a 25-35 mph (11-15 m/s) wind the generator would operate at partial load most of the time. Rather than use only one generator, Danish designers bring a smaller one on line first so that it operates at nearly full load in low to moderate winds. As wind speed increases they drop the smaller generator while energizing the larger or main generator. Thus, both generators operate more efficiently than either alone, and overall performance of the wind machine is improved.

The two generators may be in tandem and driven by the same shaft, or they can be side by side with the small generator being driven by belts from the main generator. Usually both generators are spun at the same time and are not brought on line mechanically but by energizing the field electrically. In some designs, the generator is wired in two stages: during light winds the first stage uses only a portion of the generator's capacity, and in higher winds the second stage uses the generator's full potential.

The use of dual generators permits most Danish turbines to operate at two speeds. This enables them to operate the generator and the rotor at a higher efficiency. Though they are not true variable-speed machines and can't take full advantage of the optimum tip-speed ratio, these turbines can bracket the optimum range. This is particularly useful in low winds where efficiency is most crucial.

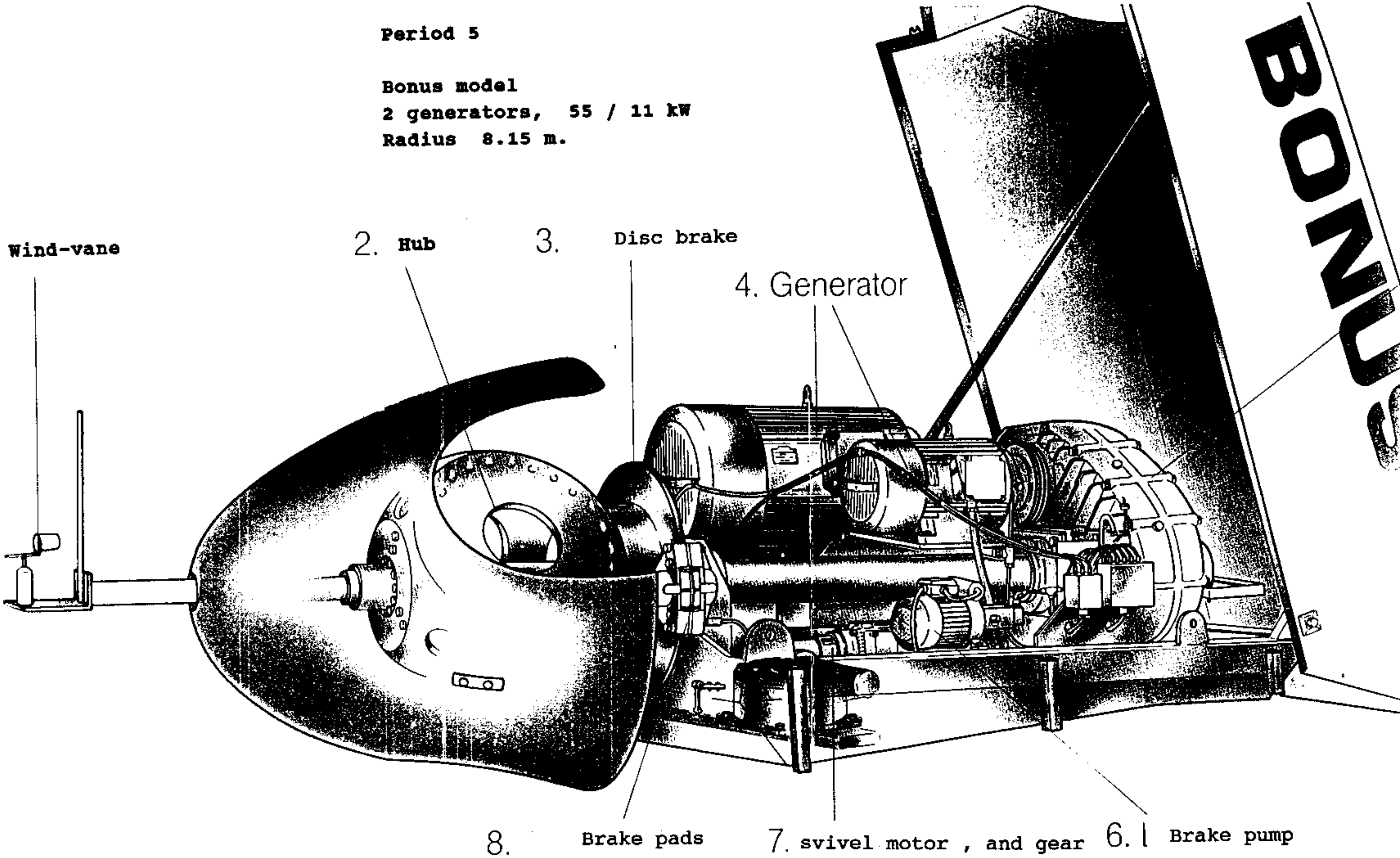
Install several wind turbines and sell as much power to the utility as you can. When you do, you're farming the wind for profit. More than 16,000 turbines have been installed in California just for this purpose (see Figure 2-4). These commercial wind farms, or wind power plants, are nothing more than a large-scale version of a small wind turbine interconnected with a residential customer's electric utility. But rather than meeting the domestic demand of a home or business, all the electricity generated by these wind power plants is delivered for sale to the utility.

In the early 1980s, some small wind turbines originally designed for homes or small businesses found their way to California's wind farms. Literally thousands of such wind machines were installed. These were 10-, 25-, and 40-kilowatt wind turbines that just a few years prior were being installed in backyards across the United States. Today the average size of wind turbines installed in California wind plants exceeds 250 kilowatts with rotors spanning 25 meters (80 feet) or more in diameter.

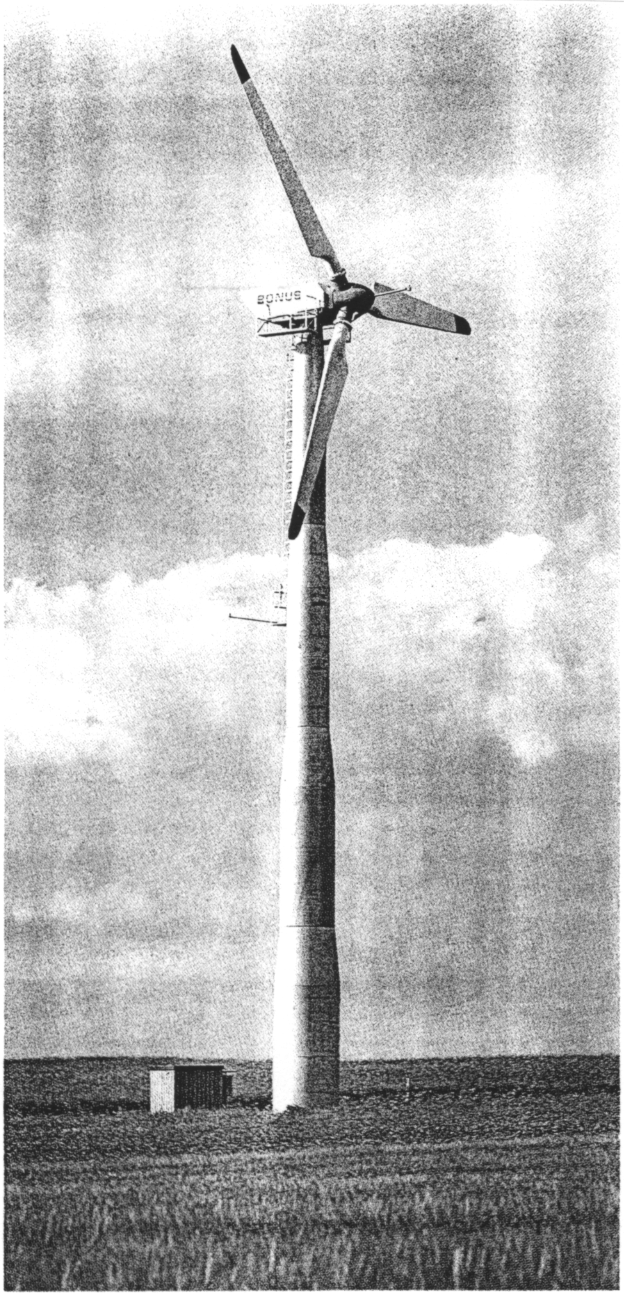
While the bulk of wind power generation in the United States is found in California's wind plants, Denmark has a far different story. Most of the 3500 wind turbines in Denmark are used by homeowners, farmers, and small businesses. While Americans were erecting 10-kilowatt wind turbines in their backyards during the early 1980s, the Danes were installing 55-kilowatt machines in theirs. Today the size of the average wind turbine installed for nonutility applications in Denmark is more than 150 kilowatts. As explained in Chapter 8 on cutting costs, Danes often join cooperatives and buy what many Americans would consider a medium-sized wind turbine and install it in the backyard of one of the co-op members. They then share in the revenues from the sale of electricity to the utility. Others install similarly sized machines for their own domestic use and sell the excess to the utility. As Denmark has decisively shown, medium-sized wind turbines need not be limited solely to commercial wind power plants; they may be successfully used to power homes, farms, and businesses.

Period 5

Bonus model
2 generators, 55 / 11 kW
Radius 8.15 m.



Bonus 55/11 kW

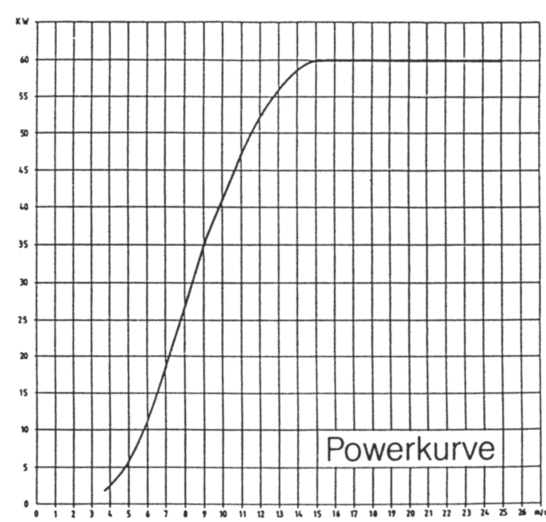


Technical Specifications

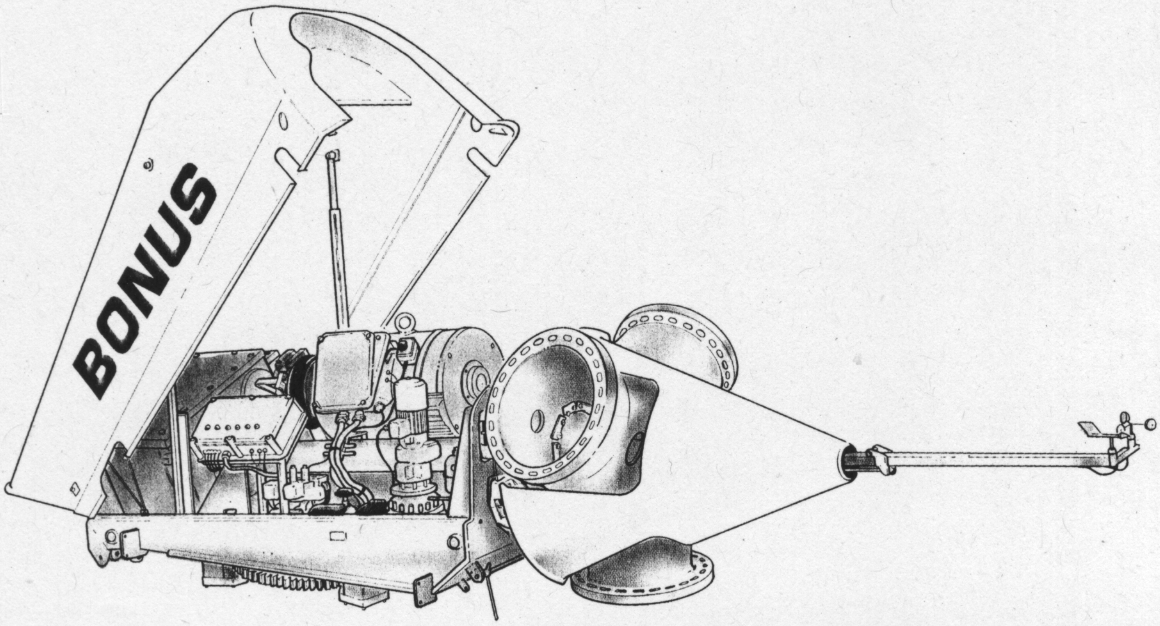
ROTOR:
Number of Blades: 3, glass-fiber
Rotor diameter: 16.3 meters
Wind-Rotor area: 209 sq.meters
Effect-control: stall-regulated
Max. production at
wind speed 12-13 m/sec.
Survival wind speed: 67 meters/sec.
WINGS:
Glass fiber re-inforced polyester,
with longitudinal beam.
GENERATOR:
Nominal effect: 55kW 6 pole 415 v 50Hz
Nominal effect: 11kW 6 pole 415 v 50Hz
Start-wind: 3-4 meters/sec.
Stop-wind: 28 meters/sec.
GEAR:
2-stage hollow-shaft gear.
STEERING:
Micro-processor, with thyristor cut-in.
TOWER:
Axle-height: 24 meters
Closed self-supporting tube-tower

Period Type 5

Bonus model
2 Generators 11/55 kW.
8.18 m. blades

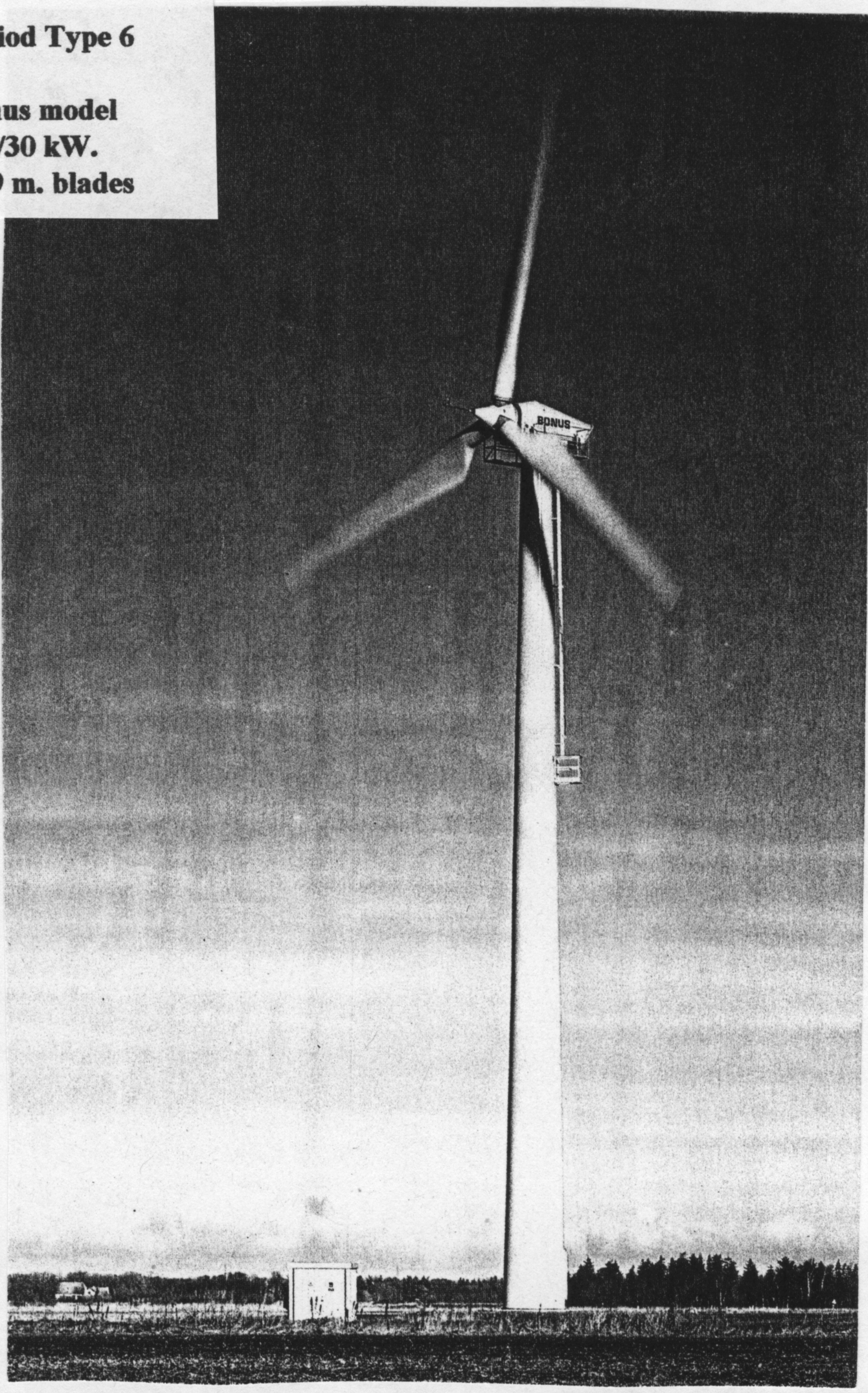


150 kW Mk III

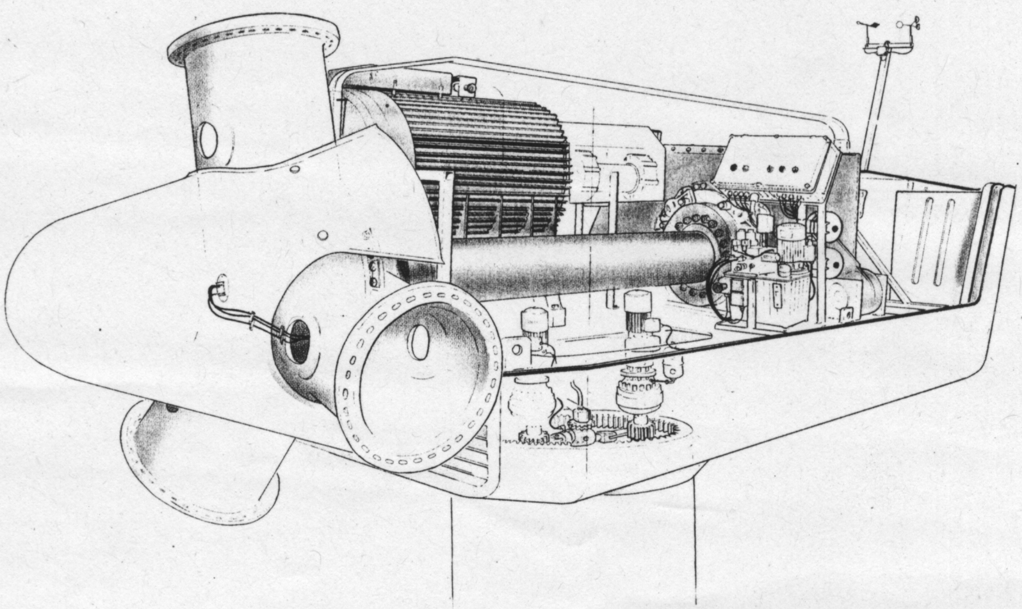


Period Type 6

Bonus model
150/30 kW.
11.9 m. blades

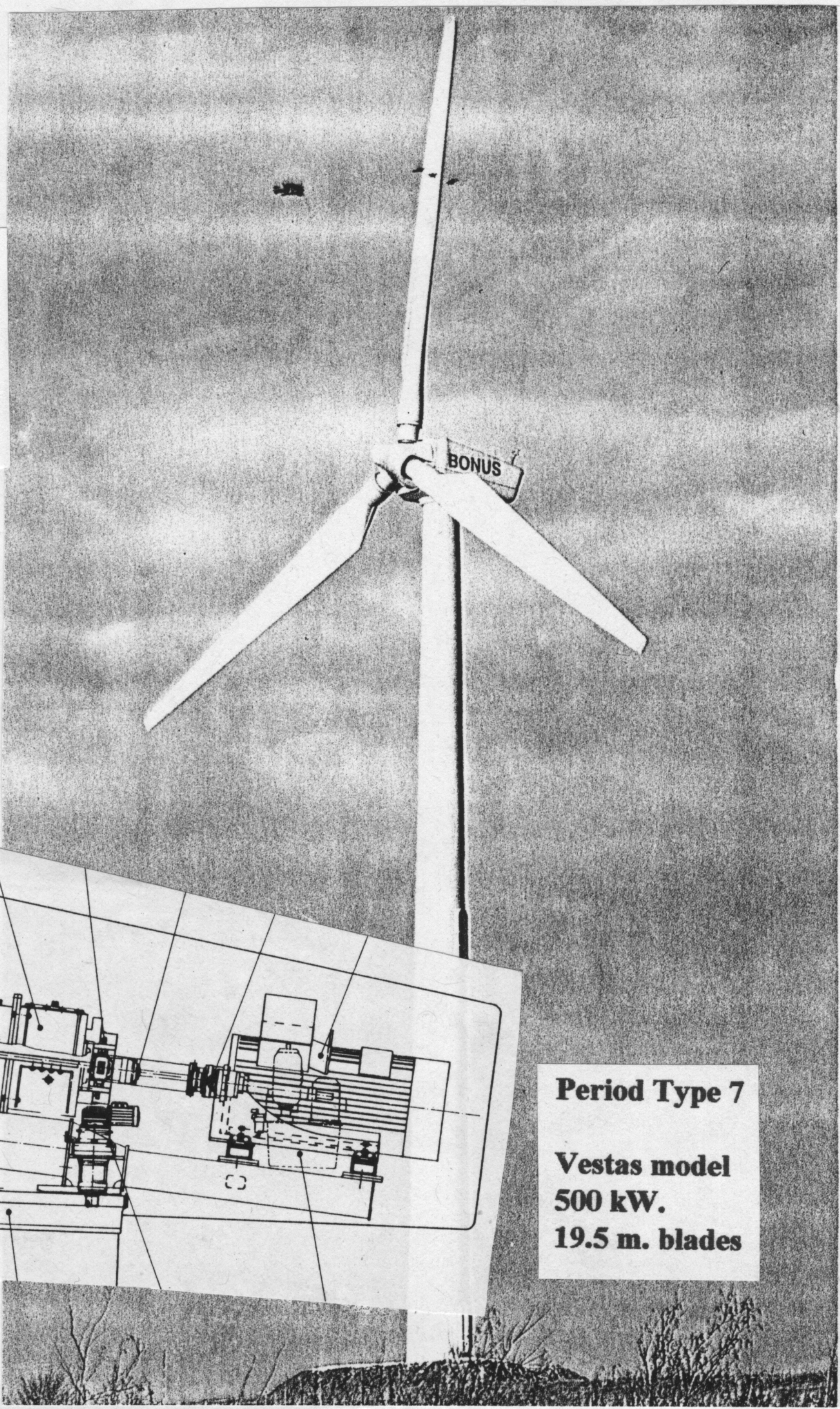


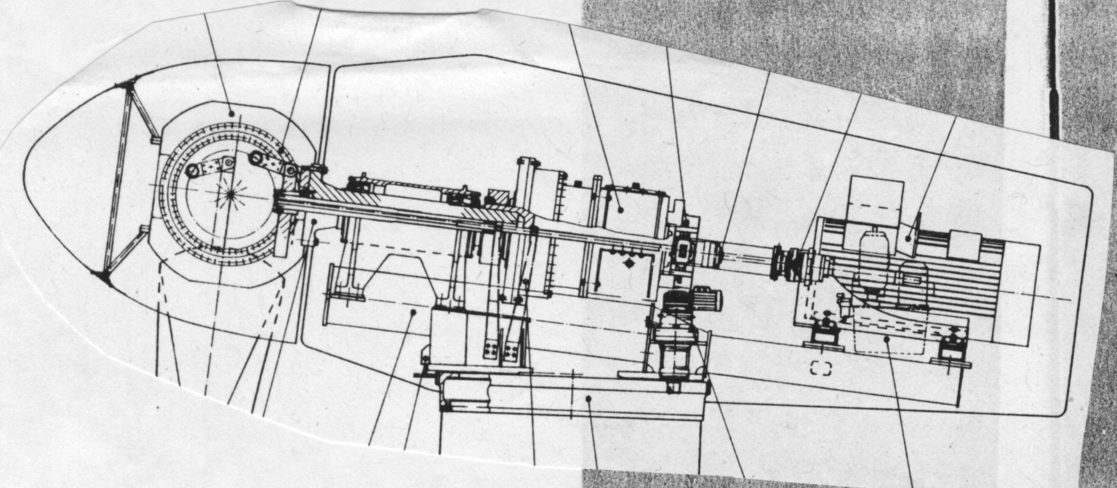
250/300 kW



Period Type 6.5

Bonus model
250-300 kW. Combi
15.5 m. blades

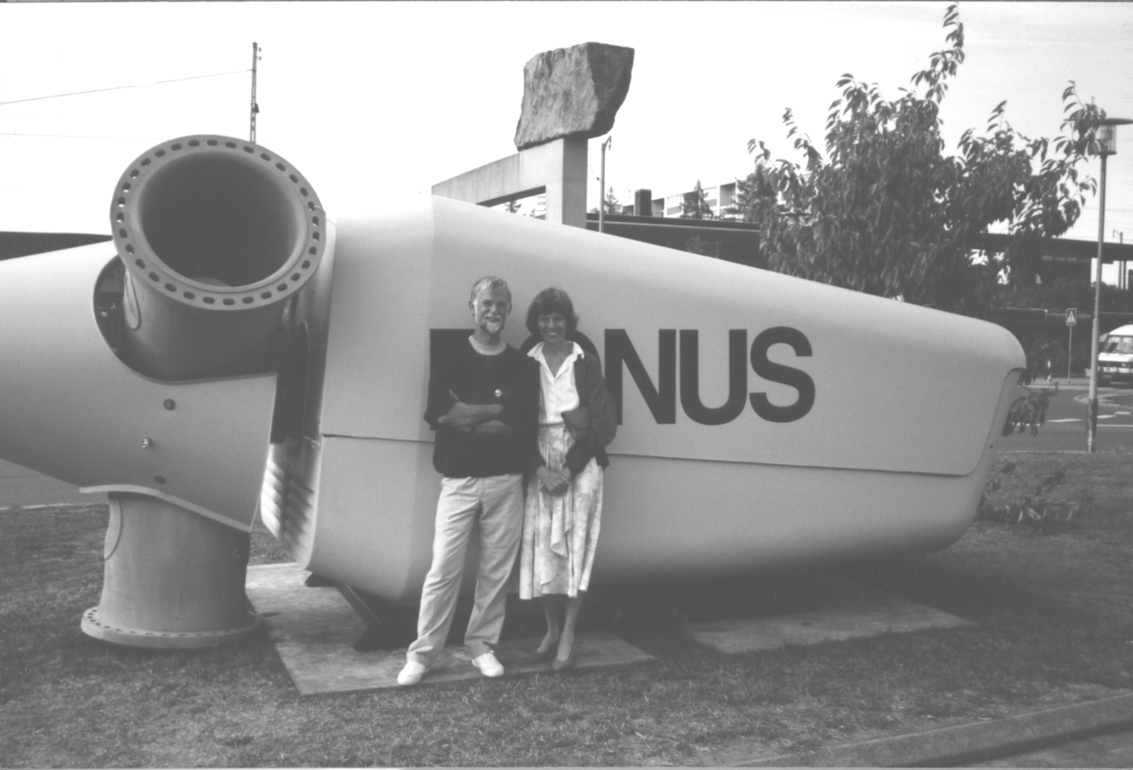




Period Type 7

Vestas model
500 kW.
19.5 m. blades


BONUS



Die technische Sensation: Enercon-40

Typenbezeichnung: Enercon-40

Nennleistung:	500 kW
Leistung (10 m/s):	321 kW
Rotordurchmesser:	40,3 m
Nabenhöhe:	50 m

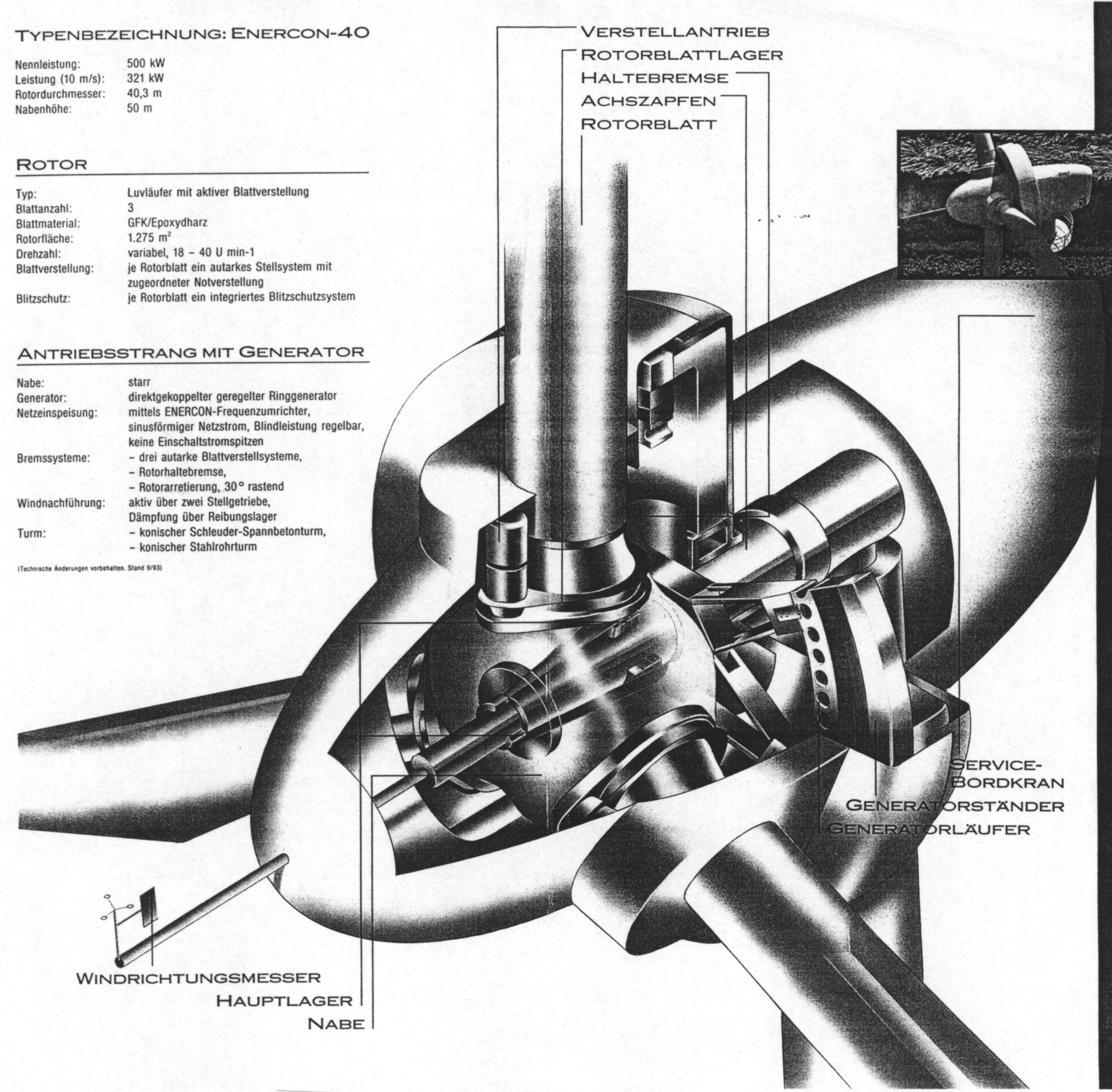
Rotor

Typ:	Luvläufer mit aktiver Blattverstellung
Blattanzahl:	3
Blattmaterial:	GFK/Epoxydharz
Rotorfläche:	1.275 m²
Drehzahl:	variabel, 18 – 40 U min-1
Blattverstellung:	je Rotorblatt ein autarkes Stellsystem mit zugeordneter Notverstellung
Blitzschutz:	je Rotorblatt ein integriertes Blitzschutzsystem

Antriebsstrang mit Generator

Nabe:	starr
Generator:	direktgekoppelter geregelter Ringgenerator
Netzeinspeisung:	mittels ENERCON-Frequenzumrichter, sinusförmiger Netzstrom, Blindleistung regelbar, keine Einschaltstromspitzen
Bremssysteme:	– drei autarke Blattverstellsysteme, – Rotorhaltebremse, – Rotorarretierung, 30° rastend
Windnachführung:	aktiv über zwei Stellgetriebe, Dämpfung über Reibungslager
Turm:	– konischer Schleuder-Spannbetonturm, – konischer Stahlrohrturm

(Technische Änderungen vorbehalten. Stand 9/93)



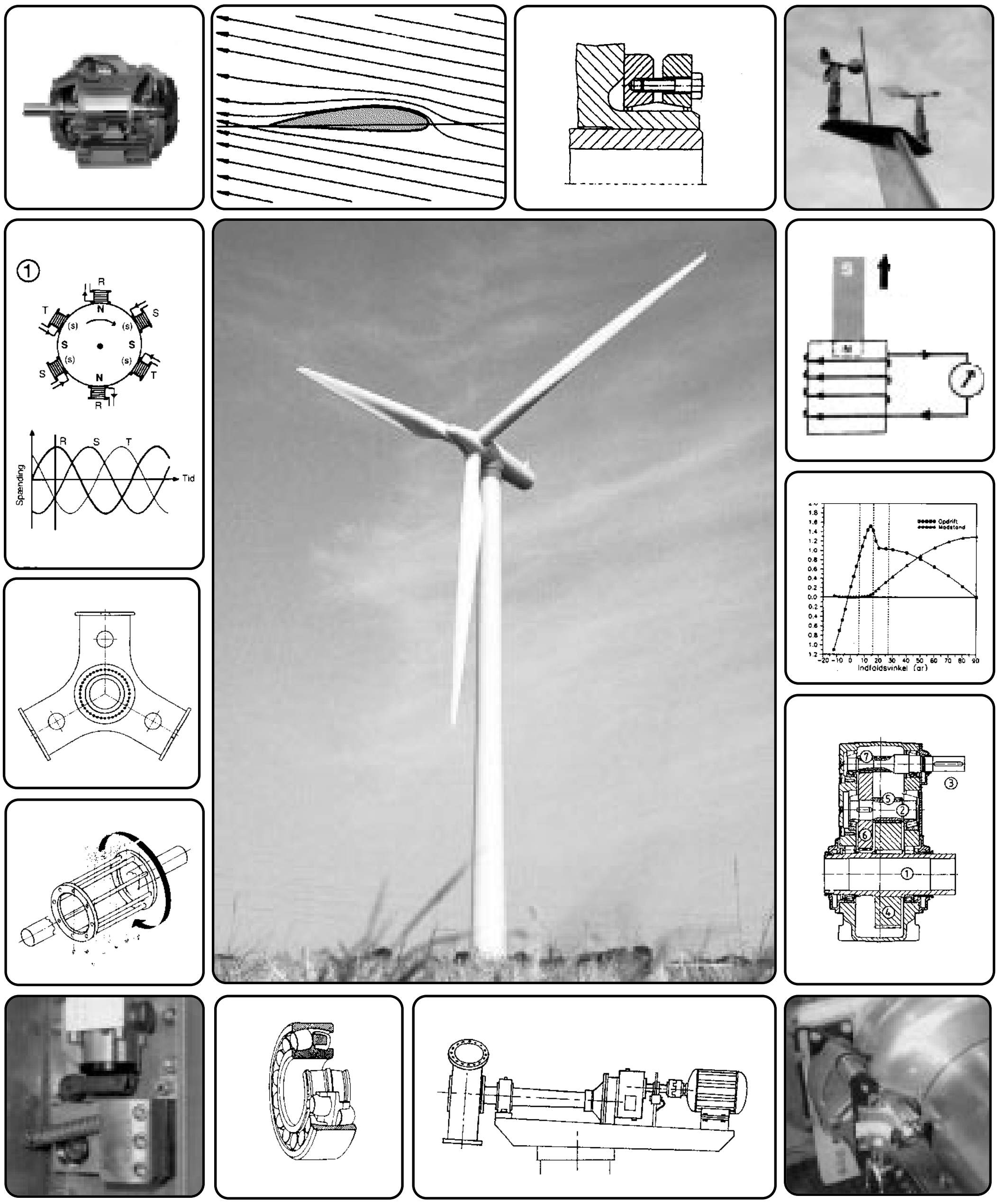
Enercon 500 kW Wind-turbine without gearbox, using ring-generator. 40.3 m. rotor diameter

Special Issue

BONUS INFO

THE NEVER ENDING STORY

Autumn 1999



THE WIND TURBINE COMPONENTS AND OPERATION

BONUS-INFO is a newsletter for customers and business associates of the Bonus Energy A/S. This newsletter is published once or twice a year.

The first number came out in 1998, and the newsletter has now been published in four issues.

Each number has included an article on the components and operation of the wind turbine. We have received many suggestions and requests that these articles should be reprinted and published as a special single issue.

Bonus is pleased to have hereby fulfilled this request with the publication of this special issue.

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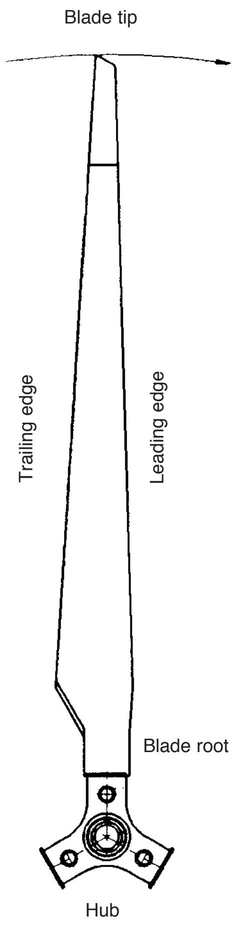
THE AERODYNAMICS OF THE WIND TURBINE

The three bladed rotor is the most important and most visible part of the wind turbine. It is through the rotor that the energy of the wind is transformed into mechanical energy that turns the main shaft of the wind turbine.

We will start by describing why the blades are shaped the way that they are and what really happens, when the blades rotate.

BASIC THEORY

Aerodynamics is the science and study of the physical laws of the behavior of objects in an air flow and the forces that are produced by air flows.



The different components of a wind turbine blade

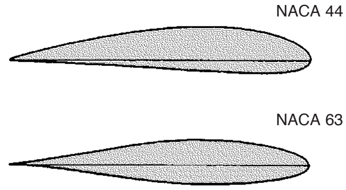
The front and rear sides of a wind turbine rotor blade have a shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root. The blade root is bolted to the hub.

The radius of the blade is the distance from the rotor shaft to the outer edge of the blade tip. Some wind turbine blades have moveable blade tips as air brakes, and one can often see the distinct line separating the blade tip component from the blade itself.

If a blade were sawn in half, one would see that the cross section has a streamlined asymmetrical shape, with the flattest side facing the oncoming air flow or wind. This shape is called the blade's aerodynamic profile

THE AERODYNAMIC PROFILE

The shape of the aerodynamic profile is decisive for blade performance. Even minor alterations in the shape of the profile can greatly alter the power curve and noise level. Therefore a blade designer does not merely sit down and outline the shape when designing a new blade. The shape must be chosen with great care on the basis of past experience. For this reason blade profiles were previously chosen from a widely used catalogue of airfoil profiles developed in wind tunnel research by NACA (The United States National Advisory Committee for Aeronautics) around the time of the Second World War.



Blade profiles

The NACA 44 series profiles were used on older Bonus wind turbines (up to and including the 95 kW models). This profile was developed during the 1930's, and has good all-round properties, giving a good power curve and a good stall. The blade is tolerant of minor surface imperfections, such as dirt on the blade profile surface.

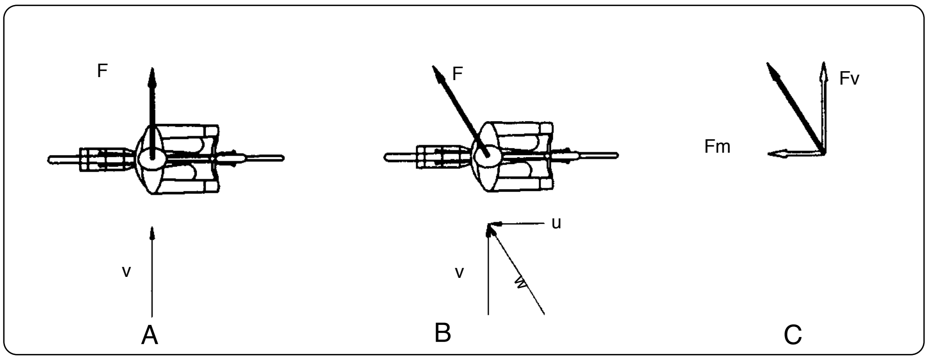
The LM blades used on newer Bonus wind turbines (from the 150 kW models) use the NACA 63 profiles developed during the 1940´s. These have slightly different properties than the NACA 44 series. The power curve is better in the low and medium wind speed ranges, but drops under operation at higher wind speeds. Likewise this profile is more sensitive with regard to surface dirt. This is not so important in Denmark, but in certain climate zones with little rain, accumulated dirt, grime and insect deposits may impair and reduce performance for longer periods.

The LM 19 blades, specifically developed for wind turbines, used on the Bonus 500 kW, have completely new aerodynamic profiles and are therefore not found in the NACA catalogue. These blades were developed in a joint LM and Bonus research project some years ago, and further developed and wind tunnel tested by FFA (The Aerodynamic Research Institute of The Swedish Ministry of Defence).

THE AERODYNAMICS OF A MAN ON A BICYCLE

To fully describe the aerodynamics of a wind turbine blade could appear to be rather complicated and difficult to understand. It is not easy to fully understand how the direction of the air flow around the blade is dependent on the rotation of the blade. Fortunately for us, air constantly flows around everyday objects following these very same aerodynamic laws. Therefore we can start with the aerodynamics of an air flow that most of us are much more familiar with: A cyclist on a windy day.

The diagrams (next page) show a cyclist as seen from above. The diagrams are perhaps rather sketchy, but with a good will one can visualize what they



Air flow around a man on a bicycle

represent. The diagram (A) on the left, illustrates a situation, during which a cyclist is stationary and can feel a side wind "v" of 10 meters per second (m/s) or roughly 22 mph (this is known as a fresh breeze). The wind pressure will attempt to overturn the cyclist. We can calculate the pressure of the wind on the windward side of the cyclist as roughly 80 Newton per square meter of the total side area presented by the cyclist against the wind. Newton, or N for short, is the unit for force used in technical calculation. 10 N is about 1kg/force (Multiply by 0.2248 to obtain lbf.). The direction of the force of the wind pressure is in line with the wind flow. If we consider that a normal sized cyclist has a side area facing the wind of about 0.6 square meters, then the force F from the pressure of the wind will be 0.6 x 80 N = app. 50 N/m^2.

In the center drawing (B) our cyclist has started out and is traveling at a speed "u" of 20 km/hour, equivalent to about 6 meters/second, still with a side wind "v" of 10 m/s. We can therefore calculate the speed of the resulting wind "w" striking the cyclist, either mathematically or by measurement on the diagram as 12 m/s. This gives a total wind pressure of 100 N/m^2. The direction of the wind pressure is now in line with the resulting wind, and this will give a force "F" on the cyclist of about 60 N/m^2.

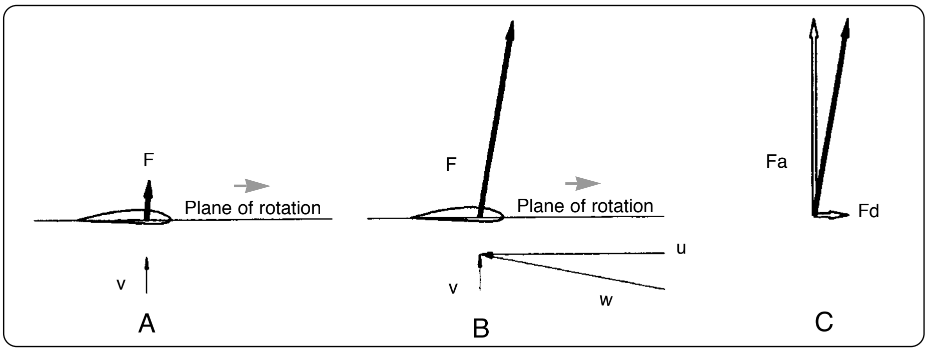
In the right hand drawing (C) the force of the wind pressure "F" is now separated into a component along the direction of the cyclist's travel and into another component at a right angle to the direction of travel. The right angled force "Fv" will attempt to overturn the cyclist, and the force "Fm" along the axis of travel gives a resistance that slows down the cyclist's forward motion. The size of "Fm" is about 30 N/m^2. This is the resistance force that the cyclist must overcome. A beginner, unused to cycling, may wonder why the wind has changed direction and a head wind is felt on reaching speed. This beginner might well ask " How can it be that I felt a side wind when I was at rest and standing still, could the wind have possibly changed its direction? " But no, as any experienced cyclist unfortunately knows, head wind is an integral component of movement itself. The wind itself has not turned. The head wind is a result of speed, the faster one travels the more wind resistance one experiences. Perhaps, as a famous Danish politician once promised his voters, that if elected he would insure favorable tailwinds on the cycle-paths, things may change in the future. However we others have learnt to live with the head winds resulting from our own forward movement, whether we run, cycle or go skiing.

WIND TURBINE BLADES BEHAVE IN THE SAME WAY

Returning to the wind turbine blade, just as in the situation for the cyclist, we can observe the aerodynamic and force diagrams in two different situations, when the wind turbine is stationary and when it is running at a normal operational speed. We will use as an example the cross section near the blade tip of a Bonus 450 kW Mk III operating in a wind speed "v" of 10 m/s.

When the rotor is stationary, as shown in drawing (A) below, the wind has a direction towards the blade, at a right angle to the plane of rotation, which is the area swept by the rotor during the rotation of the blades. The wind speed of 10 m/s will produce a wind pressure of 80 N/m^2 of blade surface, just like the effect on our cyclist. The wind pressure is roughly in the same direction as the wind and is also roughly perpendicular to the flat side of the blade profile. The part of the wind pressure blowing in the direction of the rotor shaft attempts to bend the blades and tower, while the smaller part of the wind pressure blowing in the direction of the rotation of the blades produces a torque that attempts to start the wind turbine.

Once the turbine is in operation and the rotor is turning, as is shown in the center diagram (B), the blade encounters a head wind from its own forward movement in exactly the same way as the cyclist does. The strength of head wind "u" at any specific place on the blade depends partly on just how fast the wind turbine blade is rotating, and partly how far out on the blade one is from the shaft. In our example, at the normal operating speed of 30 rpm, the head wind "u" near the tip of the 450 kW wind turbine is about 50 m/s. The "meteorological" wind "v" of 10 m/s will thus give a resulting wind over the profile of about 51 m/s.



Airflow around a blade profile, near the wing tip

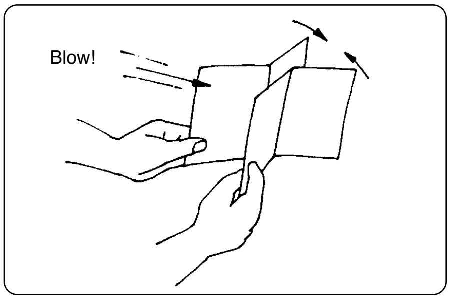
This resulting wind will have an effect on the blade surface with a force of 1500 N/m². The force "F" will not be in the direction of the resulting wind, but almost at a right angle to the resulting wind.

In the drawing on the right (C) the force of the wind pressure "F" is again split up into a component in the direction of rotation and another component at a right angle to this direction. The force "Fa" at a right angle to the plane of rotation attempts to bend the blade back against the tower, while the force "Fd" points in the direction of rotation and provides the driving torque. We may notice two very important differences between the forces on the blade in these two different situations and forces on the cyclist in the two corresponding situations. One difference is that the forces on the blade become very large during rotation. If vector arrows illustrating the forces in the diagrams were drawn in a scale that was indicative of the sizes of the different forces, then these vector arrows of a wind turbine in operation would have been 20 times the size of the vector arrows of the same wind turbine at rest. This large difference is due to the resulting wind speed of 51 m/s striking a blade during operation, many times the wind speed of 10 m/s when the wind turbine is at rest. Just like the cyclist, the blade encounters head wind resulting from its own movement, however head wind is of far greater importance on a wind turbine blade than for a cyclist in motion.

The other important difference between a wind turbine blade and a cyclist is that the force on the blade is almost at a right angle to the resulting wind striking the profile. This force is known as the lift and also produces a small resistance or drag. The direction of this lift force is of great importance. A cyclist only feels the wind resistance as a burden, requiring him to push down extra hard on the pedals. However with a wind turbine blade this extra wind resistance will act as a kind of power booster, at least in the normal blade rotational speed range. The reason for this difference is due to the blades streamlined profile, which behaves aerodynamically completely differently as compared to the irregular shaped profile of a man on a bicycle. The wind turbine blade experiences both lift and drag, while a cyclist only experiences drag.

LIFT

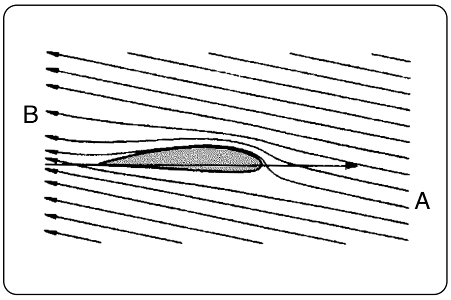
Lift is primary due to the physical phenomena known as Bernoulli's Law. This physical law states that when the speed of an air flow over a surface is increased the pressure will then drop. This law is counter to what most people experience from walking or cycling in a head wind, where normally one feels that the pressure increases when the wind also increases. This is also true when one sees an air flow blowing directly against a surface, but it is not the case when air is flowing over a surface.



An experiment with Bernoulli's Law

One can easily convince oneself that this is so by making a small experiment. Take two small pieces of paper and bend them slightly in the middle. Then hold them as shown in the diagram and blow in between them. The speed of the air is higher in between these two pieces of paper than outside (where of course the air speed is about zero), so therefore the pressure inside is lower and according to Bernoulli's Law the papers will be sucked in towards each other. One would expect that they would be blown away from each other, but in reality the opposite occurs. This is an interesting little experiment, that clearly demonstrates a physical phenomenon that has a completely different result than what one would expect. Just try for yourself and see.

The aerodynamic profile is formed with a rear side, that is much more curved than the front side facing the wind. Two portions of air molecules side by side in the air flow moving towards the profile at point A will separate and pass around the profile and will once again be side by side at point B after passing the profile's trailing edge. As the rear side is more curved than the front side on a wind turbine blade, this means that the air flowing over the rear side has to travel a longer distance from point A to B than the air flowing over the front side. Therefore this air flow over the rear side must have a higher velocity if these two different portions of air shall be reunited at point B. Greater velocity produces a pressure drop on the rear side of the blade, and it is this pressure drop that produces the lift. The highest speed is obtained at the rounded front edge of the blade. The blade is almost sucked forward by the pressure drop resulting from this greater front edge speed.



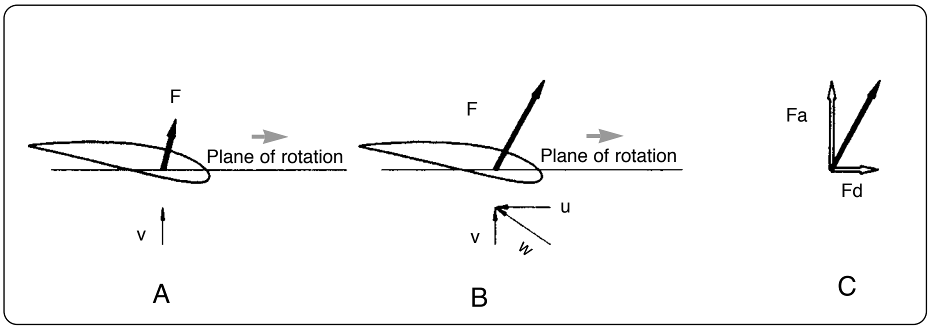
Air flow around an aerodynamic profile

There is also a contribution resulting from a small over-pressure on the front side of the blade.

Compared to an idling blade the aerodynamic forces on the blade under operational conditions are very large. Most wind turbine owners have surely noticed these forces during a start-up in good wind conditions. The wind turbine will start to rotate very slowly at first, but as it gathers speed it begins to accelerate faster and faster. The change from slow to fast acceleration is a sign that the blade's aerodynamic shape comes into play, and that the lift greatly increases when the blade meets the head wind of its own movement. The fast acceleration, near the wind turbine's operational rotational speed places great demands on the electrical cut-in system that must "capture and engage " the wind turbine without releasing excessive peak electrical loads to the grid.

THE CHANGE OF FORCES ALONG THE BLADE

The drawings previously studied, mainly illustrate the air flow situation near the



Air flow around a blade profile near the blade root

blade tip. In principle these same conditions apply all over the blade, however the size of the forces and their direction change according to their distance to the tip. If we once again look at a 450 kW blade in a wind speed of 10 m/s, but this time study the situation near the blade root, we will obtain slightly different results as shown in the drawing above.

In the stationary situation (A) in the left hand drawing, wind pressure is still 80 N/m^2. The force "F" becomes slightly larger than the force at the tip, as the blade is wider at the root. The pressure is once again roughly at a right angle to the flat side of the blade profile, and as the blade is more twisted at the root, more of the force will be directed in the direction of rotation, than was the case at the tip.

On the other hand the force at the root has not so great a torque-arm effect in relation to the rotor axis and therefore it will contribute about the same force to the starting torque as the force at the tip.

During the operational situation as shown in the center drawing (B), the wind approaching the profile is once again the sum of the free wind "v" of 10 m/s and the head wind "u" from the blade rotational movement through the air. The head wind near the blade root of a 450 kW wind turbine is about 15 m/s and this produces a resulting wind "w" over the profile of 19 m/s. This resulting wind will act on the blade section with a force of about 500 N/m^2.

In the drawing on the right (C) force is broken down into wind pressure against the tower "Fa", and the blade driving force "Fd" in the direction of rotation.

In comparison with the blade tip the root section produces less aerodynamic forces during operation, however more of these forces are aligned in the correct direction, that is, in the direction of rotation. The change of the size and direction of these forces from the tip in towards the root, determine the form and shape of the blade.

Head wind is not so strong at the blade root, so therefore the pressure is likewise not so high and the blade must be made wider in order that the forces should be large enough. The resulting wind has a greater angle in relation to the plane of rotation at the root, so the blade must likewise have a greater angle of twist at the root.

It is important that the sections of the blade near the hub are able to resist forces and stresses from the rest of the blade. Therefore the root profile is both thick and wide, partly because the thick broad profile gives a strong and rigid blade and partly because greater width, as previously mentioned, is necessary on account of the resulting lower wind speed across the blade. On the other hand, the aerodynamic behavior of a thick profile is not so effective. Further out along the blade, the profile must be made thinner in order to produce acceptable aerodynamic properties, and therefore the shape of the profile at any given place on the blade is a compromise between the desire for strength (the thick wide profile) and the desire for good aerodynamic properties (the thin profile) with the need to avoid high aerodynamic stresses (the narrow profile).

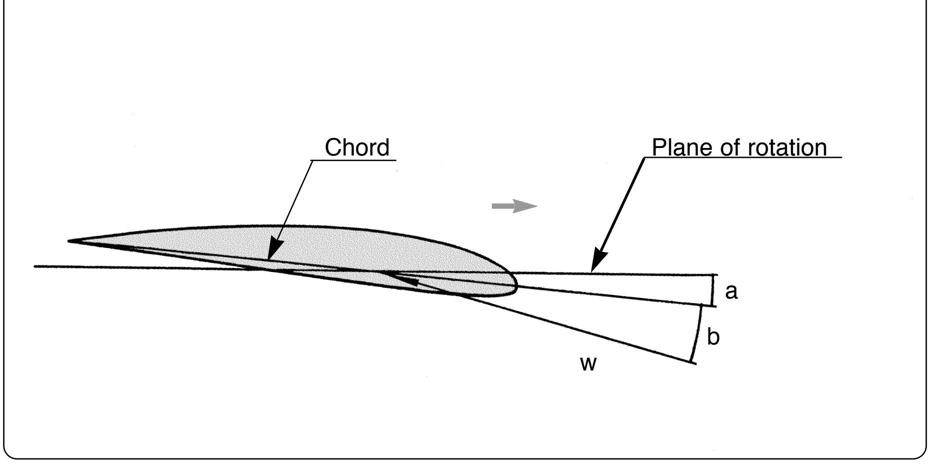
As previously mentioned, the blade is twisted so that it may follow the change in direction of the resulting wind. The angle between the plane of rotation and the profile chord, an imaginary line drawn between the leading edge and the trailing edge, is called the setting angle, sometimes referred to as "Pitch".

WHAT HAPPENS WHEN THE WIND SPEED CHANGES?

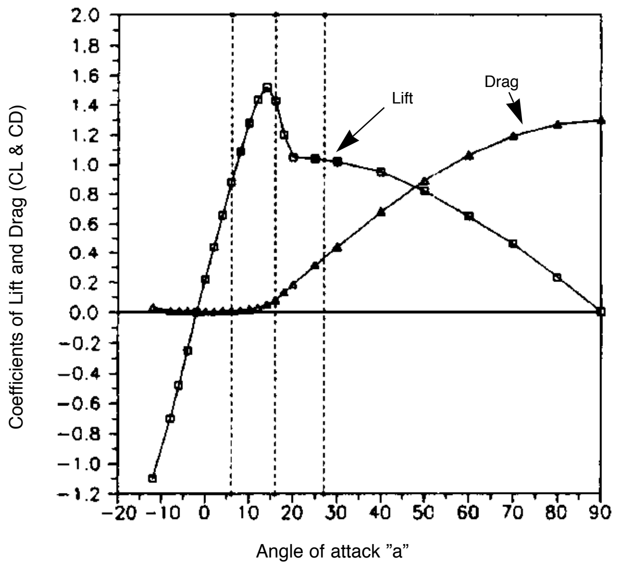
The description so far was made with reference to a couple of examples where wind speed was at a constant 10 m/s. We will now examine what happens during alterations in the wind speed.

In order to understand blade behavior at different wind speeds, it is necessary to understand a little about how lift and drag change with a different angle of attack. This is the angle between the resulting wind "w" and the profile chord. In the drawing below the angle of attack is called "a" and the setting angle is called "b".

The setting angle has a fixed value at any one given place on the blade, but the angle of attack will grow as the wind speed increases.



The angles of the profile



Relationship between lift and drag coefficients and the angle of attack

The aerodynamic properties of the profile will change when the angle of attack "a" changes. These changes of lift and drag with increasing angles of attack, are illustrated in the diagram above used to calculate the strength of these two forces, the lift coefficient "CL" and the drag coefficient "CD". Lift will always be at a right angle to the resulting wind, while drag will always follow in the direction of the resulting wind.

We will not enter into the formulas necessary to calculate these forces, it is enough to know that there is a direct connection between the size of "CL" and the amount of lift.

Both lift and drag abruptly change when the angle of attack exceeds 15-20 degrees. One can say that the profile stalls. After this stalling point is reached, lift falls and drag increases. The angle of attack changes when the wind speed changes.

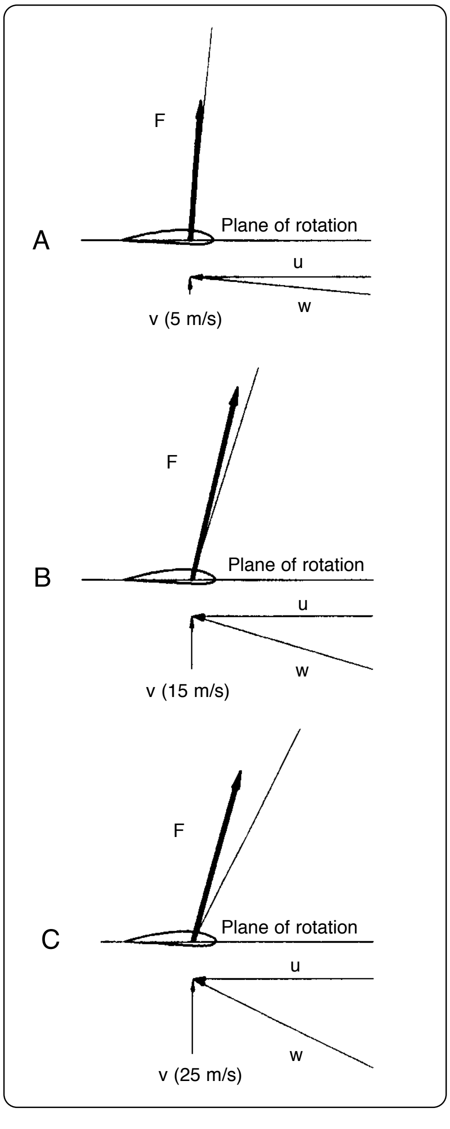
To further study these changes, we can draw diagrams, shown to the right, illustrating three different wind speeds "v" (5, 15 and 25 m/s) from our previous cross section, this time near the blade tip of a 450 kW wind turbine. This situation is rather convenient as the setting angle "b" near the wing tip is normally 0 degrees.

The head wind from the movement "u" is always the same, as the wind turbine has a constant rotational speed controlled by the grid connected generator (in these situations we do not consider the small generator used on certain small wind turbines). The free air flow "v" has three different values and this gives three different values of the resulting wind "w" across the profile. The size of "w" does not change very much, from 50 m/s at a wind speed of 5 m/s to 52 m/s in a 25 m/s wind. The reason for this relatively minor change is due to the dominating effect of the head wind.

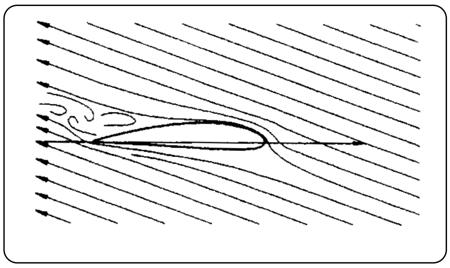
However, the angle of attack "a" between the resulting wind and the chord of the blade changes from 6 degrees at a wind speed of 5 m/s to 16 degrees at 15 m/s to 27 degrees at 25 m/s. These changes are of great importance for determining the strength of the aerodynamic forces.

Studying the diagram showing the lift coefficient "CL" and the drag coefficient "CD" we may note the following:

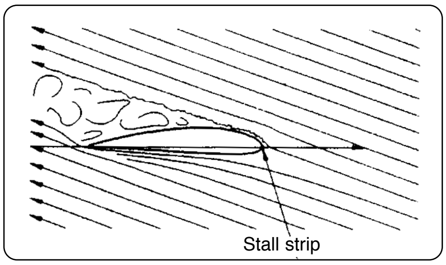
- At a wind speed of 5 m/s (A), the angle of attack is 6 degrees. The lift coefficient is 0.9 and the coefficient of drag is 0.01. Lift is therefore 90 times greater than drag, and the resultant force "F" points almost vertically at a right angle to the mean relative wind "w".
- At a wind speed of 15 m/s (B), the profile is almost about to stall. The angle of attack is 16 degrees. The lift coefficient is 1.4 and the coefficient of drag is 0.07. Lift is now 20 times drag.
- At a wind speed of 25 m/s (C), the profile is now deeply stalled, the angle of attack is 27 degrees, the lift component is 1.0 and the component of lift is 0.35. Lift is now 3 times greater than drag. We can therefore note the following:
- During the change of wind speed from 5 to 15 m/s there is a significant increase in lift, and this increase is directed in the direction of rotation. Therefore power output of the wind turbine is greatly increased from 15 kW to 475 kW.
- During the change of wind speed from 15 to 25 m/s, there is a drop in lift accompanied by an increase in drag. This lift is even more directed in the direction of rotation, but it is opposed by drag and therefore output will fall slightly to 425 kW.



Situations at three different wind speeds



Seperation of the air flow at the profile trailing edge



Interference in the stall process (stall strip)

THE STALL PHENOMENA

The diagrams showing the components of lift and drag illustrate the result of stall. Lift diminishes and drag increases at angles of attack over 15 degrees. The diagrams however do not illustrate the reasons for this stall phenomena.

A stall is understood as a situation during which an angle of attack becomes so large that the air flow no can longer flow smoothly, or laminar, across the profile. Air looses contact with the rear side of the blade, and strong turbulence occurs. This separation of air masses normally commences progressively from the trailing edge, so the profile gradually becomes semi-stalled at a certain angle of attack, but a full stall is first achieved at a somewhat higher angle. From the diagram showing the lift and drag components, one can estimate that the separation at the trailing edge starts at about 12 degrees, where the curve illustrating lift starts to fall. The profile is fully stalled, and the air flow is separated all over the rear side of the blade at about 20 degrees. These figures can greatly vary from profile to profile and also between different thicknesses of the same profile.

When the stall phenomena is used to restrict power output, as in all Bonus wind turbines, it is important that blades are trimmed correctly. With the steep lift curve, the angle of attack cannot be altered very much, before maximum output also changes, therefore it is essential that the angle of the blade is set at the correct value.

One cannot alter the different angles on the blade itself, once the form, shape and blade molding has been decided upon and fabricated. So we normally talk about calibrating the tip angle. Not because the blade tip has any special magical properties, but we can place a template at the tip, which allows us to make measurements using a theodolite. Adjusting of the tip angle can therefore be understood as an example of how the angle of the total blade is adjusted.

Of importance for power output limitation is also the fact that in practice lift and drag normally behave exactly as would be expected from the theoretical calculations. However this is not always the case. Separation can often occur before expected, for instance due to dirt on the leading edges, or it can be delayed if the air flow over the profile for some reason or other, is smoother than usual. When separation occurs before expected, the maximum obtainable lift is not as high as otherwise expected and therefore maximum output is lower. On the other hand, delayed separation can cause continuous excessive power production output.

Accordingly profile types chosen for our blades have stable stall characteristics with little tendency to unforeseen changes. From time to time, however, it is sometimes necessary to actively alter the stall process. This is normally done by alteration to the leading edge, so that a small well-defined extra turbulence across the profile is induced. This extra turbulence gives a smoother stall process.

Turbulence can be created by an area of rougher blade surface, or a triangular strip, fixed on the leading edge. This stall strip acts as a trigger for the stall so that separation occurs simultaneously all over the rear side.

On a wind turbine blade, different air flows over the different profile shapes, interact with each other out along the blade and therefore, as a rule, it is only necessary to alter the leading edge on a small section of the blade. This altered section will then produce a stall over the greater part of the blade. For example, the Bonus 450 kW Mk III turbine, is usually equipped with a 0.5 meter stall strib, which controls the stall process all over the 17 meter long blade.

SUMMARY

The main points as described in this article can be shortly stated in the following:

• The air flow around a wind turbine blade is completely dominated by the head wind from the rotational movement of the blade through the air.

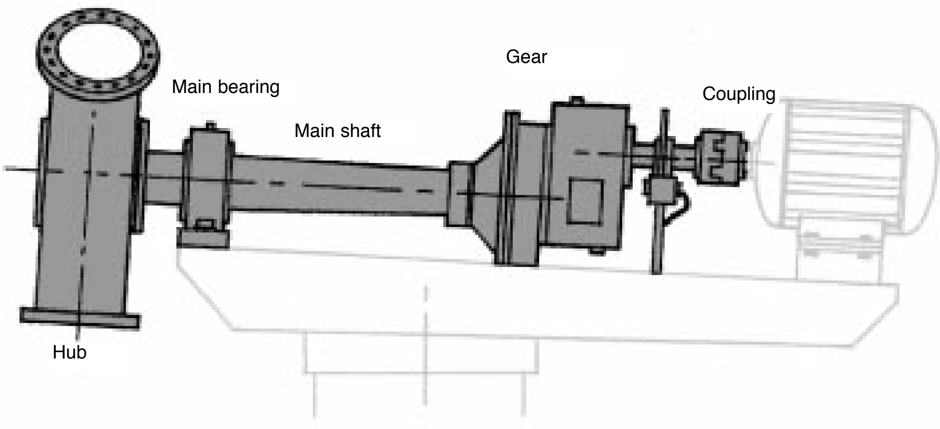
• The blade aerodynamic profile produces lift because of its streamlined shape. The rear side is more curved than the front side.

• The lift effect on the blade aerodynamic profile causes the forces of the air to point in the correct direction.

• The blade width, thickness, and twist is a compromise between the need for streamlining and the need for strength.

• At constant shaft speed, in step with the grid, the angle of attack increases with increasing wind speed. The blade stalls when the angle of attack exceeds 15 degrees. In a stall condition the air can no longer flow smoothly or laminar over the rear side of the blade, lift therefore falls and drag increases.

THE TRANSMISSION SYSTEM



The link between the wind turbine blades and the generator

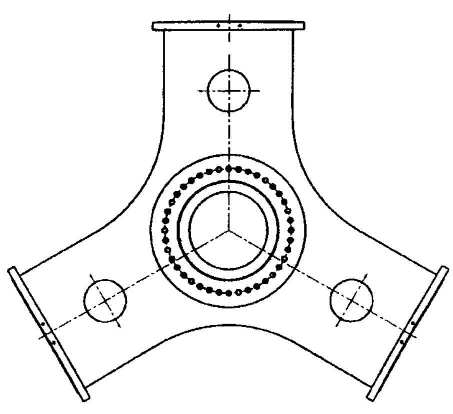
Just how much of a wind turbine that belongs to the transmission system is a matter of definition. In this chapter we will include the components that connect the wind turbine rotor to the generator.

THE HUB

The blades on all Bonus wind turbines are bolted to the hub. Older Bonus wind turbines (up to and including the 95 kW models) with Aerostar blades, have a flange joint, where the glass fiber is molded out in a ring with steel bushes for the bolts. The newer wind turbines (from the 150 kW models) have threaded bushes glued into the blade root itself. In both cases bolts from the blade pass through a flange on the cast hub. The flange bolt-holes are elongated, enabling the blade tip angle to be adjusted.

The hub is cast in a special type of strong iron alloy, called “SG cast iron”. Because of the complicated hub shape which is difficult to make in any other way, it is convenient to use cast iron. In addition the hub must be highly resistant to metal fatigue, and this is difficult to achieve in a welded construction.

In contrast to cast iron of the SG type, normal cast iron has the disadvantage of being rather fragile and often can fracture under blows. This unfortunate quality is due to the high carbon content of cast iron. High carbon content enables the cast iron to melt easily and thus easily flow out into the casting form. When cast iron solidifies, carbon exists as graphite flakes suspended in the pure iron. These flakes form weak zones in the material, easily prone to zig-zag fissures from flake to flake. These weak zones are only important, if forces attempt to pull the material apart. Graphite has great compressibility strength, and is therefore not easily compressed. Normal cast iron has the same compressibility strength as steel, but its tension resistance level is only 10% of steel tension resistance.



Wind turbine hub

For many uses these strength qualities are more than sufficient, however in constructions subject to heavy usage, properties such as low tension resistance and weakness under blows are not desirable. For this reason special SG cast iron with tension resistance equal to that of steel has been developed during the past 50 years.

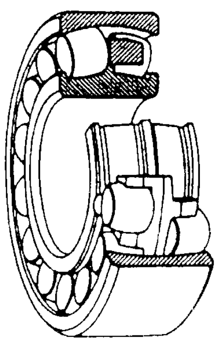
In producing SG cast iron several special materials, mainly silicium, are added during casting. After casting has taken place, it is further heat treated for about 24 hours, thereby changing the free carbon from their usual flakes into small round balls. The name SG cast iron is also short for Spherical Graphite cast iron (latin: Sphere = ball).

This round ball shape binds the necessary carbon in a more compact form. The graphite is not a hindrance for the binding structure in the metal itself, and there is likewise a better structure between the crystals of iron. Thereby achieving the higher strength qualities necessary for a wind turbine hub. On account of the extra heat treatment, SG cast iron is somewhat more expensive than normal cast iron.

MAIN SHAFT

The main shaft of a wind turbine is usually forged from hardened and tempered steel. Hardening and tempering is a result of forging the axle after it has been heated until it is white-hot at about 1000 degrees centigrade. By hammering or rolling the blank is formed with an integral flange, to which the hub is later bolted.

The shaft is reheated a final time to a glowing red, following the forging process, and then plunged into a basin of oil or water. This treatment gives a very hard, but at the same time rather brittle surface. Therefore the axle is once again reheated to about 500 degrees centigrade, tempering the metal and thereby enabling the metal to regain some of its former strength.



Spherical roller bearing • (Niemann)

MAIN BEARINGS

All modern wind turbines, including the Bonus models, have spherical rolller bearings as main bearings. The term spherical means that the inside of the bearing's outer ring is shaped like a cross section of a ball. This has the advantage of allowing the bearing's inner and outer ring to be slightly slanted and out-of-track in relation to each other without damaging the bearing while running. The maximum allowable oblique angle is normally 1/2 degree, not so large, but large enough to ensure that any possible small errors in alignment between the wind turbine shaft and the bearing housing will not give excessive edge loads, resulting in possible damage to the bearing.

The spherical bearing has two sets of rollers, allowing both absorption of radial loads (across the shaft) from the weight of the rotor, shaft, etc. and the large axial forces (along the shaft) resulting from the wind pressure on the rotor.

The main bearings are mounted in the bearing housings bolted to the main frame. The quantity of bearings and bearing seats vary among the different types of wind turbines: " Small " wind turbines up to and including 150 kW have two bearings, each with its own flanged bearing housing. The 250/300 kW wind turbines have only one main bearing, with the gearbox functioning as a second main bearing. The 450 kW, 500 kW and 600 kW wind turbine models have two main bearings, using the hub as a housing. Each bearing arrangement has advantages and disadvantages, and the evaluation of these properties have provides each individual type with its own setup.

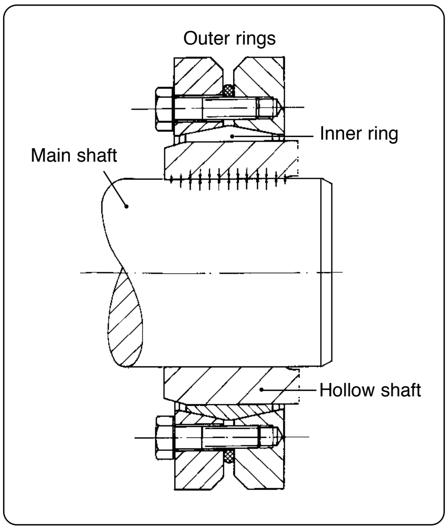
The main bearings are always lubricated by greasing, no matter which bearing arrangement is selected. Special grease having viscose properties even in hard frost is used.

Sealing of the bearing housing is insured by the use of a labyrinth packing. No rubber sealing is used, the labyrinth with its long and narrow passageway prevents grease from escaping. Water and dirt are prevented from entering from the outside by the long passageways filled with grease, which is constantly and slowly trying to escape from the bearing. This may appear to be a rather primitive arrangement, but labyrinth packing is a much used method where there is great risk of pollution by water and dirt. It is more expensive to use than a rubber sealing, because the labyrinth is complicated to fabricate on machine tools, however the seal is not subject to wear, and under normal conditions it is a safe method to keep out the pollutants that otherwise in a short time could ruin roller bearings.

THE CLAMPING UNIT

By the means of a clamping unit the main shaft of the wind turbine is coupled to the gearbox. The gear has a hollow shaft that fits over the rear end of the main shaft. Torque between the two components is transferred by friction between the two.

A clamping unit, normally composed of an inner ring and two outer rings with conical facings, is placed on the outside of the gear's hollow shaft. When the main shaft is placed inside the hollow shaft during the assembly of the wind turbine, the conical facings of the clamping unit are loosely positioned on the hollow shaft. Following control of the correct alignment of the gear and the main shaft, the rings are tightened by the means of a large number of bolts. The outer rings are thereby pressed together, while the inner ring, positioned on the hollow shaft is pressed inwards under the tightening of the bolts. The inner ring now presses so hard against the hollow shaft that the inner part of the hollow shaft is in turn pressed hard against the main shaft. It is because of this pressure that the torque is

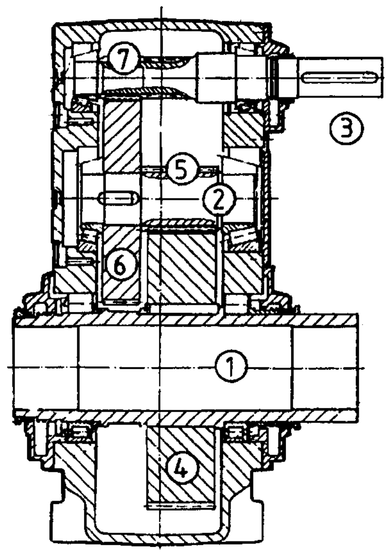


Clamping unit • (TAS Shäfer)

transferred from the main shaft to the wind turbine gear hollow shaft. One might also say that the hollow shaft is shrink-fitted on the main shaft as a result of pressure from the clamping unit.

Transferred torque is dependent upon friction between the main shaft and the hollow shaft. Therefore it is vital that the components are carefully cleaned and completely dry, before they are assembled. If they are at all greasy, they could slip in relation to each other during high loads, for example during the cut-in process in strong wind conditions.

Many know of the parallel key method, often used in assembling a shaft to a hub. The main shaft's torque is transferred by forces across the parallel key (a parallel key is often called a wedge, even though it is not wedge shaped). This assembly method is not often used with a large shaft, there being too great a risk that in time the different parts could loosen, unless they fit uncommonly well together. If the parallel key junction assembly method is used for large shafts, parts must fit so well together, that in practice one is unable to dismantle them in the field, should it be necessary during possible replacement in case of damage or repair.

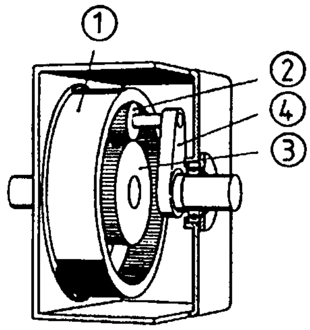


1 Hollow shaft
2 Intermediate shaft
3 High speed shaft
for the generator

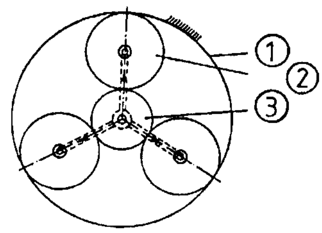
Slow set
4 Large toothed wheel
5 Small toothed wheel

High speed set
6 Large toothed wheel
7 Small toothed wheel

Flender SZAK 1380 2-trins gear



1 Ring wheel
2 Planet wheel
3 Sun wheel
4 Planet carrier



Planetgear • /DIN 686/Niemann)

THE GEARBOX

One of the most important main components in the wind turbine is the gearbox. Placed between the main shaft and the generator, its task is to increase the slow rotational speed of the rotor blades to the generator rotation speed of 1000 or 1500 revolutions per minute (rpm).

Without much previous experience with wind turbines, one might think that the gearbox could be used to change speed, just like a normal car gearbox. However this is not the case with a gearbox in a wind turbine.

In this case the gearbox has always a constant and a speed increasing ratio, so that if a wind turbine has different operational speeds, it is because it has two different sized generators, each with its own different speed of rotation (or one generator with two different stator windings).

As an example of a gearbox construction, we can study a Flender SZAK 1380 gear for a 150 kW wind turbine. This gear has two sets of toothed gear wheels, a slow speed stage and a high speed stage. In the slow speed stage the large gear wheel is mounted directly on the gear's hollow shaft, while the smaller gear wheel is machined directly on the intermediate shaft.

The difference in the size of the wheels is 1:5. The intermediate shaft therefore turns 5 times every time the hollow shaft makes one complete revolution. The large gear wheel in the high speed gear stage is also mounted on the intermediate shaft, while the small gear wheel in the high speed gear stage is machined on the generator shaft itself. Here the difference in size is also about 1:5, so that the output shaft to the generator shaft turns 5 times for every one rotation of the intermediate shaft.

When the two ratios are combined, the output shaft will turn 25 times for every rotation of the hollow shaft and the main shaft of the wind turbine combined One can say that the gear has a gear ratio of 1:25.

Normally the ratio in every set of gear wheels is restricted to about less than 1:6. The 150 kW wind turbine has a rotor rotational speed of 40 rpm and with a generator speed of about 1000 rpm, the gearbox must have a total gear ratio of 40/1000 or 1:25. This is possible using a two stage gearbox. A 300 kW wind turbine has a rotor rotational speed of 31 rpm and a generator with a rotational speed of 1500 rpm. It therefore requires a gearbox with a gearbox ratio of 31/1500 or 1:48. This is not possible using a gearbox with only two stages, so the 300 kW wind turbine gearbox has an extra intermediate shaft, giving in all a three stage gearbox.

Wind turbines, from 450 kW and larger, have an integrated gearbox with a planet gear and two normal stages. The planet gear is a special version of the toothed gear. This type of gear is of great delight to gearbox technicians, as it can be combined in countless different complicated variations, each one carefully calculated with its own special inner logic. The form of planet gear used on wind turbines is however always of the same basic design: An interior toothed gear wheel (ring wheel), three smaller toothed gear wheels (planet wheels) carried on a common carrier arm (the planet carrier) and finally a centrally placed toothed gear wheel (the sun gear wheel). It is this construction, with three smaller gear wheels orbiting a centrally placed common gear wheel that has given this type of gear its name of planet gearbox.

The ring wheel itself is stationary, while the planet carrier is mounted on the hollow shaft. When the planet carrier rotates with the same rotational speed as the rotor blades, the three planet wheels turn around inside the inner circumference of the ring wheel and thereby also greatly increase the rotational speed of the centrally placed sun gear wheel. One can usually obtain a gear ratio of up to about 1:5. The sun gear wheel is fixed to an shaft driving the two normal gear stages placed at the rear end of the gearbox.

The fact that there are always three gear wheels supporting each other and that all gear wheels are engaged at the same time, is one of the advantages of the planet gear. This means that it is possible to construct rather compact planet gearboxes, because the larger ring wheel does not need to be as large as a gear wheel in a traditional type of gearbox. In principle it only needs to be about a 1/3 of the size. However in reality it not quite so simple. If a gear is needed to transfer heavy loads, it is often somewhat cheaper to use a planet gear.

However it is in the very nature of things that trees do not grow up into heaven, and also planet gears have their own special disadvantages. The compact construction, very practical for the design and construction of the rest of the machine, can be in itself a disadvantage. The compact construction makes it difficult to effectively dissipate excess heat to the surroundings. A gear is not 100% effective, and as a rule of thumb it is estimated that roughly 1% of the power is lost at each stage. A 600 kW gearbox running at full capacity, must therefore dispose of about 18 kW of waste heat. This is equivalent to nine normal household hot air blower-heaters operating at full blast. This waste heat should preferably be radiated by surface cooling and of course the less gearbox surface area, the higher the temperature must be inside the gearbox to transfer the necessary, unavoidable excess waste heat.

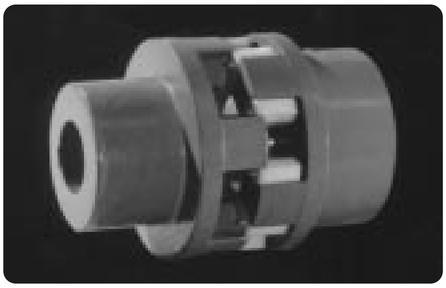
Another disadvantage of the planet gear is that they normally cannot be constructed with bevelled machined teeth. Bevelled teeth are always used in normal gearboxes in order to reduce the noise level. When the teeth are set at an angle, the next tooth will start to engage and take up the load before the previous tooth has slipped contact. This results in a quieter, more harmonious operation. For interior gear wheels bevelled teeth can only be machined using special machine tools that up until now have solely been used for the machining of very large turbine gears for use in ships. Therefore planet gears have always straight machined teeth, unfortunately however, resulting in a higher noise level. By combining a planet gear stage and two normal gear stages, one obtains an acceptable compromise of the advantages and disadvantages with the two different types of gear.

No matter what type of gear is used, the shape of the teeth in the different gear stages are adapted to the special conditions for wind turbine operation, especially those that are related to the noise level. Teeth as a rule are case-hardened and polished. Case-hardening is a method of giving surface strength to a specific material. During this process, the inner material maintains its previous strength, which can often be lost in normal steel hardening processes.

Hardening can only take place under conditions where there is a carbon content in the steel. The gear wheels are made of a special low carbon chrome-nickel steel. The teeth are first machined, and following the machining process, the gear wheels are packed into large boxes full of bone flour or some other form of high carbon-content powder. The boxes are placed in an oven and heated for about 24 hours to a red glowing temperature. During this baking process some of the free carbon will be transferred from the surrounding carbon-rich powder in the boxes to the gear wheel teeth surfaces. This is described as the method of hardening the teeth in boxes or cases, and therefore from this process comes the descriptive name of case-hardening.

The increased carbon content of the teeth surface allows the top edges of the gear wheel teeth to become harder, so following case hardening, the gear wheel is lifted out, still red hot, and lowered into an oil bath. This completes the process of hardening, and the gear wheel now has a hardened surface, while the inner material still has ductile and not hardened properties. The hardening process slightly deforms the material, so it is necessary to finish the process by grinding.

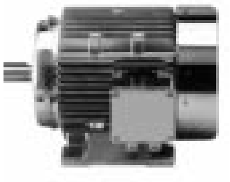
THE COUPLING



Coupling• (Flender BIPEX)

The coupling is placed between the gearbox and the generator. Once again it is not possible to consider the coupling as the same as a clutch in a normal car. One cannot engage or disengage the transmission between the gearbox and the generator by pressing a pedal, or in some other such way. The transmission is a permanent union, and the expression “coupling” should be understood as a junction made by a separate machine component.

The coupling is always a “flexible” unit, made from built-in pieces of rubber, normally allowing variations of a few millimeters only. This flexibility allows for some slight differences in alignment between the generator and the gearbox. This can be of importance under assembly and also during running operation, when both gearbox and generator can have tendencies for slight movement in relation to each other.



THE GENERATOR

The wind turbine electrical system

The generator is the unit of the wind turbine that transforms mechanical energy into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system, and the generator is the next step in the supply of energy from the wind turbine to the electrical grid.

In order to understand how a generator works, it is necessary to first of all understand the deeper principles in the electrical system to which the generator is connected. Therefore we will first discuss the electrical systems based on Direct Current (DC) and those based on Alternating Current (AC).

DIRECT CURRENT (DC)

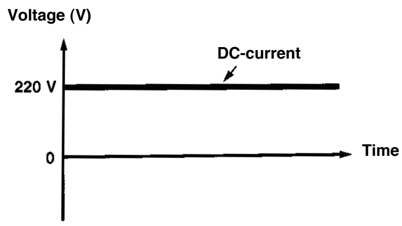
During the first use of electricity for lighting and power in the previous century, systems based on direct current were used. In DC systems the voltage is at a constant level. This could be 1.5 Volts (V) as in a modern alarm clock, 12 V as in a car or 110 V as in the first proper electrical grid.

DC has the advantage that batteries can be connected, enabling a continual supply of electrical power even if the generator at the power station ceases operation and shuts down. Therefore the first power stations had large store rooms full of long rows of batteries. Such systems were well adapted to the use of wind turbines as a main power source, for with such large stocks of batteries, power could still be supplied even in calm periods.

The battery store room of a wind power plant at the beginning of the 1900's • (H.C.Hansen: Poul la Cour)

In spite of the advantages of battery energy storage, DC is no longer used in larger grid electrical supply systems. This is due to some important disadvantages of direct current, while on the other hand the competing electrical system alternating current offers important advantages.

One of the big disadvantages of DC is the strong electrical arc produced, when the electrical current connection from supply to user is cut at higher voltages. For example, in larger installations with connections to electrical motors DC switches are both large and complicated. Therefore in practice DC systems can be rather inconvenient.



DC-system

Another "disadvantage" is that the advantages of battery energy storage do not in reality exist with the electrical grid systems in common use today. This is because our present-day energy consumption greatly exceeds the capacity of this technology.

A typical Danish family has an energy consumption of about 5.000 kWh per year, or about 13.7 kWh per day. A normal car battery has a capacity of about 60 Ah (Ampere-hours). This means that a car battery can supply an electrical current equal to 1 Ampere for about 60 hours at a battery voltage of 12 Volts. The energy in a fully charged battery can be calculated by the use of a simple formula:

$$E = 60 \text{ Ah} \times 12 \text{ V} = 0.72 \text{ kWh}$$

Therefore less than 1 kWh is stored in a fully charged car battery. A typical Danish family with a daily requirement of 13,7 kWh kWh per day will thus need 19 fully charged batteries just to cover the power consumption of a single day without a supply from the power station grid network.

Another example: In a good high wind period a 600 kW wind turbine can typically produce about 10.000 kWh per day. This is enough to charge about 14.000 car batteries per day, were it is not possible to supply this energy production for the direct consumption or use by the owner, or for supply to other consumers connected to the grid.

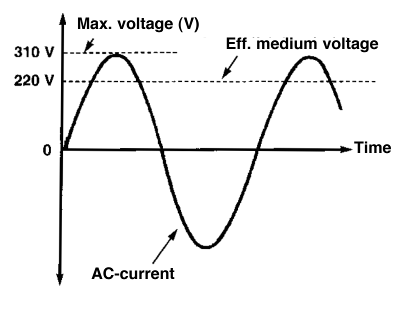
In connection with such large quantities of energy, storage in batteries is not feasible, and the storage possibilities offered by the use of DC systems are not really practically relevant.

ALTERNATING CURRENT (AC)

The voltage of the current constantly varies around zero in an AC electrical system. The maximum voltage must be somewhat higher than a DC system in order to give the same power. One can speak of an effective medium voltage as a kind of average of the voltage.

AC measuring instruments usually show the effective middle voltage value and not the maximum voltage.

A lamp connected to an alternating electrical current will blink, as the voltage constantly varies. The frequency of the voltage variation or cycles in Denmark, and most other countries is 50 Hz (50 cycles per second). Such rapid cycles make the blinking of the lamp of no real importance. The glowing wire in



AC-system

a normal electric bulb does not have time to become cold in the short period between cycles, and therefore does not in practice blink. In comparison light emitting from a neon tube is completely shut off each time the voltage is at zero. The eye however cannot distinguish variations in light intensity that occur faster than 15 times a second, so therefore we see light from a neon tube also as constant.

The main advantage of alternating current over direct current is that the voltage can be altered using transformers. This is not the place to describe in detail the functioning of a transformer, but in principal it is possible to alter from one voltage to another voltage almost without loss of energy.

Most know the small transformers used as power supply to radios, mobile telephones, etc. A small box is plugged into a 220 volt outlet connected to the grid and 9 volts comes out at the other end (normally also rectified to direct current, but that is another story). For the grid as a whole, it is the transformation to a higher voltage that is of importance.

The advantage of high voltage is that energy losses in power transmission lines, are greatly reduced by using increased voltages. In order to understand this, one must know a couple of the fundamental formulas in electrical engineering. As an example consider the case of a typical 220 volt electrical tool, a 2.200 Watt (W) grinder.

The current one obtains at specific power and voltage ratings may be calculated with the formula:

$$I = P / U$$

Where "I" is the current, "P" is the power and "U" is the voltage. In the example of the grinder, with power P = 2.200 W and voltage U = 220 V We obtain the current of 2.200 / 220 = 10 A.

The power loss from the wires may be calculated with the formula:

$$T = R \times I^2$$

Where "T" is the power loss and "R" is the resistance of the wire. A normal household electric wire with a cross section of 1.5 mm^2 has a resistance of 0.02 Ohm per meter. A 10 meter long wire will have a resistance of 0.2 Ohm and the power loss in the wire will therefore be $T = 0.2 \times 10^2 = 20$ W. This is not so much, only about 1% of the grinder's usable power.

The power loss is however quite significant, when one considers the distance from the user to the power station. With a typical distance of about 20 km , the resistance in a 1.5 mm^2 wire will be about 400 Ohm, and the power loss will therefore be $T = 400 \times 10^2 =$ 40,000 W or almost 20 times the power of the grinder! Of course small 1.5 mm^2 wires are not used as power supply cables from the power station out to the consumer, but even with large 50 mm^2 cables, the power loss is still larger than the rated power of the grinder.

It is in this situation that high voltage transmission wires have their use. If instead of 220 V the power station sends an electrical current of 10.000 V out in the electrical grid to the consumer, the first formula for current will give I = 2.200 /10.000 = 0.22 A, and the other formula for power loss will give $T = 400 \times 0.22^2 = 20$ W still using the same (unrealistic) wire dimension of 1.5 mm^2. The use of high voltage power lines has therefore reduced power loss from an unacceptable level to that which is more acceptable.

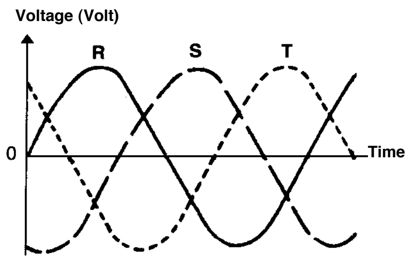
In practice current is transmitted from power stations with a voltage of up to 400,000 V . This is then transformed to a lower voltage in large centralized transformer stations, for example down to 10,000 V. Near the consumer the final transformation down to 220 V is made.

For safety reasons high voltage is not used near the consumer, as electrical current becomes more dangerous, the higher the voltage is increased. Likewise the demands on the safety insulation of electrical material also increases.

Voltage at any one given place on the grid is therefore a compromise between a desire on the one side for a minor power loss (requiring high voltage), and on the other hand the necessity of a low or moderate risk of danger and at the same time reasonably cheap electrical installations (requiring lower voltage).

THREE PHASE ALTERNATING CURRENT

Even though the cycles in the alternating current are of no great importance for lamps and other such things, it is impractical for certain other machines that the current is always alternating around zero. Therefore, years ago, it was discovered that AC could be supplied with three phases.



Three phase AC (three super-imposed sinus curves)

The principle of 3 phase electrical power is that the generator at the power station supplies 3 separate alternating currents, whose only difference is that they peak at three different times. The knack with these three separate alternating currents, or phases, is that it is thereby possible to ensure that the sum of the delivered power is always constant, which is not possible with two or four phases.

It is perhaps a little impractical with three phase current, because it is necessary to run four different wires out to the consumer, three different phase wires and a neutral wire (zero). However for electric motor use, the advantages of three phase alternating current are many. The voltage difference between two of the phases is greater than that between any one single phase and zero. Where the voltage difference is 220 V between one phase and zero, it is 380 V between two phases.

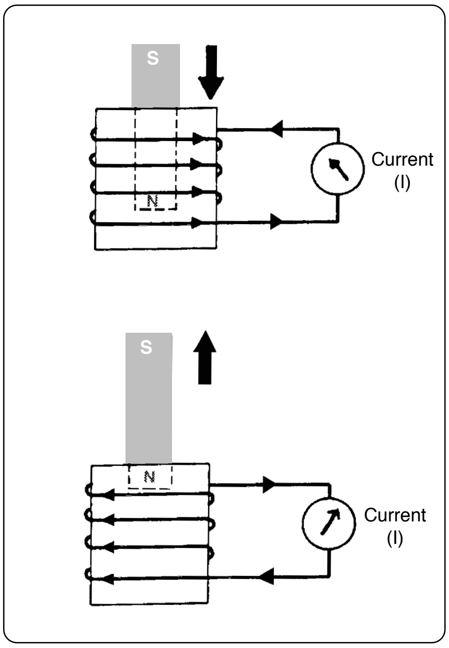
This is often used in high energy consumption equipment such as kitchen ovens etc., which normally always are connected to two phase power. In a household installation usually only one of the phases plus the neutral wire is led to an ordinary socket. Normally the installation has several groups, and one phase will typically cover one part of the house, and another phase will run to the other rooms. Three phase sockets are rather large and are often known as power sockets, mainly because of their use in electrical motor operation. For ease in distinguishing between the different phases, in Denmark the three phases have been named R, S, and T.

On the older Danish transmission lines supported by wooden masts, phases were placed in a certain specific order, reading from the bottom up, according to the Danish words for root (R), trunk (S) and top (T).

INDUCTION AND ELECTROMAGNETISM

Before finally describing the generator itself, we must briefly explain a couple of the basic principles of electromagnetism.

Many perhaps remember our school days, when the physics teacher placed a magnetic bar inside a coil of copper wire connected to a measuring instrument.



The principles of induction

If the magnet is stuck inside the coil, an electric current is registered in the coil circuit. If the magnet is withdrawn, a current of the same strength is registered, but in the opposite direction. The faster the changes of the magnetic field in the coil, the greater the current. The same occurs if instead of the magnet being stuck into the open coil it is merely moved past one of the ends of the coil. The effect is especially powerful if the coil has a iron core.

One can say that alterations in the magnetic field, induce a current in the coil, and the phenomena is known as induction.

In just the same way that a magnetic field can bring about an electric current, so can an electric current likewise cause a magnetic field to be created. Electromagnetism was first demonstrated by the Danish scientist H.C Ørsted in his famous experiment, where an electrical current was able to turn a compass needle. He had therefore demonstrated the first electromagnet.

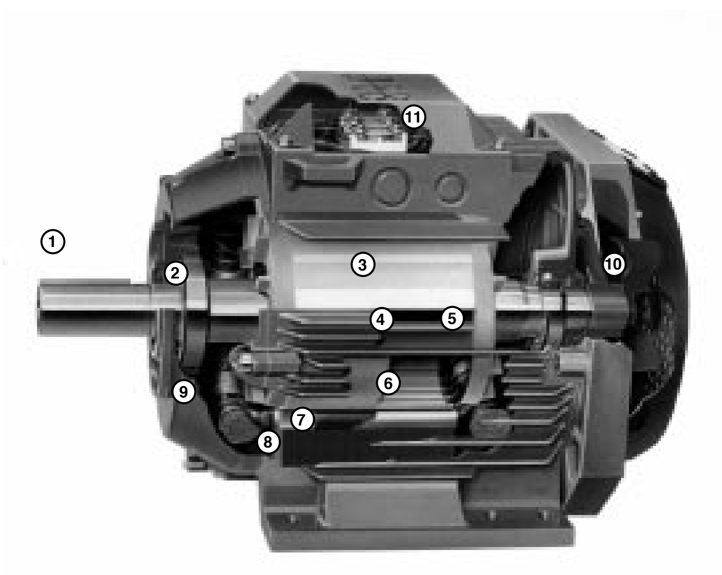
In practice a good electromagnet is best made as a coil with an iron core, in just the same way as the previously mentioned form of coil that produces an electric current when a magnet is moved past at a close distance. Like a permanent magnet an electromagnet has two poles, a north pole and a south pole. The position of these two poles depends on the direction of the flow of electrical current.

THE WIND TURBINE GENERATOR AS A MOTOR

The asynchronous generator we will describe here is the most common type of generator used in Danish wind turbines. It is often referred to as the induction generator, too. As far as we know the asynchronous generator was first used in Denmark by Johannes Juul, known for the 200 kW Gedser wind turbine from 1957. Already some years prior to this construction he erected a 13 kW experimental wind turbine with an asynchronous generator at Vester Egesborg in the south of the large Danish island of Zeeland.

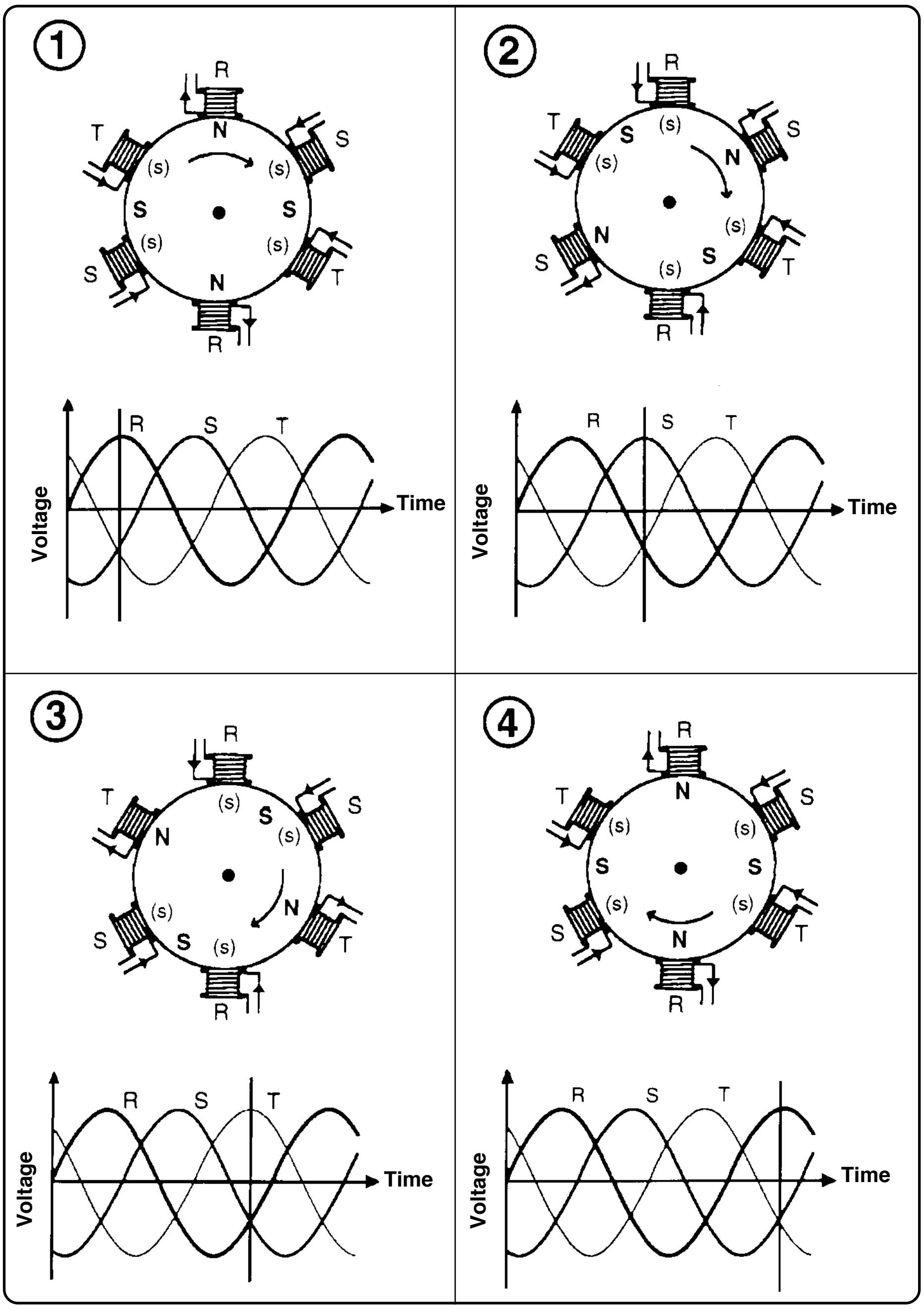
The asynchronous generator is in reality a type of motor that can also operate as a generator, and we will first consider this type as a motor. This is the most common electric motor, sitting in almost every washing machine, and widely used as a motor unit in industry.

The motor consists of two main parts, the stator and the rotor. The stator contains a series of coils, the number of which must be divisible by three. The motor illustrated on this page has six coils, placed in slots on the inside of the stator, a cylinder assembled of thin iron plates. The rotor sits on an axle placed inside this stator. The rotor is also assembled of thin iron plates. A row of thick aluminum bars joined at each end with an aluminum ring, fit in key ways on the outer surface of the rotor. This rotor construction looks a bit like a squirrel cage, and accordingly the asynchronous motor is also called a squirrel cage motor.



1. Generator shaft
2. Rolling bearings
3. Rotor
4. Rotor aluminium bar
5. Rotor aluminium ring
6. Stator
7. Coil
8. Stator plates
9. Coil heads
10. Ventilator
11. Connection box

Components of an asynchronous motor



4 situations of the rotation magnetic field

The six coils in the stator are connected together, two by two to the three different phases of the electrical grid. This arrangement insures that there is a rotating magnetic field inside the stator itself. This is best illustrated by the above diagram.

At a specific time "1" the current in phase R is at its maximum, and this produces a magnetic field with a strong north pole at both the opposite coils connected to the phase R. At phase S and phase T the current is somewhat under zero, and the two pairs of coils produce a medium strength south pole, producing a powerful south pole halfway between the two coils.

At time "2" the current at phase S is at a maximum, and the north pole is now at the two opposing coils connected to this phase. The current at phases R and T is likewise reduced to under zero, and the south pole is now between these two coils.

At time "3" the current at phase T now is at a maximum, and the north pole is at the two coils connected to phase T. The south pole has also turned, and is now halfway between the coils connected to phases R and S.

At time "4" the situation has now returned to as it was at the start of the electrical current rotation, with the north poles at the end of the coils connected to phase R.

In one complete cycle, from the current peak to the next following peak, the magnetic field has rotated through half a circle. There are 50 cycles per second, so the field turns at 25 times per second, or 60 x 25 = 1.500 rpm (revolutions per minute).

To understand how a generator works, it is easiest to first consider two different situations where a generator operates as a motor, at 0 rpm. and at 1.500 rpm.

In the first case the rotor is stationary, while the stator turns at 1.500 rpm. The coils in the rotor experience rapid variations of a powerful magnetic field. A powerful current is thereby induced in the short circuited rotor wire windings. This induced current produces an intense magnetic field around the rotor. The north pole in this magnetic field is attracted by the south pole in the stator's turning magnetic field (and of course, the other way round) and this will give the rotor a torque in the same direction as the moving magnetic field. Therefore the rotor will start turning.

In the second situation, the rotor is turning at the same speed as the stator magnetic field of 1.500 rpm. This rotational figure is called the synchronous rotational speed. When the stator magnetic field and the rotor are synchronized, the rotor coils will not experience variations in the magnetic field, and therefore current will not be induced in the short circuited rotor windings. Without induced current in the rotor, there will be no magnetic field in the rotor windings and the torque will be zero.

On account of bearing friction the motor must produce a little torque to keep rotating, and therefore cannot run at exactly the same speed as the rotating magnetic field. As soon as the speed slows down, there will be a difference between the speed of the rotating magnetic field and the rotor. The rotor thus again experiences a variation in the magnetic field that induces a current in the rotor windings. This current then produces a magnetic field in the rotor, and the rotor can produce a torque.

During motor operation, the stator experiences a constantly changing magnetic field, being dragged round by its rotating magnetic field. During this process, electrical current is induced in the stator, which results in a power consumption. In fact, the slower the rotor turns in relation to the rotating magnetic field of the stator, the stronger the induction in the stator, and therefore the greater the power consumption.

The fact that the rotor has no torque at the precise synchronous rotational speed and therefore will always run slightly slower has given this motor type its name, the asynchronous motor.

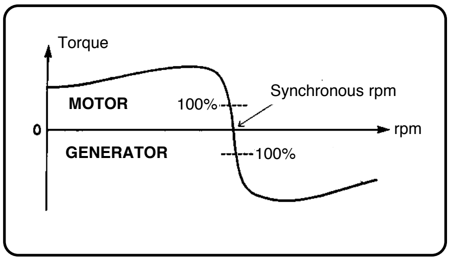
GENERATOR OPERATION

As we have previously mentioned, the asynchronous motor can also run as a generator. This simply happens when you, instead of forcing the rotor to turn at a rotational speed lower than the synchronous speed, exceed this synchronous speed by applying an outside energy source, such as a diesel motor or a set of wind turbine rotor blades.

Once again, the greater the difference between the rotating magnetic field of the stator (which is always 1.500 rpm) and the speed of the rotor, the greater the torque produced by the rotor. When a working as a generator, the rotating field however acts as a brake in slowing the rotor. The stator experiences a variable magnetic field from the rotor that "drags" its rotating magnetic field and thereby induces an electrical current in the stator. In comparison to motor operation the induced currents in the rotor and stator will flow in the opposite direction, which means that power will be sent to the grid. The faster the rotor turns in relation to the rotating magnetic field of the stator, the greater the induction in the stator and the greater the production of power.

In practice the difference between the speed of rotational magnetic field of the stator and the rotational speed of the rotor is very little. A rotor will typically turn about 1% faster at full power production. If the synchronous rotational speed is 1.500 rpm then the rotor rotational speed at full power will be 1.515 rpm.

The interesting torque curve of the asynchronous electric motor, also operating as a generator, is shown below. At speeds below the synchronous rotational speed, the motor yields a positive torque.



Torque curve

Typically a maximum torque of about 2.5 times the torque of the nominal power. If the rotational speed exceeds the synchronous level, the torque becomes negative, and the generator acts as a brake.

At the Bonus factory, we have a rather interesting apparatus, that demonstrates this shift between a motor and generator. A small asynchronous motor is connected to an electric meter. The motor has a gearbox giving a shaft speed of 60 rpm.

A small crank handle is fixed to the shaft. The motor starts when it is plugged into a normal mains socket coming from the electrical grid and consumes a small amount of electrical energy due to friction loss in the motor and gearbox.

If one attempts to resist the rotation of the shaft by holding back the crank, the consumption of energy will increase. If the crank however is used to increase the speed of the motor, then the electric meter will start to run backwards, showing that current is flowing the other way. In this way one can, by using human muscle power, feed electrical power to the grid, in just the same way that a wind turbine feeds power to the grid. It is difficult to achieve more than 1/20 kW so a work force of twelve thousand employees is needed to compete with one single 600 kW wind turbine operating in a good wind. Visitors to Bonus may try their hand at our generator demonstration model.

CUT- IN

If a wind turbine is connected to the grid during a period of no wind, the asynchronous generator will operate as a motor and drag the rotor blades round like a large electric fan. The wind turbine therefore is disconnected from the grid during periods of calm.

The wind turbine is likewise disconnected during periods of low wind speeds, allowing the blades to slowly rotate. The control system of the wind turbine however constantly monitors the rotational speed, and after the blades reach a certain pre-set level, the system permits a gradual cut-in to the grid.

The cut-in to the grid is carried out by the use of a kind of electronic contacts called thyristors, allowing continuously variable up and down regulation of the electrical current. Such thyristors allow smoother and gentler generator cut-in, thus preventing sudden surges of current causing possible grid damage. Likewise this gentler switching procedure prevents stress forces in the gearbox and in other mechanical components. A direct cut-in, using a much larger electrical switching unit result in violent shock-effects, not only to the grid but also to the whole transmission system of the wind turbine itself.

Unfortunately, thyristors have the disadvantage of an power loss of about 1-2%, so after the finish of the cut-in phase, current is led past the thyristors direct to the grid by the means of a so-called " by-pass switch ".

CLOSING REMARKS

It has been necessary to make many simplifications in the above description. We have considered such important terms, as self-induction, reactive current and phase compensation to be too complicated in a more general description such as this. During the induction process, in reality it is not an electric current that is created, but an electromotive force giving rise to a certain current dependent upon the resistance.

We have used the rotational speed for a 4-pole and 6 coil generator (3 x 2). In the diagram showing the rotating field, one can observe that there are 2 north poles and 2 south poles, 4 in all. Other generators may have 9 coils, which would mean 3 north poles and 3 south poles. Such a 6 pole generator has a synchronous rota-tional speed of 1.000 rpm.

Bonus wind turbines up to and including the 150 kW models have 6 pole generators, while the larger models have 4 pole generators.

CONTROL AND SAFETY SYSTEMS

Control and safety systems comprise many different components. Common for all of these is that combined together they are part of a more comprehensive system, insuring that the wind turbine is operated satisfactory and preventing possible dangerous situations from arising.

Details in control and safety systems are somewhat different according to different types of wind turbines. We have in previous articles described components and their functions that roughly cover most Bonus wind turbine models, regardless of their age. However it is necessary in this article to be much more specific, so we choose to concentrate on the Bonus 600 kW Mk IV.

PROBLEM DESCRIPTION

In constructing wind turbine control and safety systems one is soon aware of a couple of rather important problems. These problems pose special demands on the systems, because they have to function in the complex environment of a wind turbine.

The first problem is common to all control and safety systems: A wind turbine is without constant supervision, apart from the supervision of the control system itself. The periods between normal qualified maintenance schedules is about every 6 months, and in the intervening 4,000 hours or so the control system must function trouble-free, whether the wind turbine is in an operational condition or not.

In almost every other branch of industry there is a much higher degree of supervision by trained and qualified staff. On factory production lines, operatives are normally always present during production. For example, in power stations the system is constantly supervised from a central control room. Should a fault or breakdown occur, rapid intervention is possible and, as a rule, one has always some sort of good impression of what has actually happened in any unforeseen occurrence. However a wind turbine must be able to look after itself and in addition have the ability to register faults and retrieve this stored information concerning any special occurrence, should things possibly not go exactly quite as expected.

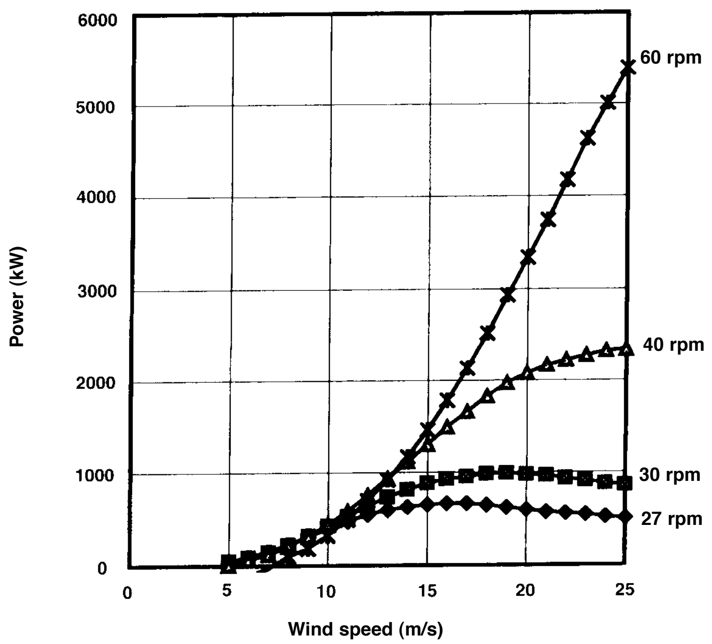
The high demands on reliability require systems that are simple enough to be robust, but at the same time give the possibility for necessary supervision. The number of sensors and other active components need to be limited as far as possible, however the necessary components must be of the highest possible quality. The control system has to be constructed so that there is a high degree of internal control, and to a certain degree the system must be able to carry out its own fault finding.

The other problem most of all relates to the safety systems. A wind turbine, if not controlled, will spontaneously overspeed during high wind periods. Without prior control it can then be almost impossible to bring to a stop.

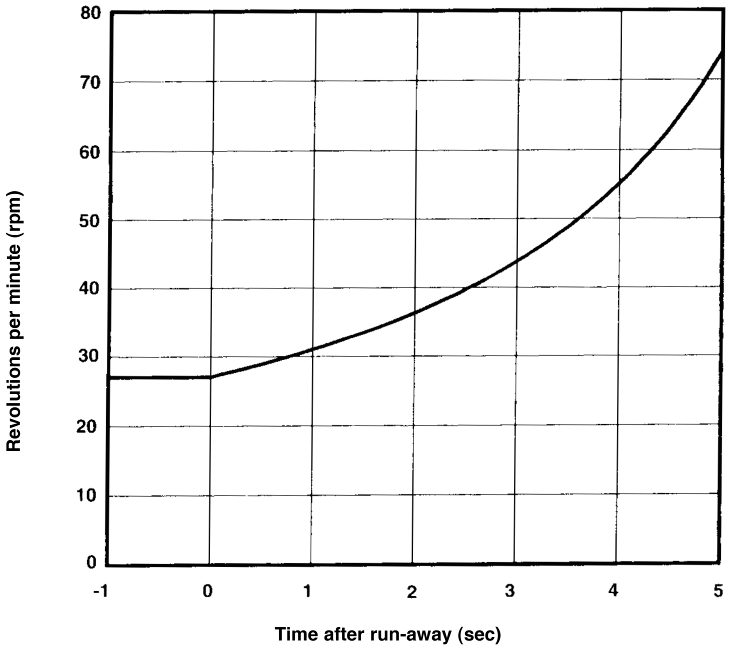
During high wind, a wind turbine can produce a much higher yield than its rated power. The wind turbine blade rotational speed is therefore restricted, and the wind turbine maintained at the rated power, by the grid-connected generator.

If the grid connection is lost, by reason of a power line failure or if the generator for some other reason is disconnected, while the wind turbine is in operation, the wind turbine would immediately start to rapidly accelerate. The faster the speed, the more power it is able to produce. The wind turbine is in a run-away condition.

The following diagrams dramatically illustrates run-away in high wind. The first graph shows the power curve for the 600 kW wind turbine as a function of the blade rotational speed. The bottom curve illustrates the normal power curve controlled by the generator, at a blade rotational speed of 27 rpm. The three other curves show power production at 30 rpm, 40 rpm and 60 rpm.



Power curves at different rotational speeds (rpm)



Rotational acceleration during run-away

At a wind speed of 20 m/s, a wind turbine will normally produce slightly under 600 kW. Allowed to accelerate a mere 10% to a blade rotational speed of 30 rpm, it is then able to increase power production to 1.000 kW. At a blade rotational speed of 40 rpm the power increases to 2.000 kW and 3.300 kW at 60 rpm. At a wind speed of 25 m/s, if the blades were permitted to rotate at a speed of 60 rpm, the power production would be as high as 5.400 kW.

The second graph illustrates just how rapidly the blade rotational speed accelerates in a run-away situation. After a mere 0.6 seconds the rotor speed accelerates to 30 rpm, and after 2.5 seconds the blades achieve 40 rpm. As noted above the power output at 40 rpm is 2.000 kW, an output far above the ability of the braking system to restrain.

So it is vital that the safety systems must possess very rapid reactive response in order to prevent such runaway.

95% of all deliberations behind design of wind turbine safety systems have to do with this one task of safely regaining control of the wind turbine, should the generator speed control suddenly become non-operative during high wind conditions, and thereafter securely bring the wind turbine to a halt.

Basically there are two main methods by which one prevents a run-away:

1. Either one can prevent that the blades are actually able to achieve this increased power production under this condition of rapidly accelerating blade rotational speed.

2. Or by some other means one can prevent the rotational speed from rising to an unacceptably dangerous level.

Here we have the principles for the use of aerodynamic braking (1) and the mechanical brake (2).

THE CONTROLLER

In one way or another the controller is involved in almost all decision-making processes in the safety systems in a wind turbine. At the same time it must oversee the normal operation of the wind turbine and carry out measurements for statistical use etc.

The controller is based on the use of a micro computer, specially designed for industrial use and therefore not directly comparable with a normal PC. It has a capacity roughly equivalent to that of a 80286 PC system processor. The control program itself is not stored in a hard disk, but is stored in a microchip called an EPROM. The processor that does the actual calculations is likewise a microchip.

Most wind turbine owners are familiar with the normal keyboard and display unit used in wind turbine control. The computer is placed in the control cabinet together with a lot of other types of electro-technical equipment, contactors, switches, fuses, etc.

The many and varied demands of the controller result in a complicated construction with a large number of different components. Naturally, the more complicated a construction and the larger the number of individual components that are used in making a unit, the greater the possibilities for errors. This problem must be solved, when developing a control system that should be as fail-safe as possible.

To increase security measures against the occurrence of internal errors, one can attempt to construct a system with as few components as possible. It is also possible to build-in an internal automatic “self-supervision“, allowing the controller to check and control its own systems. Finally, an alternative parallel back-up system can be installed, having more or less the same functions, but assembled with different types of components. On the 600 kW Mk. IV wind turbine, all three principles are used in the control and safety systems. These will be further discussed one at a time in the following.

A series of sensors measure the conditions in the wind turbine. These sensors are limited to those that are strictly necessary. This is the first example of the targeted approach towards fail-safe systems. One would otherwise perhaps think, as we now have access to computers and other electronic devices with almost unlimited memory capacity, that it would merely be a matter of measuring and registering as much as possible. However this is not the case, as every single recorded measurement introduces a possibility for error, no matter how high a quality of the installed sensors, cables and computer. The choice of the necessary sensors is therefore to a high degree a study in the art of limitation.

The controller measures the following parameters as analogue signals (where measurements give readings of varying values) :

- Voltage on all three phases
- Current on all three phases
- Frequency on one phase
- Temperature inside the nacelle
- Generator temperature
- Gear oil temperature
- Gear bearing temperature
- Wind speed
- The direction of yawing
- Low-speed shaft rotational speed
- High-speed shaft rotational speed

Other parameters that are obviously interesting are not measured, electrical power for example. The reason being that these parameters can be calculated from those that are in fact measured. Power can thus be calculated from the measured voltage and current

The controller also measures the following parameters as digital signals (where the measurements do not give readings of varying values, but a mere an on/off signal) :

- Wind direction
- Over-heating of the generator
- Hydraulic pressure level
- Correct valve function
- Vibration level
- Twisting of the power cable
- Emergency brake circuit
- Overheating of small electric motors for the yawing, hydraulic pumps, etc.
- Brake-caliper adjustment
- Centrifugal-release activation

Even though it is necessary to limit the number of measurements, certain of these are duplicated, for example at the gearbox, the generator and the rotational speed. In these cases we consider that the increased safety provided, is more important than the risk of possible sensory failure.

Internal supervision is applied on several levels. First of all the computer is equipped with certain control functions, known as "watchdogs". These supervise that the computer does not make obvious calculation errors. In addition the wind turbine software itself has extra control functions. For example in the case of wind speed parameters. A wind turbine is designed to operate at wind speeds up to 25 m/s, and the signal from the anemometer (wind speed indicator) is used in taking the decision to stop the wind turbine, as soon as the wind speed exceeds 25 m/s.

Cup anemometer for wind speed indication (left) • Lightning conductor (middle) • Wind direction indicator (right)

As a control function of the anemometer the controller supervises wind speed in relation to power. The controller will stop the wind turbine and indicate a possible wind measurement error, if too much power is produced during a period of low wind, or too little power during a period of high wind.

A wind measurement error could be caused by a fault in the electrical wiring, or a defect bearing in the anemometer. A constant functional check of the relationship between wind speed and power production ensures that it is almost impossible for the wind turbine to continue operation with a wind measurement error, and the possibility of a wind turbine being subject to stronger winds than its designed wind speed rating, is therefore more or less eliminated.

The third safety principle for the controller lies in duplication of systems. A good example is the mechanical centrifugal release units. These supervise the blade rotational speed and activate the braking systems, even if the speed measurement system of the controller should fail.

A 600 kW Mk IV wind turbine has two centrifugal release units. One of these is hydraulic and placed on the wind turbine hub. It is normally called a CU (Centrifugal release Unit). Should the wind turbine operate at too high a rotational speed, a weight will be thrown out and thereby open a hydraulic valve.

Interior view of the CU

Once the valve is open, hydraulic oil will spill out from the hydraulic cylinders that hold the blade tips in place, thereby activating the blade tip air brakes. No matter what actions the controller or the hydraulic system thereafter attempts to carry out, pressure cannot be maintained in the cylinders and the air brakes will continue to remain activated, until a serviceman resets the centrifugal release manually.

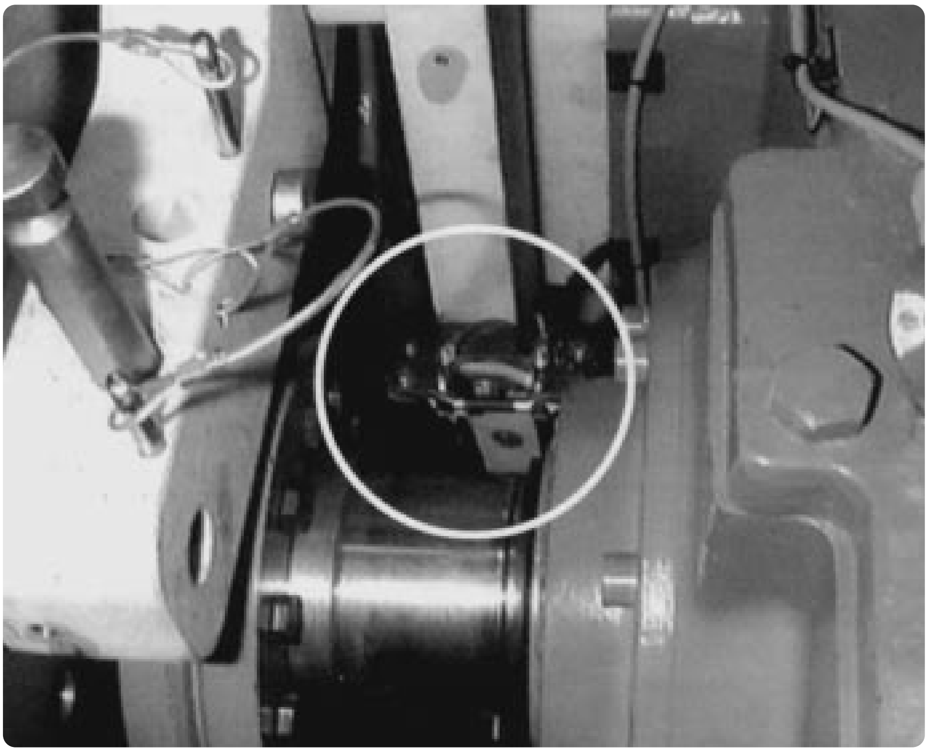
The advantages of the hydraulic centrifugal release units is that it is completely independent the controller and the hydraulic system. This ensures that a possible fatal software design error, not discovered during design review, will not result in a possible run-away of the wind turbine.

The second centrifugal release unit is an electro-mechanical unit, fixed to the high speed shaft of the gearbox. This is normally called an HCU, where H is short for "high-speed". Should the wind turbine over-speed, two small arms are thrown out mechanically cutting off the electrical current to the magnetic valves of the air brakes and the mechanical braking system.

This is a so-called fail-safe system, where the electrical circuit must remain switched on in order to maintain the valves for the air brakes and for the mechanical brake in a closed position. Should the electrical circuit be broken because of a disconnection from the grid or as a result of a shut down from the controller itself, the valves will open and activate the brakes causing the wind turbine to slow down and stop.

The HCU is able to mechanically cut the braking circuit, and thereby activate both braking systems. The hub-mounted CU only cuts the blade hydraulic system. The HCU therefore is superior, however its successful operation is based in turn upon satisfactory operation of the normal valve systems, while the CU has its own extra valve system. Both systems thus have their own advantages and disadvantages considered from the point of view of safety.

Both centrifugal release units are adjusted to be activated at very near the normal operational rotational speed, therefore, on rare occasions, release can occur prematurely. This is not normally the case in Denmark, but following from unexpected power cuts at certain foreign projects, causing the turbines shortly to operate in stand-alone mode, we have experienced release activation. Otherwise centrifugal release systems are only intended to be activated during maintenance testing.



HCU placed on the high speed shaft of the gearbox

HYDRAULICS

The controller decides which operations are to be carried out in the safety system, while the hydraulic system operates the braking systems.

In a hydraulic system a liquid under pressure is used to move certain components. This liquid is called hydraulic oil, having a resemblance to lubricating oil. The operating pressure is about 1.000 Bar (one Bar is equivalent to one atmosphere). The moving components are pistons in hydraulic cylinders. With a pressure of 100 Bar a piston in a 50 mm hydraulic cylinder (similar to the units used in pulling the blade tips into position) produces a force of 2 tons.

The hydraulic systems of both the tip-brakes and the mechanical brake are also fail-safe systems, i.e. hydraulic pressure is necessary for the wind turbine to operate. The hydraulic system ensures that pressure is established when the wind turbine starts. It also releases the pressure when the turbine must stop.

Pressure is built up with a pump controlled by a pressure sensitive switch. Following attainment of the required pressure level, occasional operation of the pump maintains the level. A reserve pressure tank is also included in the system. This small steel tank contains a rubber membrane separating the hydraulic oil from an enclosed body of air. When the oil is under pressure, this will press against this body of air, which in turn will act as a kind of cushion giving a counter pressure, thereby enabling the pressure in the whole system to be maintained.

The release of pressure from the tip-brakes and the mechanical brake is carried out by the means of magnetic valves. These are held in a closed position by the use of an electromagnet and will automatically open with a lack of electrical current. They are therefore operated by being simply switched off.

In order to avoid operational failure problems that any one specific make of valve could possibly produce, two different makes of valves from two different manufacturers are placed in parallel in each of the two different systems for both air brakes and the mechanical brake. Secure and safe operation is ensured even with only one single operational valve, and their functioning is checked at every routine maintenance schedule.

In addition the mechanical hydraulic CU is fixed at the hub of the rotor blade itself. This unit is completely independent of the functioning of the magnetic valves in releasing the pressure in the air brake hydraulic cylinders.

Tip brake in function

TIP BRAKES

The moveable blade tips on the outer 2.8 meters of the blades function as air brakes, usually called tip brakes.

The blade tip is fixed on a carbon fiber shaft, mounted on a bearing inside the main body of the blade. On the end of the shaft inside the main blade, a construction is fixed, which rotates the blade tip if subject to an outward movement. The shaft also has a fixture for a steel wire, running the length of the blade from the shaft to the hub, enclosed inside a hollow tube.

During operation the tip is held fast against the main blade by a hydraulic cylinder inside the hub, pulling with a force of about 1 ton on the steel wire running from the hub to the blade tip shaft.

When it is becomes necessary to stop the wind turbine, the restraining power is cut-off by the release of oil from the hydraulic cylinder, thereby permitting centrifugal force to pull the blade tip outwards. The mechanism on the tip shaft then rotates the blade tip through 90 degrees, into the braking position. The hydraulic oil outflow from the hydraulic cylinder escapes through a rather small hole, thus allowing the blade tip to turn slowly for a couple of seconds before it is fully in position. This thereby avoids excessive shock loads during braking.

As previously described in the section on the hydraulic system, the construction set-up is fail-safe requiring an active component (oil pressure) in order to keep the turbine in an operational mode, while a missing active component (no oil pressure) activates the system.

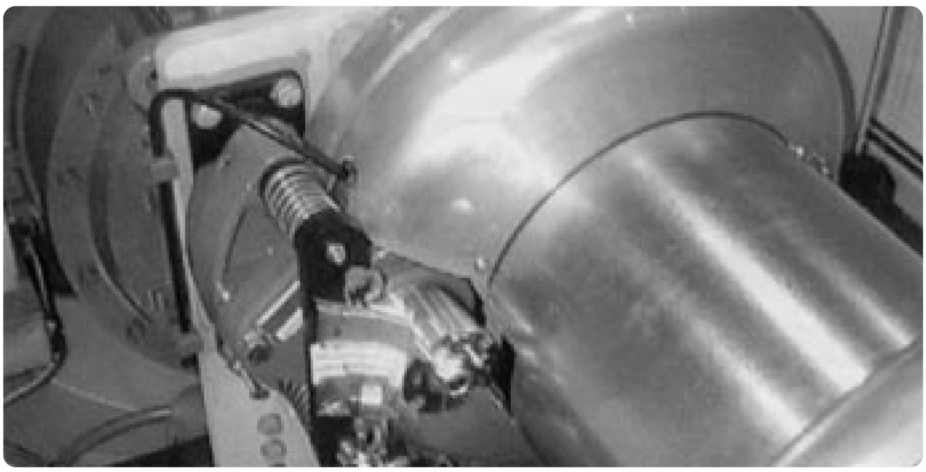
The tip brakes effectively stop the driving force of the blades. They therefor have the function as described under point 1 in the section dealing with problems - to prevent the blades having a greatly increased power production with increased rotational speed. They cannot however normally completely stop blade rotation, and therefore for every wind speed there is a corresponding free-wheeling rotational speed. However even for the highest wind speeds experienced in Denmark, the free-wheeling rotational speed is much lower than the normal operational rotational speed, so the wind turbine is in a secure condition, even if the mechanical brake should possibly fail.

THE MECHANICAL BRAKE

The Mechanical brake is a disc brake placed on the gearbox high-speed shaft. The brake disc, made of steel, is fixed to the shaft. The component that does the actual braking is called the brake caliper. Likewise this is also a fail-safe system, hydraulic oil pressure is necessary to prevent the brake unit from braking. Should oil pressure be lacking, a powerful spring presses the brake blocks in against the brake disc.

Braking is a result of friction between the brake block and the disc. Wind turbine brakes experience large stress forces, therefore it is necessary to use special materials for brake blocks on large wind turbines. These are made of a special metal alloy, able to function under high temperatures of up to 700 degrees Centigrade. By comparison, the temperature of the brakes on a car rarely exceed 300 degrees.

The mechanical brake function is as described under point 2 of the section dealing with the possible problem situations - to prevent the rotational speed of the blades from increasing above the rated rotational speed.



The Mechanical Brake

WIND EFFECT PROPORTIONS / RELATIONSHIPS

1. Average Wind Speed

$$v_m = 0{,}01 \cdot \sum (v_i \cdot q_i) \qquad m/s$$

v_i = wind speed in i-interval
q_i = % occurence / frequency in i-interval

2. Wind Gust Factor

$$C_B = \frac{V_B}{V_{MAX}}$$

V_B = max wind speed in wind gust

V_{MAX} = max registered wind speed

(In praxis, C_B circa 1,5)

3. Wind Effect

$$P_V = \frac{\varrho}{2} \cdot v^3 \cdot A \qquad \text{Watt}$$

ϱ = weight of air mass (kg / m^3)
v = wind speed (m / s)
A = 90 degree, swept area (m^2)

4. If $A = 1m^2$, and weight of air mass = $1{,}26\ kg /m^3$

$$P_V = 0{,}63 \cdot v^3 \qquad W / m^2$$

a: Wind speed 5 m/s $\Rightarrow$ $P_5 = 0.63 \cdot 5^3 = 79\ W/m^2$

b: Wind speed 10 m/s $\Rightarrow$ $P_{10} = 0.63 \cdot 10^3 = 630\ W/m^2$

5. Yearly Energy Content of Wind

$$E = \frac{0{,}63 \cdot \sum (y_i^3 \cdot h_i)}{1000} \quad \text{kWh/m}^2\text{/year}$$

h_i = hours in i-interval

6. One can also use the following formula

$$E = 0{,}055 \cdot \sum (v_i^3 \cdot q_i) \quad \text{kWh/m}^2\text{/year}$$

q_i = frequency in i-interval

7. Wind Power System Max Theoretical Effect

$$P_{MAX} = 0{,}593 \cdot \frac{\varrho}{2} \cdot v^3 \cdot A \quad \text{Watt}$$

A = swept rotor area (m^2)

0,593 = max value of effect coefficient, in praxis, the values are, 0,30 - 0,45.

Rotor Efficiency

$$\eta_p = \frac{C_p}{0{,}593}$$

η_p = 0,60, equivlent to ,---
C_p = 0,356

9. Real Rotor Effect

$$P = 0{,}593 \cdot \frac{\varrho}{2} \cdot \eta_p \cdot v^3 \cdot A \quad \text{W.}$$

10. $$P = 0{,}37 \cdot \eta_p \cdot v^3 \cdot A \quad \text{W.}$$

11. Wind Power System Effect including Transmission Loss from Gearbox, etc.

$$P_t = 0{,}37 \cdot \eta_p \cdot \eta_t \cdot v^3 \cdot A \quad \text{W.}$$

Transmission efficiency = η_t

12. Wind Power System Effect including Transmission Lost Effect, and Loss from Generator Efficiency

$$\eta_g = \text{circa } 0{,}85$$

$$P_g = 0{,}37 \cdot \eta_g \cdot \eta_t \cdot \eta_g \cdot v^3 \cdot A \qquad W.$$

Therefore modern systems can utilize, about 30 - 50 % of the potential wind energy

13. Propeller Blade Relationships / Blade tip speed relationships.

$$\lambda = \frac{\text{wing tip speed}}{\text{wind speed}}$$

14. Angle Speed

$$\omega = \frac{\lambda \cdot v}{R} \qquad \text{radians / second}$$

15. Tangential Speed

$$v_r = \omega \cdot r \qquad m/s$$

16. One can also use the following formula

$$v_r = \frac{\lambda \cdot v}{R} \cdot r \qquad m/s$$

17. Rotation Speed (rpm)

$$n = \frac{\omega \cdot 60}{2\pi} \qquad rpm$$

18. Or ----

$$n = v \cdot \frac{\lambda \cdot 60}{2\pi R} \qquad rpm$$

19. Propeller Area relationship

$$S = \frac{\text{total wing blade area}}{\text{area of rotation}}$$

20. Centrifugal Force

(1 kg. = 9.8 Newton)

$$F = m \cdot \frac{(v_t \cdot C_B)^2}{r_t} \quad \text{N.}$$

m = wing mass

v_t = tangential speed at the point of balance of the wing. **C.G.**

r_t = radius at the point of balance of the wing. **(Center of Gravity)**

21. Max Longitudinal Force (axial force) at nominal wind speed , v_N

$$T_{a-max} = 0,75 \cdot \varrho \cdot C_p \cdot (v_N \cdot C_B)^2 \cdot A \quad \text{N.}$$

22. $$T_{a-max} = 0,95 \cdot C_p \cdot (v_N \cdot C_B)^2 \cdot A \quad \text{N.}$$

23. If the number of blades is " i ", then the axial pressure / axial thrust on each wing is:

$$T_{ai} = \frac{T_{a-max}}{i} \quad \text{N.}$$

24. Axial Pressure / Thrust per meter of wing [t_{ai}]

$$t_{ai} = 6 \cdot \frac{C_p}{i} \cdot (v_N \cdot C_B)^2 \cdot r \quad \text{N/m.}$$

25. With Locked Wings (Locked fast, and not moving), the wings are subject to a longitudinal force, when the wind blows. The strength of the individual wing is:

$$T_{as} = 2 \cdot \frac{T_a}{i} \cdot S \quad \text{N.}$$

26. Moment of Flexation (bending)

$$M_b = \frac{T_{a-max}}{i} \cdot 0,7 \cdot R \quad \text{Nm}$$

27. Torque on Propeller Axle

$$P = M_d \cdot \omega \qquad \text{W.}$$

28. $$M_d = 0,63 \cdot \frac{C_p}{\lambda} \cdot v^2 \cdot R \cdot A \qquad \text{Nm}$$

29. $$M_d = 0,37 \cdot \frac{\eta_p}{\lambda} \cdot v^2 \cdot R \cdot A \qquad \text{Nm}$$

<u>Water Pump Type Windmill</u>

Propeller efficiency = 0,25 - 0,50

Effect coefficient = 0,15 - 0,30

Area relationship / proportion = 0,5 - 0,8

Tip speed relationship = max 2

<u>" Super " Fan Type (Similar to a large bicycle wheel)</u>

Effect coefficient = 0,45

Area relationship = 0,30

Blade tip speed = 3

<u>Wind Turbine Blades</u>

Effect coefficient = 0,35 - 0,45 +

Area relationship = 0,1 - 0,2

Blade tip speed relationship = 5 - 7.

Appendix

Windpower equations

(These equations are in a form suitable for use in a computer programme.)

* means 'multiply by', / means 'divide by', and ^ means 'to the power of' the first thing (only) that follows the symbol.

Variable	Symbol	Units	Notes or Equation
Pi	Pi	none	pi = 3.14 (geometrical constant)
Density of air	rho	kg/m^3	rho = 1.2 (temperature dependent)
Power coeff.	Cp	none	Cp < 0.6, say 0.15
Windspeed	V	m/s	try 10m/s (= 22mph)
Diameter	D	metres	D = (P/(Cp*rho/2*Pi/4*V^3))^0.5
Power	P	watts	P = Cp*rho/2*pi/4*D^2*V^3
Mean windspeed	Vm	m/s	Vm = around 5 m/s usually
Mean power	Pm	watts	Pm = 0.14*D^2*Vm^3 (approx.)
Tip speed ratio	tsr	none	tsr = rpm x π x D/60/V
Shaft speed	rpm	rpm	rpm = 60 x V x tsr/(π x D)
Blade Design			
Radius (station)	Rs	metres	distance from central axis
No. of blades	B	none	An integer (3 is best)
Lift coeff.	Cl	none	Cl = 0.8 say (alpha dependent)
Angle of attack	alpha	degrees	alpha = 4 say (chosen for best lift/drag)
Setting angle	beta	degrees	beta = ATAN(D/3/Rs/tsr)*57.3-alpha

(NOTE:'ATAN( )' is a software function giving 'the angle whose tangent is' in radians.)

Chord width	Cw	m	Cw = 1.4*D^2/Rs*COS(beta/57.3)^2/tsr^2/B/Cl

Variable	Symbol	Units	Notes or Equation
Alternators			
No. of poles	Np	even no	Np = 120*f/rpm
Frequency	f	Hz	f = Np*rpm/120
Length of airgap	Lgap	m	length parallel to axis
Diam. of airgap	Dgap	m	Dgap = radius from shaft axis*2
Area of air gap	Agap	m^2	Agap = Lgap*Pi*Dgap
Cut-in speed	Crpm	rpm	Crpm = 12 volt cut-in speed
No. of coils		Ncoils	Ncoils = no. of coils in series
Turns/coil		Nturns	Nturns = 1200/Agap/Crpm/Ncoils
(Note this is only approximate. Increase by 50% for very large airgaps			
Copper loss in wires/cables			
Copper diam.	Wdiam	mm	Wdiam = diameter of wire
Copper area	Warea	mm^2	Warea = Wdiam^2*0.785
Twin cable len.	Tcl	m	if investigating cable
Single wire len.	Swl	m	Swl = Tcl*2 (or Swl = length of wire in coils)
Single wire res.	Swr	ohms	Swr = Swl/Warea/50
(NOTE: Resistance is at copper temp. = 40 deg.C, increasing by factor of.004/degC.)			
Current	I	amps	I = current through coil or cable
Volt drop	Vdrop	volts	Vdrop = Swr*I
Power lost	Ploss	watts	Ploss = Vdrop*I
Tail Vane side force			
Area of vane	Avane	m^2	Avane > D^2/40
Side force	Fside	kg	Fside = Avane*V^2/16
Rotor thrust	Frotor	kg	Frotor = D^2*V^2/24

SECTION E --- ESTIMATING WIND SPEED

As we have already pointed out, wind is almost never directly measured, rather, it is averaged over greater or lesser periods of time, and, as well, the amount of estimation involved is greater or lesser.

It is recommended that you buy some kind of wind-measuring device (anemometer). There are several good but more or less inexpensive anemometers made by Dywer -- see Data Sheet Three (Sources) in this chapter.

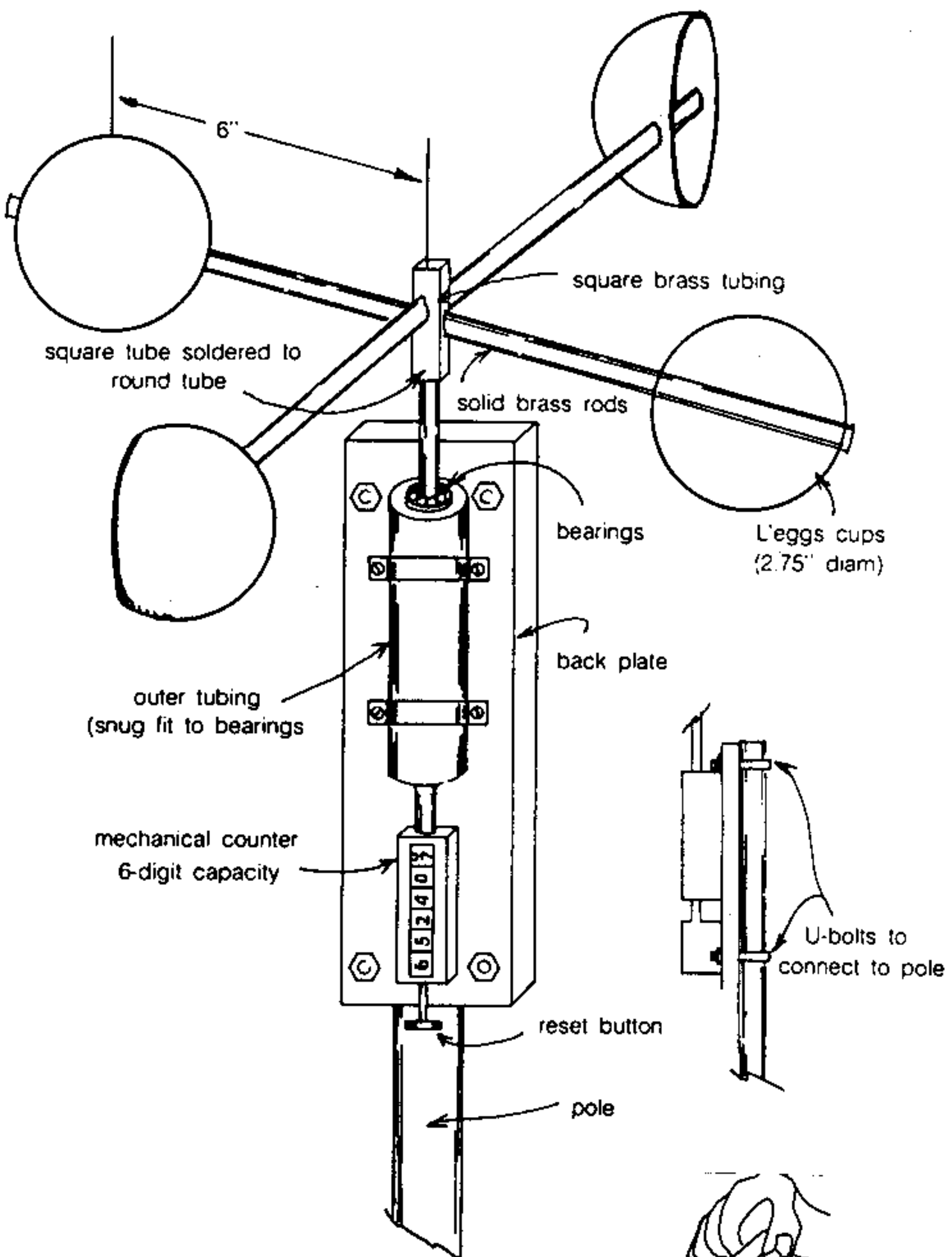
If you don't have access to an anemometer of any kind, Table # 3, which follows, will allow you some kind of wind-speed estimation by phenomena:

TABLE # 3

SPEED RANGE	PHONOMENA	DESCRIPTION
0	Smoke rises vertically	Calm
1-3	Direction of wind shown by drift of smoke, but not by wind vane.	Light air
4-7	Wind felt in the face; leaves of trees rustle; wind vane moves easily	Light breeze
8-12	Leaves and small twigs in a constant motion; wind extends a light flag.	Gentle breeze
13-18	Raises dust and loose paper; small branches are moved.	Moderate breeze
19-24	Small trees in leaf begin to sway; crested wavelets form on lakes and ponds.	Fresh breeze
25-31	Large branches in motion; telegraph wires whistle; difficult to use an umbrella	Strong breeze
32-38	Whole trees move in wind; walking difficult	Moderate gale
39-46	Breaks twigs and branches off trees Generally impedes progress	Fresh gale
47-54	Outdoor flower pots and house tiles or slates are removed	Strong gale

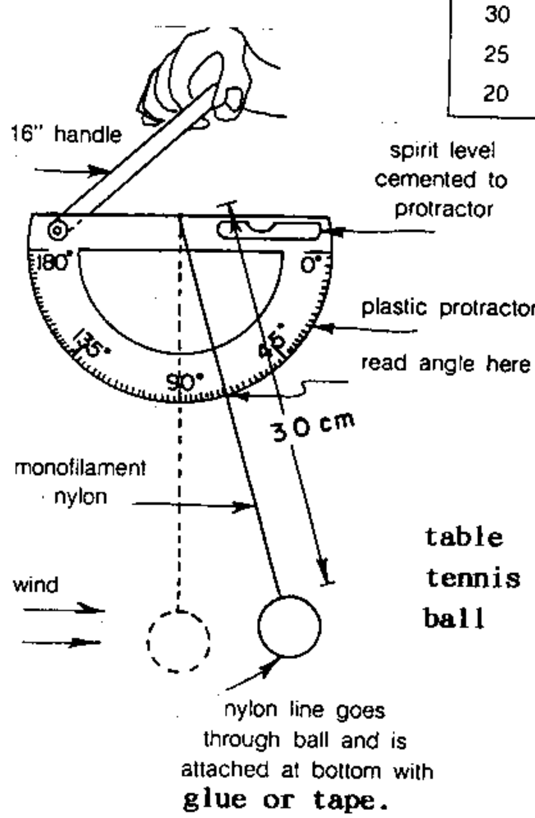
By the way, if you should chance to build an anemometer (or buy one), which needs calibration, an excellent method of doing this was described in an article in 'The Amateur Scientist' section of Scientific American for October, 1971.

A do-it-yourself cup anemometer for measuring average wind speeds.



calibration data

angle	mph
90	0
85	5.8
80	8.2
75	10.1
70	11.8
65	13.4
60	14.9
55	16.4
50	18.0
45	19.6
40	21.4
35	23.4
30	25.8
25	28.7
20	32.5



A do-it-yourself, hand-held wind gauge with calibration data (based on C.L. Strong, *Scientific American*, October 1971).

stand away to minimize
air disturbance

WIND ANEMOMETER

Wind Machines work best when exposed to regular high wind speeds in open areas where there are few obstacles such as buildings, trees etc. Good positions are often along coastlines, on mountain sides, hilltops or on plains.

Wind machines on high towers are exposed to stronger winds so they can produce more power than those at lower levels. They are also out of the way of turbulent winds at the earth's surface, which can damage the machines.

You can find out about wind patterns for particular areas by consulting weather stations, topographic maps (which show land forms) and even just by observing wind blown vegetation (such as bent trees).

The best way to get accurate information about the wind pattern of a site is to actually set up instruments to measure wind speeds for 12 to 18 months. A device called the anemometer measures wind speed, and wind direction can be recorded on computer for later analysis.

You will need

- 2 PLASTIC BALLS
- 2 WOODEN STICKS of 24-30 cm length
- PINS
- 40-45 cm long thicker WOODEN STICKS
- One HARD BOARD SHEET with a hole to fix the longer and thicker wooden sheet
- SCISSORS
- FEVICOL
- STRING

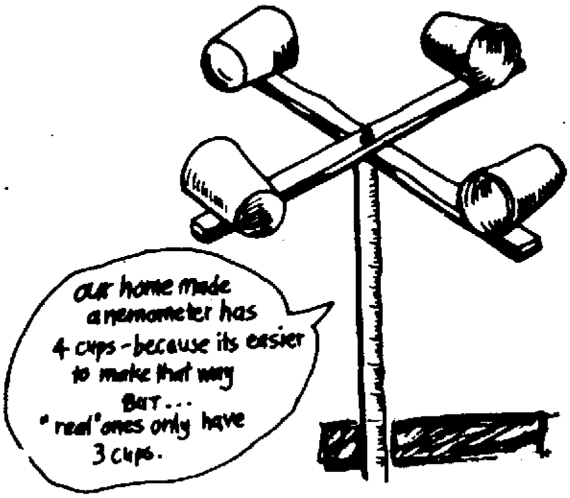
1 Making a Wind Anemometer

Take one ball at a time and cut it into half. Repeat with another ball. Insert all pins in all the four halves from the outside. Take two wooden sticks. Join them at right angles to make a cross, keep equal distance on all four sides/directions. Tightly secure the joint with a string so that the 90° angle does not change. Fix the four ball halves at the 4 ends of the cross you have made. Fix the cross with the 4 ball halves to the bigger stick with the help of an all pin so that it can spin freely in the wind. Insert this into the flower pot placed in the open space, or under the fan.

Observe

Does the anemometer rotate at different speeds when speed of the fan is altered ?

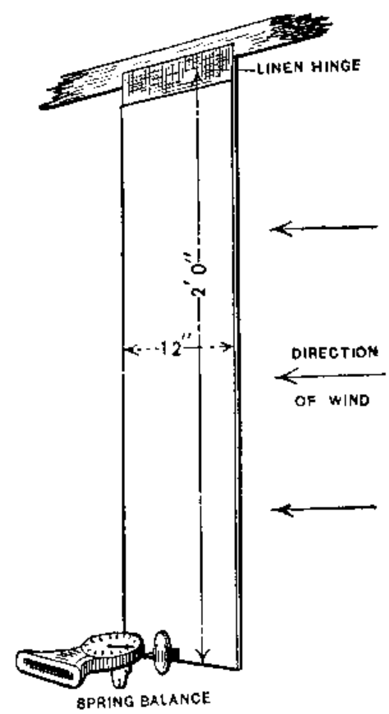
Will the height of the anemometer make any difference in the rotation speed of the anemometer ?



If the loan of an anemometer cannot be obtained, a simple form of wind-pressure meter should be used to determine the right weight (R, fig. 49) required to just hold the windmill sails at the velocity decided upon. Such an apparatus is sketched in fig. 76. It is merely a sheet of stout cardboard, 2 feet × 1 foot, hung on one of the narrow edges by a hinge of linen, the middle of the lower edge being connected as shown to a small spring letter balance capable of reading up to at least one pound. A table of wind-pressures and velocities is given below, by which any pressure registered can be converted into velocity. The pressure-board must, of course, squarely face the wind blowing at the time of the experiment. Note that the spring balance is just at zero when no wind is impressed on the board, or a false reading may be obtained. If made to the given sizes, the readings will be direct measurements of the pressure per square foot.

TABLE OF WIND PRESSURE AND VELOCITIES.

Miles per hour.	Feet per minute.	Feet per second.	Force in lbs. per sq. foot.	Description.
1	88	1.47	.005	Hardly perceptible.
2	176	2.93	.020	Just perceptible.
3	264	4.4	.044	
4	352	5.87	.079	Gentle breeze.
5	440	7.33	.123	
10	880	14.67	.492	Pleasant breeze.
15	1320	22	1.107	
20	1760	29.3	1.968	Brisk gale.
25	2200	36.6	3.075	
30	2640	44	4.428	High wind.
35	3080	51.3	6.027	
40	3520	58.6	7.872	Very high wind.
45	3960	66	9.963	
50	4400	73.3	12.300	Storm.
60	5280	88	17.712	Great storm.
70	6160	102.7	24.108	
80	7040	117.3	31.488	Hurricane.
100	8800	146.6	49.200	



A Simple Wind-pressure Gauge.

The Beaufort scale of wind forces

Beaufort number (B)	Description of wind	Equivalent mean velocity in knots	Limits of mean speed at 33 ft above flat ground in an open situation*			Mean wind force in lb/ft² at standard density ($P = 0{\cdot}0105B^3$)
			Knots	*Statute miles per hour*	*Metres per second*	
0	Calm	0	Less than 1	Less than 1	Less than 0·3	0
1	Light air	2	1– 3	1– 3	0·3– 1·5	0·01
2	Light breeze	5	4– 6	4– 7	1·6– 3·3	0·08
3	Gentle breeze	9	7– 10	8– 12	3·4– 5·4	0·28
4	Moderate breeze	13	11– 16	13– 18	5·5– 7·9	0·67
5	Fresh breeze	19	17– 21	19– 24	8·0–10·7	1·31
6	Strong breeze	24	22– 27	25– 31	10·8–13·8	2·3
7	Moderate gale	30	28– 33	32– 38	13·9–17·1	3·6
8	Fresh gale	37	34– 40	39– 46	17·2–20·7	5·4
9	Strong gale	44	41– 47	47– 54	20·8–24·4	7·7
10	Whole gale	52	48– 55	55– 63	24·5–28·4	10·5
11	Storm	60	56– 63	64– 72	28·5–32·6	14·0
12	Hurricane	68	64– 71	73– 82	32·7–36·9	18
13	—	76	72– 80	83– 92	37·0–41·4	23
14	—	85	81– 89	93–103	41·5–46·1	29
15	—	94	90– 99	104–114	46·2–50·9	35
16	—	104	100–108	115–125	51·0–56·0	43
17	—	114	109–118	125–136	56·1–61·2	52

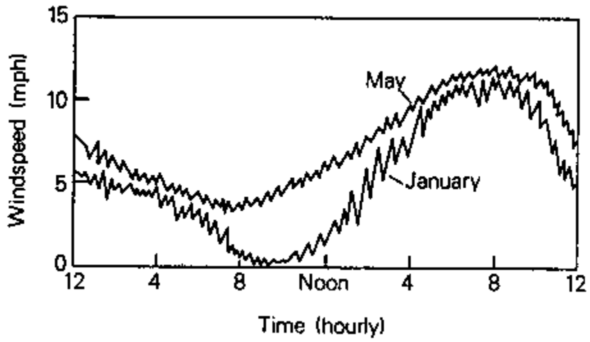
The figures in this table have been abstracted from a specification published by the Air Ministry Meteorological Office which gives also descriptions of the effects of the various wind forces to enable them to be estimated. *Approximate corrections: for 50 ft add 10 per cent, for 100 ft add 25 per cent, for 20 ft subtract 10 per cent, for 10 ft subtract 20 per cent.

How do you go about determining the windspeed distribution for your site? There are four basic options:

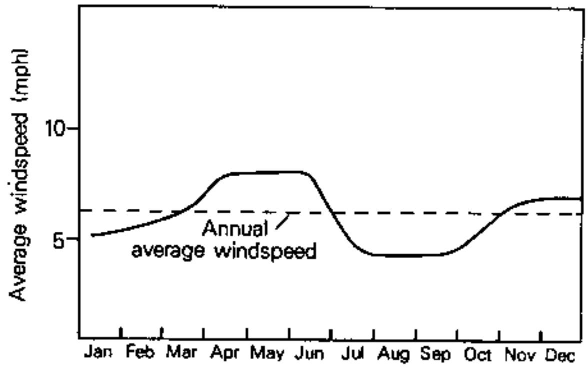
1. Ignore windspeed distribution entirely and base your design calculations on annual average windspeed and a correction factor.
2. Using the annual average windspeed at your site and a mathematical equation that describes the windspeed distribution fairly accurately, calculate the duration of each windspeed.
3. Actually measure and record the windspeed at your site for at least one year.
4. Measure and record the windspeed for a shorter period—perhaps three months—and try to establish a correlation with wind data from a nearby weather station or airport.

The *annual* windspeed distribution is, from the overall planning viewpoint, the most important factor to understand. Daily and monthly windspeed variations are, perhaps, the easiest to determine, but wind researchers increasingly favor an *assumed* annual windspeed distribution. You then make design calculations based on such an assumption, rather than actually measuring the windspeed for more than a year.

The *Rayleigh distribution* provides a reasonable description of windspeed characteristics in some locations. National Weather Service (NWS) wind data for several hundred locations have been compared with results from an assumed Rayleigh distribution. The comparisions have been promising, but there are a few problems of interpretation. Most of the NWS anemometers have been sited for monitoring airport winds, for making forest fire predictions and for a host of other uses unrelated to windpower production. Although the Rayleigh distribution doesn't work for all sites, it has been reputed to work with an error less than 10 percent. In the absence of better data, it can be used for reasonably good energy estimation.



The diurnal variation of windspeed at a hypothetical site. May winds blow harder than January winds at this site.



Monthly variation of windspeed at a hypothetical site.

The two graphs here show typical Rayleigh windspeed distribution curves for two sites with different annual average windspeeds. Notice that the energy content of these winds increases dramatically as the average speed increases from 10 mph to 14 mph. The vastly greater energy available at windier sites makes the required site analysis worth the effort. Energy distribution curves similar to these will be used later to design a wind machine that achieves optimum performance at windspeeds where the most energy occurs. In fact, peek windmill performance ought to occur at or near the same windspeed as the peak of the energy distribution curve.

With a year or more of windspeed data measured for a given site, you often need to find an equation that describes, within reasonable accuracy, the windspeed distribution. The most important parameter you should have by now is the mean windspeed. Within certain limits, a single parameter equation known as the Rayleigh distribution may be used to describe the windspeed distribution. Here the single parameter is mean windspeed. At windspeeds below 10 mph, the Rayleigh distribution has low reliability; it should not be used at all at sites with mean windspeeds below 8 mph.

The Rayleigh distribution takes the following form:

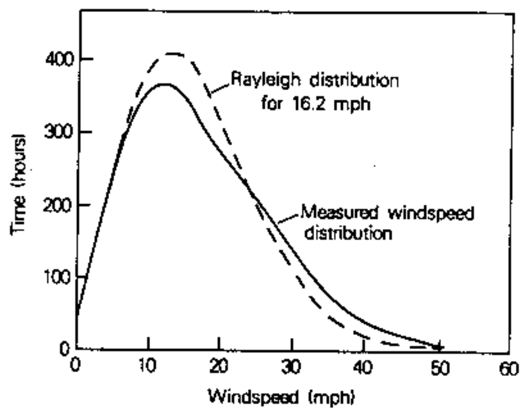
$$\text{Hours} = 8{,}760 \times \frac{\pi}{2} \times \frac{V}{\bar{V}^2} \times e^{-k}, \quad \text{(Eq. 3)}$$

where V = windspeed
$\bar{V}$ = mean windspeed
$\pi = 3.1416$
$e = 2.718$
$k = \frac{\pi}{4} \times \left(\frac{V}{\bar{V}}\right)^2.$

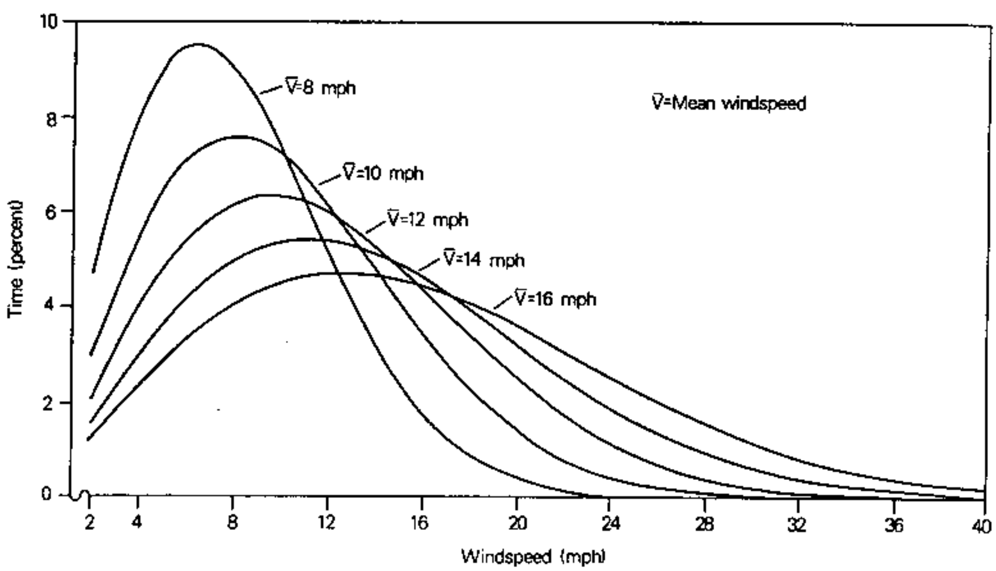
This equation gives you the total number of hours per year you can expect the wind to blow at a windspeed V when the mean windspeed is $\bar{V}$ at that site.

A graph of this complex equation is presented at right, with percent time as the vertical scale. To get the result in hours per year, multiply by 8,760. Appendix 2.1 presents numerical values of the Rayleigh distribution for mean windspeeds ranging from 8 to 17 mph. You can read percent of time from this graph or consult the Appendix to get a more accurate value in hours per year. For example, for mean windspeed of 14 mph, you can expect wind to blow at 23 mph for about 2.2 percent of the time, or 194 hours per year.

The other graph here shows the agreement between a measured windspeed distribution and a calculated Rayleigh distribution for St. Ann's Head, England—with a mean windspeed of 16.2 mph. The Rayleigh distribution is slightly low at high windspeeds and high at low windspeeds (from 10 to 20 mph). As power is proportional to the cube of the windspeed, the higher speed end carries more weight in power calculations, but the greatly reduced duration of time at high windspeed reduces the overall energy impact. Rayleigh calculations are not recommended as a replacement for actually measuring your site's wind characteristics, but they can serve as a reasonable approximation when all you have is the annual average windspeed.



Comparison of Rayleigh and measured windspeed distributions for St. Ann's Head, England.



The Rayleigh distribution versus windspeed for sites with mean windspeeds between 8 and 16 mph.

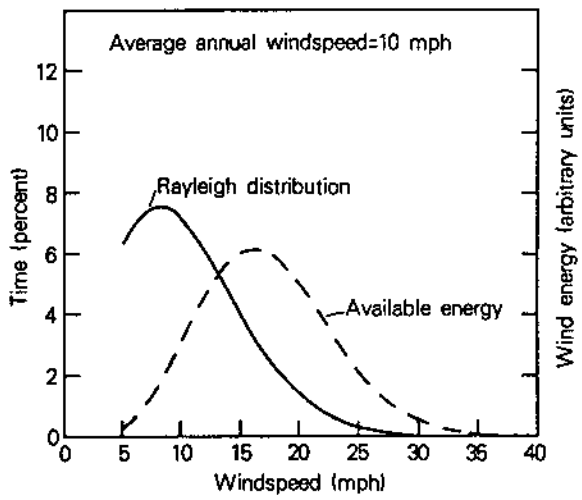
Measuring the Windspeed

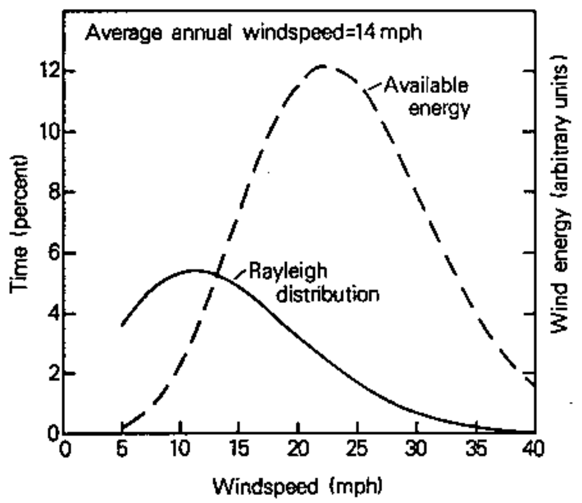
Measuring an actual windspeed distribution curve means taking many readings and filling many "bins" with this data. If you have a table covered with tea cups and you toss dried peas out onto that table you will be filling bins—in this case, tea cups. Throw enough peas out and a filling pattern will begin to take place that reflects the likelihood of that bin receiving a flying pea. The Rayleigh curves give a possible likelihood of any particular windspeed occurring.

If you look at a windspeed meter once each minute and add a "1" to the bin that corresponds to the windspeed you read, you are filling bins with minutes—the number of minutes the wind blows at each windspeed. Do this once each hour, and the bins contain hours. A simple daily reading will represent a "daily average" windspeed, and the number of readings in a bin will represent the number of days at a particular windspeed. A bin, then, contains the number of days, hours, or minutes that the windspeed happens to be measured at the value associated with that bin. More frequent readings will give a better representation of the actual windspeed distribution. One-minute readings are quite reasonable for electronic recording equipment, while hourly or daily readings are commonly taken by human meter readers at airport control towers, forest lookout stations, and other permanently staffed facilities.

Virtually all methods of calculating the annual average windspeed involve filling bins of one sort or another. If windspeed bins are filled electronically and accurately, the values in each bin can be used instead of the assumed Rayleigh distribution because they represent the entire windspeed distribution.

In another approach, you measure windspeed periodically during the course of a day, and average all the readings during that day to get the daily average windspeed. To arrive at an annual average windspeed, do this for a whole year, and average all daily readings. For maximum reliability, the readings should be taken at regularly scheduled intervals. As you might guess, this process becomes burdensome over an entire year.





Rayleigh windspeed distributions for sites with 10 mph and 14 mph average winds. The available wind energy is far greater at the windier site.

A simpler alternative is to use a special device called a wind energy monitor. It adds up the total miles of wind that have passed the anemometer's sensor. Divide the total miles by the number of hours between readings on a daily, monthly, or annual basis, and you get daily, monthly, or annual average windspeed—simply and directly.

In addition, a wind energy monitor records the total wind energy available at a site. Each windspeed reading is converted directly into an energy value that is accumulated minute by minute. Such an approach eliminates the errors that might occur if you measured an average windspeed and later calculated the available wind energy using the Rayleigh distribution.

Rayleigh Windspeed Distribution

The Rayleigh distribution is a one-parameter equation that can be used to estimate the number of hours the wind blows at any particular windspeed. The single parameter in the equation is the annual average windspeed (the *mean* windspeed) at the site in question. The accompanying table presents values of the Rayleigh distribution for mean windspeeds ranging from 8 to 17 mph. Along each horizontal line in this table are the numbers of hours one would expect the wind to blow at each value of the windspeed listed in the leftmost column.

For example, suppose your site had a mean windspeed of 14 mph, and you wanted to estimate how often the wind blew at 23 mph. Just read down the column marked "14" at the top until you reach the horizontal line marked "23" at the left. You get the result "194," which means that the wind will blow at 23 mph approximately 194 hours per year at this site.

To get the result in terms of the *percent* of time each windspeed occurs, divide the table entry by 8760—the number of hours in a year. Thus, the wind blows at 23 mph for 194/8760, or 2.2 percent of the time.

RAYLEIGH DISTRIBUTION FOR VARIOUS MEAN WINDSPEEDS

Windspeed mph	Mean Windspeed, mph									
	8	9	10	11	12	13	14	15	16	17
8	784	731	666	601	539	484	435	391	353	320
9	716	697	656	605	553	503	457	415	377	344
10	630	644	627	594	554	512	470	431	395	363
11	536	578	585	570	543	510	476	441	408	377
12	441	504	533	536	523	500	473	443	415	386
13	351	429	474	494	494	483	464	441	416	391
14	272	356	413	446	459	458	448	432	412	391
15	204	288	353	396	420	429	427	418	404	387
16	149	227	295	345	378	396	403	400	392	380
17	105	175	242	296	336	361	375	379	377	369
18	73	132	194	250	294	325	345	355	358	355
19	49	97	153	207	253	289	314	330	337	339
20	32	70	119	170	216	254	283	303	315	321
21	20	50	90	136	181	220	252	275	291	302
22	12	34	68	108	150	189	222	248	268	281
23	7	23	50	84	123	160	194	222	244	260
24	4	15	36	65	99	134	168	197	220	239
25	3	10	25	49	79	111	143	173	198	218
26	1	6	18	37	62	91	122	150	176	197

RAYLEIGH DISTRIBUTION FOR VARIOUS MEAN WINDSPEEDS										
Windspeed mph	Mean Windspeed, mph									
	8	9	10	11	12	13	14	15	16	17
27	.8	4	12	27	48	74	102	130	155	177
28	.4	2	8	20	37	60	85	111	136	158
29	.2	1	5	14	28	47	70	94	118	140
30	.1	.8	4	10	21	37	57	79	102	124
31	0	.5	2	7	16	29	46	66	87	108
32	0	.3	1	5	11	22	37	55	74	94
33	0	.1	.9	3	8	17	29	45	63	81
34	0	0	.5	2	6	13	23	37	53	70
35	0	0	.3	1	4	10	18	30	44	60
36	0	0	.2	.9	3	7	14	24	36	51
37	0	0	.1	.6	2	5	11	19	30	43
38	0	0	0	.4	1	4	8	15	24	36
39	0	0	0	.2	.9	3	6	12	20	30
40	0	0	0	.1	.6	2	5	9	16	25
41	0	0	0	0	.4	1	3	7	13	20
42	0	0	0	0	.3	.9	3	5	10	17
43	0	0	0	0	.2	.6	2	4	8	13
44	0	0	0	0	.1	.4	1	3	6	11

Windspeed versus Height

If you know the surface friction coefficient α (Greek "alpha") at a wind site (see Chapter 3), you can readily estimate the windspeed at a given height h_B from measurements at another height h_A. The equation used to accomplish this feat is:

$$V_B = V_A \times \left(\frac{h_B}{h_A}\right)^{\alpha} ,$$

where V_A = the windspeed measured at height h_A,
V_B = the windspeed estimated at height h_B.

The surface friction coefficient α usually has a value between 0.10 (very smooth terrain) and 0.40 (very rough terrain). Typical values for α can be found in the table at left.

The equation above can be used with various values of α to develop the series of "height correction factors" presented in the table on page 165. Here, α is listed at the top of each column, and the leftmost column lists the height in feet. To get the windspeed V_B at height h_B when you have measured the windspeed V_A at height h_A, use the following simple equation:

$$V_B = V_A \times \frac{H_B}{H_A} ,$$

where H_A and H_B are the height correction factors read from the table.

These correction factors have been normalized to an assumed anemometer height of 30 feet above ground. They are also based on an assumption that the anemometer is not immersed within the layer of slow-moving air below the tops of trees or other nearby obstructions. For level terrain with few or no trees, height measurements start at ground level. When there is a grove of trees nearby, start all your height measurements at tree-top level.

Example: Suppose your anemometer is mounted 50 feet above ground level, but there is a grove of 30-foot trees just upstream. If your wind machine is to be mounted atop an 80-foot tower at this site, and the anemometer measures a mean windspeed of 10 mph, what is the mean windspeed at the machine height?

Solution: First you have to correct the machine height and the anemometer height for the grove of 30-foot trees. Subtracting 30 feet from each of the respective heights, the effective machine height (h_B) is 50 feet and the effective anemometer height (h_A) is 20 feet. Assuming a surface friction coefficient $\alpha = 0.28$ for wooded terrain, and reading down the column marked "0.28" in the table of height correction factors, we find that $H_A = 0.892$ and $H_B = 1.153$. Thus, the mean windspeed at the position of the wind machine is expected to be:

$$V_B = 10 \times \frac{1.153}{0.892} = 12.9 \text{ mph} .$$

If there were no trees nearby (level country with only an occasional tree), and the anemometer measured 10 mph at 30 feet high, the mean windspeed at the 80-foot level would be, assuming $\alpha = 0.16$:

$$V_B = 10 \times \frac{1.170}{1.000} = 11.7 \text{ mph} .$$

So the extra 50 feet of tower height gains you only 1.7 mph in mean windspeed over level terrain. But remember that wind power is proportional to the *cube* of the windspeed. The wind power available at the 80-foot level is 60 percent greater than that available at 30 feet.

SURFACE FRICTION COEFFICIENT	
Description of Terrain	α
Smooth, hard ground; lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22 - 0.24
Wooded country; small towns and suburbs	0.28 - 0.30
Urban areas, with tall buildings	0.40

HEIGHT CORRECTION FACTOR , H									
Height	**Surface Friction Coefficient, α**								
(ft.)	**0.100**	**0.140**	**0.160**	**0.200**	**0.220**	**0.240**	**0.280**	**0.300**	**0.400**
10	0.895	0.857	0.839	0.802	0.785	0.768	0.735	0.719	0.644
15	0.933	0.908	0.895	0.870	0.858	0.846	0.823	0.812	0.757
20	0.960	0.945	0.937	0.922	0.914	0.907	0.892	0.885	0.850
25	0.981	0.975	0.971	0.964	0.960	0.957	0.950	0.946	0.929
30	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
35	1.016	1.022	1.025	1.031	1.034	1.037	1.044	1.047	1.063
40	1.029	1.041	1.047	1.059	1.065	1.071	1.083	1.090	1.121
45	1.041	1.058	1.067	1.084	1.098	1.102	1.120	1.129	1.176
50	1.052	1.074	1.085	1.107	1.118	1.130	1.153	1.165	1.226
55	1.062	1.089	1.102	1.128	1.142	1.156	1.184	1.199	1.274
60	1.072	1.102	1.117	1.148	1.164	1.180	1.214	1.231	1.319
65	1.080	1.114	1.132	1.167	1.185	1.203	1.241	1.261	1.362
70	1.088	1.126	1.145	1.184	1.204	1.225	1.267	1.289	1.403
75	1.096	1.137	1.158	1.201	1.223	1.245	1.292	1.316	1.442
80	1.103	1.147	1.170	1.216	1.240	1.265	1.316	1.342	1.480
85	1.110	1.157	1.181	1.231	1.257	1.283	1.338	1.366	1.516
90	1.116	1.166	1.192	1.245	1.273	1.301	1.360	1.390	1.551
95	1.122	1.175	1.203	1.259	1.288	1.318	1.380	1.413	1.585
100	1.128	1.184	1.212	1.272	1.303	1.335	1.400	1.435	1.618
105	1.133	1.192	1.222	1.284	1.317	1.350	1.420	1.456	1.650
110	1.139	1.199	1.231	1.296	1.330	1.365	1.438	1.476	1.681
115	1.144	1.207	1.240	1.308	1.343	1.380	1.456	1.496	1.711
120	1.149	1.214	1.248	1.319	1.356	1.394	1.474	1.515	1.741
125	1.154	1.221	1.257	1.330	1.368	1.408	1.491	1.534	1.769
130	1.158	1.228	1.264	1.340	1.380	1.421	1.507	1.552	1.797
135	1.162	1.234	1.272	1.350	1.392	1.434	1.523	1.570	1.825
140	1.167	1.241	1.280	1.360	1.403	1.447	1.539	1.587	1.851
145	1.171	1.247	1.287	1.370	1.414	1.459	1.554	1.604	1.878
150	1.175	1.253	1.294	1.379	1.424	1.471	1.569	1.620	1.903

Air Density

The density of any substance is a measure of how much of it can fit in a given volume. We usually want to know how much air, or how many molecules, interacts with a rotor as the wind passes through it. Kinetic energy in the wind is a function of the air mass and windspeed. Therefore, we need to know the mass density of air, ρ, to calculate wind energy and power. This density is based on the air temperature and altitude, usually referenced to sea level.

A "standard day" is an average day that scientists and engineers use for purposes of design. On a standard day, certain standard values can be used for temperature, pressure and density of the air (depending on altitude). Naturally, performance calculations on wind machines will vary somewhat from this standard, because a standard day is actually very rare. Summer days are generally hotter and winter days cooler. Standard conditions for air at sea level are, in English units:

$$\begin{aligned}\text{Temperature} &= 59.9^\circ\text{F}\\ \text{Pressure} &= 14.7\ \text{psi}\\ \text{Density} &= 0.002378\ \text{slug/ft}^3.\end{aligned}$$

Here, the "slug" is the English unit of mass, not a slimy animal resembling a snail. One slug weighs 32.2 pounds at sea level. To calculate the air density ρ at a specific windmill site, you need to correct for altitude and temperature differences from the standard case. Use the following formula:

$$\rho = C_A \times C_T \times 0.002378\ \text{slug/ft}^3. \tag{Eq. 2}$$

The altitude correction factor C_A and the temperature correction factor C_T are taken from the two accompanying tables. For example, suppose that the average temperature at your site is 80°F, and the altitude is 2500 feet above sea level. Then $C_A = 0.912$ and $C_T = 0.963$ from these tables, and

$$\begin{aligned}\rho &= 0.912 \times 0.963 \times 0.002378\ \text{slug/ft}^3\\ &= 0.002088\ \text{slug/ft}^3,\end{aligned}$$

or about 88 percent of the standard air density. More frequently, you will have to know these two correction factors at altitudes and air temperatures not listed directly in the tables. In such cases, just interpolate between the values given.

Altitude Correction Factor

Altitude (feet)	C_A
0	1.000
2,500	0.912
5,000	0.832
7,500	0.756
10,000	0.687

Temperature Correction Factor

Temperature (°F)	C_T
0	1.130
20	1.083
40	1.040
60	1.000
80	0.963
100	0.929

*Battelle Classes of Wind Power Density**

Table D

	Wind Speed and Power at 10 m			Wind Speed and Power at 30 m			Wind Speed and Power at 50 m		
Class	Power Density (W/m²)	Speed (m/s)	Speed (mph)	Power Density (W/m²)	Speed (m/s)	Speed (mph)	Power Density (W/m²)	Speed (m/s)	Speed (mph)
	50	3.5	7.8	80	4.1	9.2	100	4.4	9.9
1									
	100	4.4	9.9	160	5.1	11.4	200	5.5	12.3
2									
	150	5.0	11.5	240	5.9	13.2	300	6.3	14.1
3									
	200	5.5	12.3	320	6.5	14.6	400	7.0	15.7
4									
	250	6.0	13.4	400	7.0	5.7	500	7.5	16.8
5									
	300	6.3	14.1	480	7.4	16.6	600	8.0	17.9
6									
	400	7.0	15.7	640	8.2	18.4	800	8.8	19.7
7									
	1000	9.5	21.3	1600	11.1	24.7	2000	11.9	26.7

*Increase in speed and power with height assumes one-seventh power law.

Battelle's maps don't show wind power density directly. Instead they present a range of possible values as *wind power classes* as shown in Table D. Residential wind systems are suitable in regions with wind power Class 2 or greater. Small wind turbines begin to look more economically attractive in Class 3 areas and above. Commercial wind power plants have been developed in Class 5 resources, though the most successful are sited in areas with Class 6 or better.

CLASSES OF WIND ENERGY FLUX (WEF)

WIND ENERGY CLASS	10m (33 ft) WEF W/m²	10m SPEED m/s	10m SPEED mph	50m (164 ft) WEF W/m²	50m SPEED m/s	50m SPEED mph
	0	0	0	0	0	0
1	100	4.4	9.8	200	5.6	12.5
2	150	5.1	11.5	300	6.4	14.3
3	200	5.6	12.5	400	7.0	15.7
4	250	6.0	13.4	500	7.5	16.8
5	300	6.4	14.3	600	8.0	17.9
6	400	7.0	15.7	800	8.8	19.7
7	800	8.8	19.7	1600	10.1	22.6
8	1200	10.1	22.6	2400	12.7	28.4
9	1600	11.1	24.9	3200	14.0	31.3
10	>1600	>11.1	>24.9	>3200	>14.0	>31.3

RIDGE CREST ESTIMATES (LOCAL RELIEF >1500 m)

SPEED ASSUMES A RAYLEIGH DISTRIBUTION

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

This legend corresponds to the world wind resource maps.

WIND SPEEDS & DESCRIPTION.

Description	Speed knots	Mean speed knots	Beaufort force	MPH	km/h	m/s	Weather forecast
Calm	< 1	0	0	0.5	1.0	0.2	Calm
Light air	1-3	2	1	2.3	3.7	1	Light
Light breeze	4-6	5	2	5.7	9.3	2.6	-
Gentle breeze	7-10	9	3	10.4	16.7	4.6	-
Moderate breeze	11-16	13	4	15.0	24.0	6.7	Moderate
Fresh breeze	17-21	19	5	22.0	35.2	9.8	Fresh
Strong breeze	22-27	24	6	27.6	44.5	12.4	Strong
Near gale	28-33	30	7	34.5	55.6	15.4	-
Gale	34-40	37	8	42.6	68.6	19.0	Gale
Strong gale	41-47	44	9	50.6	81.5	22.7	Severe gale
Storm	48-55	52	10	60.0	96.4	26.8	-
Violent Storm	56-63	60	11	69.0	111.2	31.0	-
Hurricane	64-71	68	12	78.3	126.0	35.0	-

RELATIONSHIP BETWEEN GRIGGS-PUTNAM INDEX [G] & ANNUAL MEAN WIND SPEED [V] - IN m/sec.

G	V [m/sec]	MPH	W/sq.m. #	Batelle Class *
0	< 3	< 7	< 50	0
1	3 - 4	7 - 9	50 - 80	0 - 1
2	4 - 5	9 - 11	80 - 125	1 - 2
3	5 - 6	11 - 13	125 - 250	2 - 4
4	6 - 7	13 - 16	250 - 400	4 - 6
5	7 - 8	16 - 18	400 - 600	6 - 7
6	8 - 11	18 - 25	600 - 1600	7 - 9
7	> 11	> 25	> 1600	9 - 10

See also:

A: A Handbook on the use of Trees for Wind Power Potential. E.W.Hewson, Wade N.T.I.S. USA 1979

B: * Siting Handbook for Small Wind-energy Conversion Systems. [PNL-2521 Rev. 1.] Nat. Tech. Info. Service USA Dept. of Commerce Springfield VA 22161 USA

C: Wind-Atlas computer-program. RISØ National Laboratory Roskilde Denmark

Measured at standard height of 10 m. [at 50 m. height => a: wind speed + 26 % b: energy + 100 %].

APPROXIMATE WIND SPEED ENERGY EFFECTS:

A: < 2.5 m/s => Slight effects, no damage to crops or structures.

B: 4.5 - 6.5 m/s => Damage to very susceptible species.

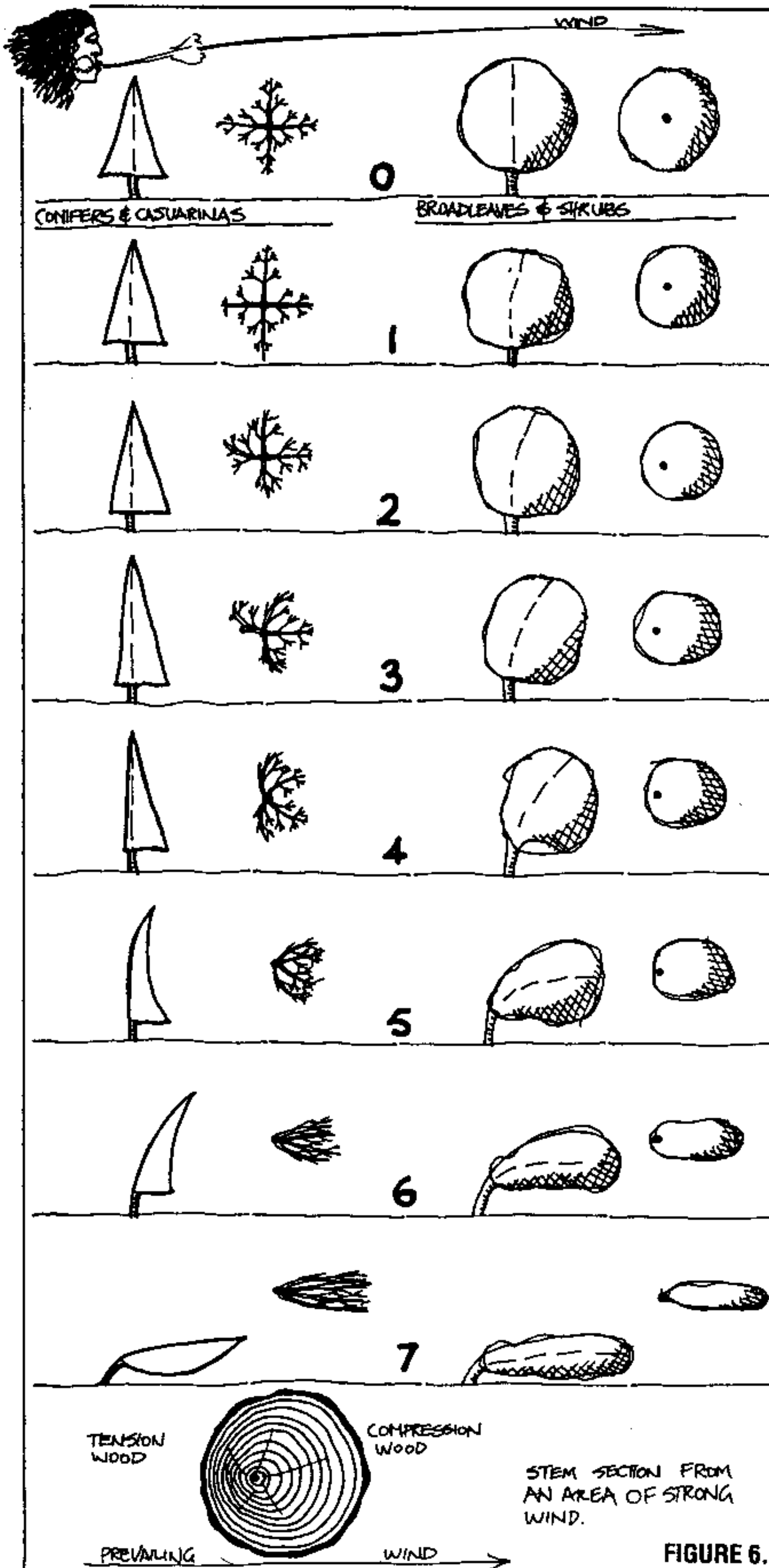
C: 9.5 - 12.5 m/s => Mechanical damage to crops, some damage to structures.

D: 15.5 - 35.0 m/s => Severe structural & crop damage. Damage to some windmill types & models. [Most useful wind-turbine electrical energy is produced in wind-sectors B. and C. - However an Australian model can produce useful electricity at app. 2.5 m/sec.].

REDUCTION OF WIND VELOCITY IN FORESTS:

Penetration in meters:	Remaining velocity in % :
30 m.	60 - 80 %
60 m.	50 %
120 m.	15 %
300 - 1,500 m.	Negligible wind.

GRIGGS AND PUTNAM INDEX



0
NO EFFECT
No deformations of branches

1
BRUSHING
Branches or needles bent away from prevailing winds. Crown slightly deformed.

2
SLIGHT FLAGGING
Small branches bent. Tree markedly asymmetric.

3
MODERATE FLAGGING
Larger branches bent away from the wind.

4
STRONG FLAGGING
All branches swept to leeward. Tree a "banner".

5
PARTIAL THROW
Trunk bent to leeward but vertical near ground.

6
COMPLETE THROW
Trunk now quite bent to leeward.

7
CARPETING
Tree a creeping shrub-like layer of prostrate growth.

THE ABOVE EFFECTS ARE STANDARD FOR TREES NOT AFFECTED BY SALT, ICE, OR SNOW LOAD.

FIGURE 6.2
WIND EFFECTS ON TREES
As winds cross tree lines they are deflected in a new direction. Trees deform or "flag" permanently in prevailing strong winds and can be used to assess the effects of such winds; they form a site-record of wind history.

B. Air Density Corrections for Temperature

*Relative Change in Air Density with Temperature**

Temperature Celsius	Relative Change	Temperature Fahrenheit	Relative Change
−20	1.138	0	1.131
−15	1.116	10	1.106
−10	1.095	20	1.083
−5	1.075	30	1.061
0	1.055	40	1.040
5	1.036	50	1.020
10	1.018	60	1.000
15	1.000	70	0.981
20	0.983	80	0.963
25	0.966	90	0.945
30	0.951	100	0.929
35	0.935	110	0.912
40	0.920	120	0.896
45	0.906		
50	0.892		

*Change in air density relative to standard temperature of 15°C or 60°F. Battelle's atlas of wind power density includes average temperature.

C. Rayleigh Wind Speed Distribution

You need only the average wind speed to determine the Rayleigh speed distribution. Use Table C-1 for average speeds in m/s, Table C-2 for speeds in mph. The average speed is in the top row. The *distribution* is the column below the average speed. The *wind speed bin* corresponds to the horizontal axis on graphs of wind turbine power curves. The *probability of occurrence* is the percentage of time the wind occurs within that wind speed bin.

Table C-1

Rayleigh Wind Speed Distribution for Annual Average Wind Speed in m/s

Wind Speed Bin (m/s)	(mph)	Probability of Occurrence at Annual Average Wind Speeds in m/s: 4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9
4	9.0	0.179	0.1668	0.152	0.1371	0.1231	0.1105	0.0992	0.0893	0.0807	0.0731	0.0664
5	11.2	0.1439	0.1471	0.1432	0.1357	0.1264	0.1168	0.1074	0.0985	0.0903	0.0828	0.0761
6	13.4	0.1006	0.1152	0.1217	0.1224	0.1194	0.1142	0.108	0.1014	0.0947	0.0882	0.0821
7	15.7	0.062	0.0812	0.0943	0.1019	0.1049	0.1047	0.1023	0.0986	0.0942	0.0893	0.0844
8	17.9	0.0339	0.0519	0.0673	0.0789	0.0864	0.0905	0.0919	0.0914	0.0895	0.0867	0.0834
9	20.2	0.0166	0.0302	0.0444	0.0571	0.0671	0.0742	0.0788	0.0811	0.0817	0.0811	0.0796
10	22.4	0.0072	0.016	0.0272	0.0387	0.0492	0.0579	0.0645	0.0691	0.0719	0.0733	0.0735
11	24.6	0.0028	0.0078	0.0154	0.0247	0.0343	0.0431	0.0507	0.0567	0.0612	0.0642	0.066
12	26.9	0.001	0.0035	0.0082	0.0148	0.0226	0.0307	0.0383	0.0449	0.0503	0.0545	0.0576
13	29.1	0.0003	0.0014	0.004	0.0084	0.0142	0.0209	0.0278	0.0343	0.0401	0.045	0.049
14	31.4	0.0001	0.0005	0.0019	0.0045	0.0085	0.0136	0.0194	0.0253	0.031	0.0361	0.0406
15	33.6	0	0.0002	0.0008	0.0023	0.0048	0.0085	0.0131	0.0181	0.0233	0.0283	0.0328
16	35.8	0	0.0001	0.0003	0.0011	0.0026	0.0051	0.0085	0.0125	0.017	0.0215	0.0259
17	38.1	0	0	0.0001	0.0005	0.0014	0.0029	0.0053	0.0084	0.012	0.016	0.02
18	40.3	0	0	0	0.0002	0.0007	0.0016	0.0032	0.0055	0.0083	0.0116	0.0151
19	42.6	0	0	0	0.0001	0.0003	0.0009	0.0019	0.0034	0.0056	0.0082	0.0111
20	44.8	0	0	0	0	0.0001	0.0004	0.0011	0.0021	0.0036	0.0056	0.008
21	47.0	0	0	0	0	0.0001	0.0002	0.0006	0.0012	0.0023	0.0038	0.0057
22	49.3	0	0	0	0	0	0.0001	0.0003	0.0007	0.0014	0.0025	0.0039
23	51.5	0	0	0	0	0	0	0.0002	0.0004	0.0009	0.0016	0.0026
24	53.8	0	0	0	0	0	0	0.0001	0.0002	0.0005	0.001	0.0017
25	56.0	0	0	0	0	0	0	0	0.0001	0.0003	0.0006	0.0011
26	58.2	0	0	0	0	0	0	0	0.0001	0.0002	0.0004	0.0007
27	60.5	0	0	0	0	0	0	0	0	0.0001	0.0002	0.0004
28	62.7	0	0	0	0	0	0	0	0	0	0.0001	0.0003

Table C-2

Rayleigh Wind Speed Distribution for Average Annual Wind Speed in mph

Wind Speed Bin (mph)	(m/s)	Probability of Occurrence at Annual Average Wind Speeds in mph: 9	10	11	12	13	14	15	16	17	18	19	20
8	3.6	0.0834	0.076	0.0686	0.0616	0.0552	0.0496	0.0447	0.0403	0.0365	0.0332	0.0303	0.0277
10	4.5	0.0735	0.0716	0.0678	0.0632	0.0584	0.0537	0.0492	0.0451	0.0414	0.038	0.035	0.0323
12	5.4	0.0576	0.0608	0.0612	0.0597	0.0571	0.054	0.0507	0.0473	0.0441	0.041	0.0382	0.0355
14	6.2	0.0406	0.0472	0.0509	0.0524	0.0523	0.0512	0.0493	0.0471	0.0447	0.0422	0.0398	0.0374
16	7.1	0.0259	0.0337	0.0394	0.0432	0.0453	0.046	0.0457	0.0448	0.0434	0.0417	0.0399	0.038
18	8.0	0.0151	0.0222	0.0285	0.0335	0.0371	0.0394	0.0406	0.0409	0.0406	0.0398	0.0387	0.0374
20	8.9	0.008	0.0136	0.0194	0.0246	0.029	0.0323	0.0346	0.036	0.0367	0.0368	0.0365	0.0358
22	9.8	0.0039	0.0077	0.0123	0.0171	0.0216	0.0254	0.0284	0.0306	0.0321	0.033	0.0334	0.0334
24	10.7	0.0017	0.0041	0.0074	0.0113	0.0153	0.0191	0.0224	0.0252	0.0273	0.0288	0.0298	0.0304
26	11.6	0.0007	0.002	0.0042	0.0071	0.0104	0.0139	0.0171	0.0201	0.0225	0.0245	0.026	0.0271
28	12.5	0.0003	0.0009	0.0022	0.0042	0.0068	0.0097	0.0127	0.0155	0.0181	0.0203	0.0221	0.0236
30	13.4	0.0001	0.0004	0.0011	0.0024	0.0043	0.0065	0.0091	0.0116	0.0141	0.0164	0.0184	0.0201
32	14.3	0	0.0002	0.0005	0.0013	0.0026	0.0042	0.0063	0.0085	0.0108	0.013	0.015	0.0168
34	15.2	0	0.0001	0.0002	0.0007	0.0015	0.0027	0.0042	0.006	0.008	0.01	0.012	0.0138
36	16.1	0	0	0.0001	0.0003	0.0008	0.0016	0.0027	0.0041	0.0058	0.0075	0.0093	0.0111
38	17.0	0	0	0	0.0002	0.0004	0.0009	0.0017	0.0028	0.0041	0.0056	0.0071	0.0088
40	17.9	0	0	0	0.0001	0.0002	0.0005	0.001	0.0018	0.0028	0.004	0.0054	0.0068
42	18.8	0	0	0	0	0.0001	0.0003	0.0006	0.0012	0.0019	0.0028	0.0039	0.0052
44	19.6	0	0	0	0	0.0001	0.0002	0.0004	0.0007	0.0012	0.002	0.0028	0.0039
46	20.5	0	0	0	0	0	0.0001	0.0002	0.0004	0.0008	0.0013	0.002	0.0028
48	21.4	0	0	0	0	0	0	0.0001	0.0003	0.0005	0.0009	0.0014	0.002
50	22.3	0	0	0	0	0	0	0.0001	0.0001	0.0003	0.0006	0.0009	0.0014
52	23.2	0	0	0	0	0	0	0	0.0001	0.0002	0.0004	0.0006	0.001
54	24.1	0	0	0	0	0	0	0	0	0.0001	0.0002	0.0004	0.0007
56	25.0	0	0	0	0	0	0	0	0	0.0001	0.0001	0.0003	0.0005
58	25.9	0	0	0	0	0	0	0	0	0	0.0001	0.0002	0.0003
60	26.8	0	0	0	0	0	0	0	0	0	0	0.0001	0.0002
62	27.7	0	0	0	0	0	0	0	0	0	0	0.0001	0.0001

Table E-1

Estimated Annual Energy Output

at Hub Height in Thousand kWh/yr

Average Speed (m/s)	(mph)	Power Density (W/m^2)	Total Effic.	Rotor Diameter in meters (feet) 1 (3.3)	1.5 (4.9)	2 (6.6)	3 (9.8)	4 (13.1)	5 (16.4)	6 (19.7)	7 (23)
4.0	9.0	75	0.28	0.1	0.3	0.6	1.3	2.3	3.6	5.2	7.1
4.5	10.1	110	0.28	0.2	0.5	0.8	1.9	3.4	5.3	7.6	10
5.0	11.2	150	0.25	0.3	0.6	1.0	2.3	4.1	6.5	9.3	13
5.5	12.3	190	0.25	0.3	0.7	1.3	2.9	5.2	8.2	12	16
6.0	13.4	250	0.21	0.4	0.8	1.4	3.3	5.8	9.0	13	18
6.5	14.6	320	0.19	0.4	0.9	1.7	3.8	6.7	10	15	20
7.0	15.7	400	0.16	0.4	1.0	1.8	4.0	7.0	11	16	22
7.5	16.8	490	0.15	0.5	1.1	2.0	4.6	8.1	13	18	25
8	17.9	600	0.12	0.5	1.1	2.0	4.5	7.9	12	18	24
8.5	19.0	720	0.12	0.6	1.3	2.4	5.3	9.5	15	21	29
9	20.2	850	0.12	0.7	1.6	2.8	6.3	11	18	25	34

*Assumed efficiency based on published data.

Table E-1.1

Estimated Annual Energy Output

at Hub Height in Thousand kWh/yr

Average Speed (m/s)	(mph)	Power Density (W/m^2)	Total Effic.	Rotor Diameter in meters (feet) 10 (33)	11 (36)	12 (39)	13 (43)	15 (49)	17 (56)	18 (59)	19 (62)	20 (66)	21 (69)	22 (72)	23 (75)	24 (79)	25 (82)	26 (85)	27 (89)	28 (92)	30 (98)	33 (108)	34 (112)	35 (115)	39 (128)	41 (134)	43 (141)
4.0	9.0	75	0.25	13	16	19	22	29	37	42	46	52	57	62	68	74	80	87	94	100	120	140	150	160	200	220	240
4.5	10.1	107	0.25	19	23	27	32	43	55	61	68	73	81	90	100	110	110	120	130	140	170	200	210	220	280	310	340
5.0	11.2	146	0.3	31	37	45	52	70	89	100	110	120	130	150	160	170	190	200	220	240	270	330	350	370	460	510	560
5.5	12.3	195	0.3	39	47	56	66	88	110	130	140	160	180	190	210	230	250	270	290	310	360	440	460	490	610	680	740
6.0	13.4	253	0.3	52	62	74	87	120	150	170	190	210	230	250	280	300	330	350	380	410	470	570	600	640	790	880	960
6.5	14.6	321	0.3	66	80	100	110	150	190	210	240	270	290	320	350	380	410	450	480	520	600	720	770	810	1000	1100	1200
7.0	15.7	401	0.28	80	90	110	130	170	220	250	280	310	340	370	410	450	480	520	560	610	700	840	890	950	1200	1300	1400
7.5	16.8	494	0.28	90	110	140	160	210	270	310	340	380	420	460	500	550	590	640	690	750	860	1000	1100	1200	1400	1600	1800
8	17.9	599	0.25	100	120	150	170	230	300	330	370	410	450	500	550	590	640	700	750	810	930	1100	1200	1300	1600	1700	1900
8.5	19.0	718	0.25	120	150	180	210	280	360	400	450	490	540	600	650	710	770	840	900	1000	1100	1300	1400	1500	1900	2100	2300
9	20.2	853	0.22	130	160	190	220	290	370	420	460	520	570	620	680	740	810	870	940	1000	1200	1400	1500	1600	2000	2200	2400

*Assumed efficiency based on published data.

Table E-2

Estimated Annual Energy Output for Batelle Wind Power Classes

at 30 m (98 ft) Hub Height in Thousand kWh/yr *

Battelle Power Class at 10 m			Wind Speed and Power at 30 m hub height			Rotor Diameter in meters (feet)							
Class	Power Density (W/m²)	Speed (m/s)	Power Density (W/m²)	Speed (m/s)	Total Effic.	1 (3.3)	1.5 (4.9)	2 (6.6)	3 (9.8)	4 (13.1)	5 (16.4)	6 (19.7)	7 (23)
1	50	3.5	80	4.1	0.28	0.2	0.3	0.6	1.4	2.5	3.9	5.6	7.6
2	100	4.4	160	5.1	0.25	0.3	0.6	1.1	2.5	4.4	6.9	9.9	13
3	150	5.0	240	5.9	0.21	0.3	0.8	1.4	3.1	5.6	8.7	12	17
4	200	5.5	320	6.5	0.19	0.4	0.9	1.7	3.8	6.7	10	15	21
5	250	6.0	400	7.0	0.16	0.4	1.0	1.8	4.0	7.1	11	16	22
6	300	6.3	480	7.4	0.15	0.5	1.1	2.0	4.5	7.9	12	18	24
7	400	7.0	640	8.2	0.14	0.6	1.4	2.5	5.5	9.9	15	22	30
	1000	9.5	1600	11.1	0.12	1	3	5	12	21	33	48	65

Table E-2.1

Estimated Annual Energy Output for Batelle Wind Power Classes

at 30 m (98 ft) Hub Height in Thousand kWh/yr *

Battelle Power Class at 10 m			Wind Speed and Power at 30 m hub height			Rotor Diameter in meters (feet)								
Class	Power Density (W/m²)	Speed (m/s)	Power Density (W/m²)	Speed (m/s)	Total Effic.	10 (33)	11 (36)	12 (39)	13 (43)	15 (49)	17 (56)	18 (59)	19 (62)	20 (66)
1	50	3.5	80	4.1	0.25	14	17	20	23	31	40	45	50	55
2	100	4.4	160	5.1	0.3	33	40	48	56	74	96	110	120	130
3	150	5.0	240	5.9	0.3	50	60	71	84	110	140	160	180	200
4	200	5.5	320	6.5	0.3	66	80	95	110	150	190	210	240	260
5	250	6.0	400	7.0	0.28	80	90	110	130	170	220	250	280	310
6	300	6.3	480	7.4	0.28	90	110	130	160	210	270	300	330	370
7	400	7.0	640	8.2	0.25	110	130	160	190	250	320	360	400	440
	1000	9.5	1600	11.1	0.22	240	290	350	410	540	700	780	870	970

Class	21 (69)	22 (72)	23 (75)	24 (79)	25 (82)	26 (85)	27 (89)	28 (92)	30 (98)	33 (108)	34 (112)	35 (115)	39 (128)	41 (134)	43 (141)
1	61	67	73	79	86	90	100	110	120	150	160	170	210	230	250
2	150	160	170	190	210	220	240	260	300	360	380	400	500	560	610
3	220	240	260	290	310	340	360	390	450	540	570	610	750	830	920
4	290	320	350	380	410	450	480	520	590	700	800	800	1000	1100	1200
5	340	370	410	440	480	520	560	600	690	800	900	900	1200	1300	1400
6	410	450	490	530	580	630	670	700	800	1000	1100	1100	1400	1600	1700
7	490	530	580	630	690	740	800	900	1000	1200	1300	1300	1700	1900	2000
	1100	1200	1300	1400	1500	1600	1800	1900	2200	2600	2800	3000	3700	4100	4500

Increase in speed and power with height assumes one-seventh power law.

*Assumed efficiency based on published data.

Table 3-3

Changes in Wind Speed with Height

Site	Speed at Height (m/s) 9.1 m (30 ft)	45.7 m (150 ft)	Speed Increase	Approx. α
San Gorgonio Pass	6.2	7.7	1.24	0.13
Livingston, Montana	6.8	8.4	1.24	0.13
Clayton, New Mexico	5.4	7.3	1.35	0.18
Minot, North Dakota	6.5	8.4	1.29	0.16
Amarillo, Texas	6.3	8.1	1.29	0.16

Source: Battelle, PNL

Table 3-4

Increase in Wind Speed with Height

Above 30 ft (10 m)*

Height		Surface Roughness Exponent (α)			
		1/10	1/7	1/5	1/4
(ft)	(m)	(0.10)	(0.14)	(0.20)	(0.25)
30	9	1.00	1.00	1.00	1.00
60	18	1.07	1.10	1.15	1.19
80	24	1.10	1.15	1.22	1.28
100	30	1.13	1.19	1.27	1.35
120	37	1.15	1.22	1.32	1.41
140	43	1.17	1.25	1.36	1.47
150	46	1.17	**1.26**	1.38	1.50
160	49	1.18	1.27	1.40	1.52

*30 feet is approximately equivalent to a 10-meter anemometer mast.

Table 3-5

Increase in Wind Power Density with Height

Above 30 ft (10 m)*

Height		Surface Roughness Exponent (α)			
		1/10	1/7	1/5	1/4
(ft)	(m)	(0.10)	(0.14)	(0.20)	(0.25)
30	9	1.00	1.00	1.00	1.00
60	18	1.23	1.35	1.52	1.68
80	24	1.34	1.52	1.80	2.09
100	30	1.44	1.68	2.06	2.47
120	37	1.52	1.81	2.30	2.83
140	43	1.59	1.94	2.52	3.18
150	46	1.62	1.99	2.63	3.34
160	49	1.65	2.05	2.73	3.51

*30 feet is approximately equivalent to a 10-meter anemometer mast.

Table 3-6

Changes in Power Density with Height

Site	Power Density at Height (W/m^2) 9.1 m (30 ft)	45.7 m (150 ft)	Power Increase
San Gorgonio Pass	351	712	2.03
Livingston, Montana	457	794	1.74
Clayton, New Mexico	162	334	2.06
Minot, North Dakota	271	533	1.97
Amarillo, Texas	228	464	2.04

Source: Battelle, PNL

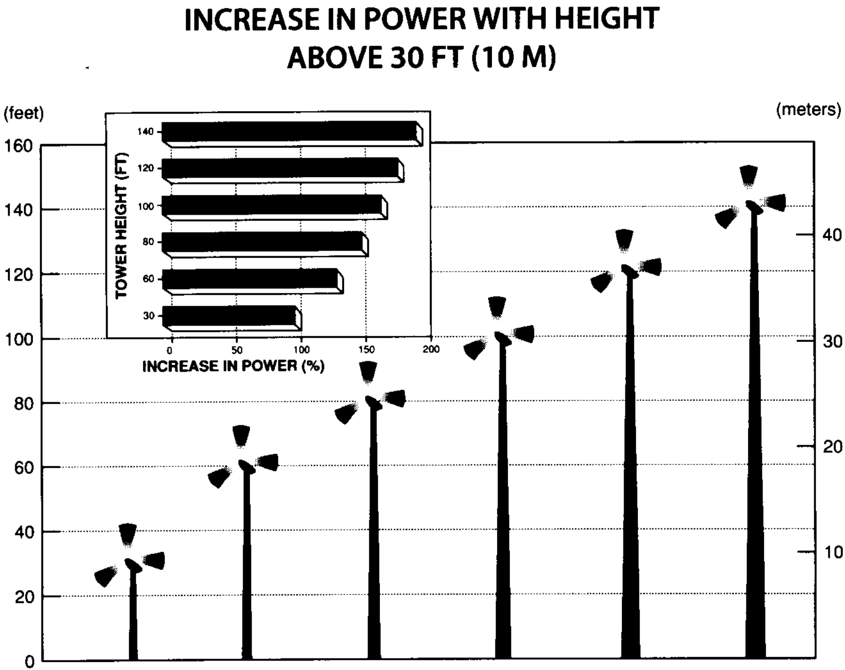


Figure 3-6. *The power available to a wind machine increases with height. The power available at 80 feet (24 meters) above the ground is 150% of that at 30 feet.*

Table 4-2

Estimated Annual Energy Output

at Hub Height in Thousand kWh/yr *

Average Speed (m/s)	(mph)	Power Density (W/m²)	Total Effic.	Rotor Diameter, m (ft) 1 (3.3)	1.5 (4.9)	2 (6.6)	3 (9.8)	4 (13.1)	5 (16.4)	6 (19.7)	7 (23.0)
4.0	9.0	75	0.28	0.1	0.3	0.6	1.3	2.3	3.6	5.2	7.1
4.5	10.1	110	0.28	0.2	0.5	0.8	1.9	3.4	5.3	7.6	10
5.0	11.2	150	0.25	0.3	0.6	1.0	2.3	4.1	6.5	9.3	13
5.5	12.3	190	0.25	0.3	0.7	1.3	2.9	5.2	8.2	12	16
6.0	13.4	250	0.21	0.4	0.8	1.4	3.3	5.8	9.0	13	**18**
6.5	14.6	320	0.19	0.4	0.9	1.7	3.8	6.7	10	15	20
7.0	15.7	400	0.16	0.4	1.0	1.8	4.0	7.0	11	16	22
7.5	16.8	490	0.15	0.5	1.1	2.0	4.6	8.1	13	18	25
8	17.9	600	0.12	0.5	1.1	2.0	4.5	7.9	12	18	24
8.5	19.0	720	0.12	0.6	1.3	2.4	5.3	9.5	15	21	29
9	20.2	850	0.12	0.7	1.6	2.8	6.3	11	18	25	34

*Assumed effeciency based on published data.

Table 4-3

Estimated Annual Energy Output

at 30 m (98 ft) Hub Height in Thousand kWh/yr

	Battelle Power Class at 10 m		Wind Speed and Power at 30 m Hub Height			Rotor Diameter, m (ft)							
Class	Power Density (W/m^2)	Speed (m/s)	Power Density (W/m^2)	Speed (m/s)	Total Effic.	1 (3.3)	1.5 (4.9)	2 (6.6)	3 (9.8)	4 (13.1)	5 (16.4)	6 (19.7)	7 (23)
	50	3.5	80	4.1	0.28	0.2	0.3	0.6	1.4	2.5	3.9	5.6	7.6
1													
	100	4.4	160	5.1	0.25	0.3	0.6	1.1	2.5	4.4	6.9	9.9	13
2													
	150	5.0	240	5.9	0.21	0.3	0.8	1.4	3.1	5.6	8.7	12	17
3													
	200	5.5	320	6.5	0.19	0.4	0.9	1.7	3.8	6.7	10	15	21
4													
	250	6.0	400	7.0	0.16	0.4	1.0	1.8	4.0	7.1	11	16	22
5													
	300	6.3	480	7.4	0.15	0.5	1.1	2.0	4.5	7.9	12	18	24
6													
	400	7.0	640	8.2	0.14	0.6	1.4	2.5	5.5	9.9	15	22	30
7													
	1000	9.5	1600	11.1	0.12	1	3	5	12	21	33	48	65

Table 4-4

Estimating Annual Energy Output from Manufacturer's Power Curve for Bergey 1500

Average Annual Wind Speed = 5.5 m/s (12.3 mph), Rayleigh Distribution

Wind Speed Bin (m/s)	Instantaneous Power (kW)	Rayleigh Frequency Distribution	Hours/ Year	Energy (kWh/yr)
4	0	0.1371	1,201	0
5	0.1	0.1357	1,188	119
6	0.3	0.1224	1,072	322
7	0.5	0.1019	892	446
8	0.8	0.0789	691	553
9	1	0.0571	500	500
17	0.55	0.0005	4	2
18	0.575	0.0002	2	1
19	0.6	0.0001	1	0
20	0.6	.0000	0	0
Annual Energy Output (kWh/yr) =				3,025

Table 4-5

Estimating Annual Energy Output from Manufacturer's Power Curve for Bergey 1500 by Adjusting Speed Distribution to New Height

Average Annual Wind Speed = 5.5 m/s (12.3 mph) at 30 ft Rayleigh Distribution

30 ft Wind Speed Bin (m/s)	100 ft Wind Speed Bin (m/s)	Instantaneous Power (kW)	Rayleigh Frequency Distribution	Hours/ Year	Energy (kWh/yr)
4	4.8	0.075	0.1371	1,201	90
5	6.0	0.3	0.1357	1,188	357
6	7.2	0.5	0.1224	1,072	536
7	8.4	0.9	0.1019	892	803
8	9.6	1.1	0.0789	691	760
9	10.8	1.3	0.0571	500	650
17	20.4	0.6	0.0005	4	3
18	21.6	0.6	0.0002	2	1
19	22.8	0.6	0.0001	1	0
20	24.0	0.6	.0000	0	0
Annual Energy Output (kWh/yr) =					4,261

Understanding Table 4-5

Table 4-5 illustrates how to adjust the speed in a wind speed bin to a new height using the previous example. Assume that we measured the distribution at 30 feet and want to estimate the turbine's output on a 100-foot tower in a region where the one-seventh power law applies.

To do so, increase each speed bin by 1.2 (the increase in speed with height). Thus, the 5 m/s speed bin becomes 6 m/s. Because the turbine produces 0.3 kilowatts at the higher speed instead of only 100 watts, the turbine generates more kilowatt-hours.

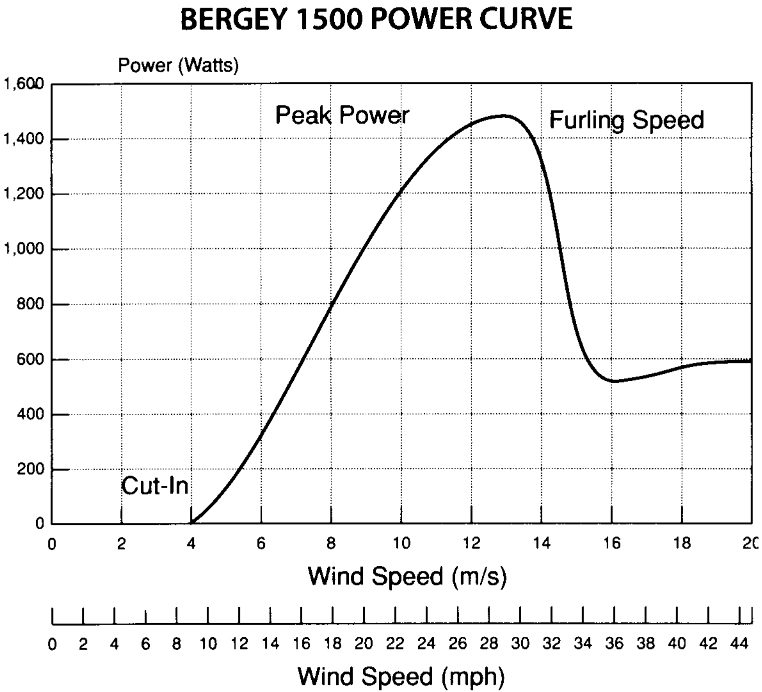


Figure 4-2. Nomenclature for power curve of the Bergey 1500, a small wind machine 3 meters (10 feet) in diameter. (Bergey Windpower)

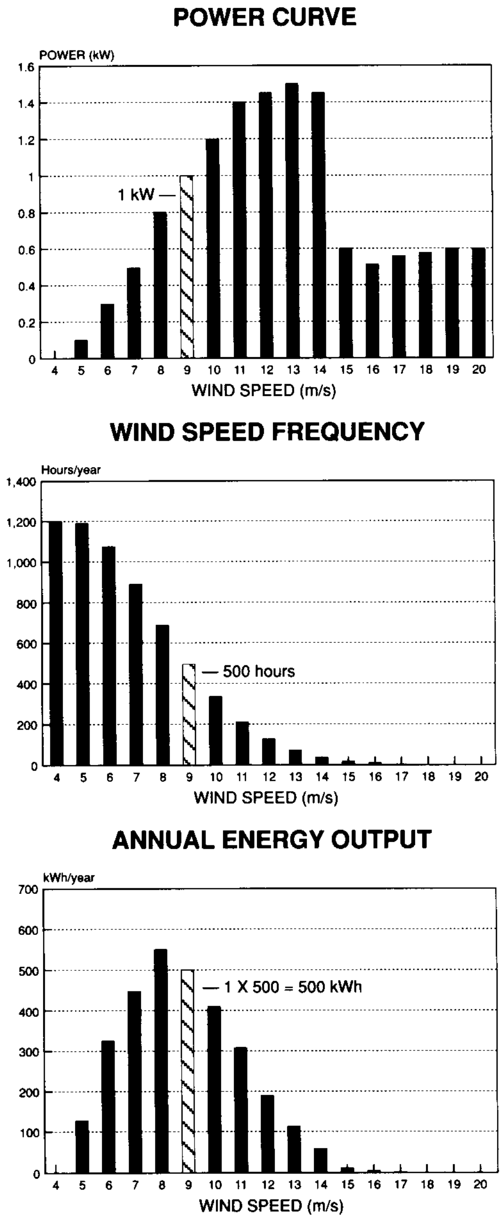


Figure 4-3. *Power curve method of calculating annual energy output. At 9 m/s the Bergey 1500 will produce 1 kilowatt. At a site with a 5.5 m/s (12.3 mph) average wind speed and a Rayleigh frequency distribution, winds occur at this speed 500 hours per year. Winds in the 9 m/s bin contribute 500 kilowatt-hours of the wind machine's total annual generation.*

**Boatowner's Mechanical & Electrical Manual. Calder.
Allard Coles Nautical Publishers. UK/USA. 1996. 0-7136-4291-2.**

Cable construction. Nothing but copper cable is suitable for use in the marine environment. Sometimes aluminum cable is found in household wiring, but this has a lower conductivity than copper and builds up a layer of aluminum oxide on the surface of the cable which creates resistance in connections and terminals—it is not suited to marine use (similarly, because of the corrosion problem, aluminum and unplated steel are not to be used for studs, nuts, washers, and cable terminations). An added measure of protection against corrosion can be gained by drawing the individual strands of a copper cable through a tin "bath" before assembling the cable, to form what is known as *tinned* cable. Tinned cable is more expensive than regular cable, but will provide troublefree service for much longer and is, in the long run, an excellent investment.

Cables in boat use are subjected to vibration and, at times, considerable shocks. Solid-cored cable of the kind used in household wiring is liable to fracture. Stranded cable must be used in boats. The ABYC lists three types, based upon the number of strands (column 6 of Table 3-6 on page 116). Recently the use of Type 1 cable (solid) has been discontinued for marine use; the more flexible Type 2 (19 strands) is recommended for use in general-purpose boat wiring, with Type 3 (many strands—the number varies with cable size) used if frequent flexing occurs.

Insulation is the other critical factor in cable construction. It must be able to withstand the ever present salt-laden atmosphere; contamination by various chemicals, particularly oil, diesel, and dirty bilge water; and exposure to ultraviolet rays from sunlight.

The most commonly available wire in the USA that may be suitable for general-purpose marine wiring is classified as THWN (Thermoplastic, Heat resistant, for Wet locations, and with a Nylon jacket—Table 3-1), or XHHW (cross-linked polyethylene, High-Heat resistant, for Wet locations). Other grades are MTW (Machine Tool Wire), which is rated for wet locations and is oil-, gasoline-, and diesel-resistant, and AWM (Appliance Wiring Material), which is similar to MTW but with a Higher Heat rating (up to 221°F; 105°C), making it suitable for engine rooms.

Wire insulation will frequently carry more than one designation, for example: THHN/THWN. In this instance the insulation has a higher heat (HH) rating in dry locations (up to 194°F/90°C) than it does in wet locations (up to 167°F/75°C).

The problem with Table 3-1 is that the requirements that have to be met for these designations are not rigorous enough to determine whether the cable is really suitable for marine use. A good-quality marine-rated cable will exceed all existing UL, Coast Guard, and ABYC standards. Consequently it is not possible simply to recommend buying a cable that meets a particular standard or has a certain designation, although in the USA it should at the least be labeled as meeting "BC5W2" or "UL1426." To be on the safe side, *tinned, multi-stranded* cable should always be bought from a recognized marine outlet. The cable will be more expensive than that bought from a local electrical wholesaler or retailer, but the added cost is insignificant when compared to the cost of troubleshooting and rectifying faulty circuits in the future.

No normal insulation is suitable for prolonged immersion in water. Sooner or later current leaks will develop. Even good-quality boat cable

Table 3-1 Common Electric Cables Acceptable to the ABYC and Their Designations (USA)

TW: *T*hermoplastic insulation (usually PVC), suitable for *W*et locations (60°C/140°F heat- resistance rating).

THW: *T*hermoplastic insulation (usually PVC), *H*eat resistant (75°C/167°F rating) suitable for *W*et locations.

HWN: *H*eat-resistant (75°C/167°F rating) suitable for *W*et locations, with a *N*ylon jacket for abrasion resistance.

THWN: Same as for HWN, but with *T*hermoplastic insulation.

XHHW: Cross-linked synthetic polymer insulation, *H*igh *H*eat resistant (90°C/194°F rating) suitable for *W*et locations (but in this case de-rated to a 75°C/167°F rating).

MTW: *M*achine *T*ool *W*ire. Usually thermoplastic insulation (PVC) or thermoplastic with a nylon jacket. Moisture-, heat-, and oil-resistant. Most MTW is rated 60°C/140°F. *The ABYC requires it to be rated 90°C/194°F.*

AWM: *A*ppliance *W*iring *M*aterial. Usually thermoplastic insulation (PVC) or thermoplastic with nylon jacket. Thermosetting. 105°C/221°F rating.

BC5W2 and UL 1426 "Boat Cable": Any cable with this designation is good for general- purpose boat wiring. 5 = the heat rating in a dry environment (there are 5 ratings: 1 = 60°C; 2 = 75°C; 3 = 85°C; 4 = 95°C; and 5 = 105°C); 2 = the heat rating in a wet environment (there are two ratings: 1 = 60°C and 2 = 75°C). The insulation on UL 1426 cable is self-extinguishing, which is to say in a fire it will simply char down and drip rather than melt.

For shore-power cords:

SO: Hard *S*ervice cord, *O*il resistant compound.

ST: Hard *S*ervice cord, *T*hermoplastic.

STO: Hard *S*ervice cord, *T*hermoplastic with *O*il-resistant rating.

All are available with several temperature ratings (e.g., 60°C/140°F and 75°C/167°F)

Key: T = *Thermoplastic*, a plastic that can be softened by heating, as opposed to *Thermosetting*, a plastic that is heat-cured into an insoluble and infusible end product

W = Moisture-resistant

H = Heat-resistant (75°C/167°F rating)

HH = Higher-heat-resistant (90°C/194°F rating)

N = Nylon jacket

X = Cross-linked synthetic polymer, a plastic in which polymers are linked chemically by polymerization

BC = Boat Cable

should not be run through perpetually damp or wet areas of a boat. For this, special waterproof, oil-resistant insulation is required, and naturally this is more expensive.

Welding cable. Welding cable is sometimes used on boats for high-current DC circuits (notably for high-output alternator and DC/AC inverter installations), and in fact I recommended it for these purposes in the first edition of this book. The reason for using welding cable is its extreme flexibility, which is particularly useful when running heavy cables in tight quarters, and its tolerance of vibration (for example, when attached to the back of an alternator). The problem with welding cable is that its flexibility comes from its large number of very small strands and its soft insulation. These strands tend to wick up moisture, encouraging corrosion, and the insulation is not as moisture-resistant as other insulation and is easily damaged. For these reasons I am persuaded that welding cable should not be used on boats: It does not, in any case, meet the applicable ABYC standards.

Color coding. A standardized system of DC color coding has been adopted by the ABYC (Tables 3-2 and 3-3). However, in many instances it is not feasible to follow this entirely. The primary consideration (USA) is to use red leads on DC positive circuits, and black or yellow on DC negative. AC color coding is explained on page 103. (Note that black is also used for the "hot" leads on AC circuits in the USA, creating the possibility of dangerous confusion. When rewiring a boat I would strongly recommend the use of yellow for the DC negative).

Cable sizes. Selecting the proper wire size for a given application is critical, especially when electric motors are concerned. Undersized cables introduce unwanted resistance, resulting in voltage drop at appliances, reduced performance, and premature failure.

In the USA, two tables developed by the ABYC are commonly used to determine wire sizes in the marine field. The first assumes that a 10% voltage drop at the appliance is acceptable; the second is based on a 3% voltage drop (Tables 3-4 and 3-5). The tables are entered on

Table 3-2. ABYC DC Color Coding

Color	Use
Red	DC positive conductors
Black or Yellow	DC negative conductors
Green or Green with Yellow stripe(s)	DC grounding (bonding) conductors (see Chapter 4)

Table 3-3. ABYC Color Code for Engines and Accessory Wiring

Color	Item	Use
Yellow w/Red Stripe (YR)	Starting Circuit	Starting Switch to Solenoid
Brown/Yellow Stripe (BY) or Yellow (Y)—see note	Bilge Blowers	Fuse or Switch to Blowers
Dark Gray (Gy)	Navigation Lights	Fuse or Switch to Lights
	Tachometer	Tachometer Sender to Gauge
Brown (Br)	Generator Armature	Generator Armature to Regulator
	Alternator Charge Light	Generator Terminal/Alternator
		Auxiliary Terminal to Light and Regulator
	Pumps	Fuse or Switch to Pumps
Orange (O)	Accessory Feed	Ammeter to Alternator or Generator Output and Accessory Fuses or Switches
	Accessory Feeds	Distribution Panel to Accessory Switch
Purple (Pu)	Ignition	Ignition Switch to Coil and Electrical Instruments
	Instrument Feed	Distribution Panel to Electrical Instruments
Dark Blue	Cabin and Instrument Lights	Fuse or Switch to Lights
Light Blue (Lt Bl)	Oil Pressure	Oil Pressure Sender to Gauge
Tan	Water Temperature	Water Temperature Sender to Gauge
Pink (Pk)	Fuel Gauge	Fuel Gauge Sender to Gauge
Green/Stripe (G/x) (Except G/Y)	Tilt down and/or Trim in	Tilt and/or Trim Circuits
Blue/Stripe (Bl/x)	Tilt up and/or Trim out	Tilt and/or Trim Circuits

NOTE: *If yellow is used for DC negative, blower must be brown with a yellow stripe. (ABYC)*

one side by the total length of the wiring in a circuit (which includes both the hot and the ground wire) and on the other side by the maximum current draw (amps) of the appliance on the circuit. The required wire size, in American Wire Gauge (AWG), for the given voltage drop is then read in the body of the table. Note that the larger the AWG number, the smaller the wire size.

If more than one appliance is to be operated from common cables, *the cables must be rated for the total load of all the appliances. The ground cables to all fixtures must be sized the same as the hot cables, since they carry an equal load.*

Many appliances, particularly lights, will work with a 10% voltage drop, but nevertheless I recommend that you use the 3% voltage drop tables at all times. Given the harshness of the marine environment, it just does not pay to start out by trying to cut calculations as fine as possible.

Cable ampacity. All wire has some internal resistance, and so the passage of any current will generate heat. If this heat builds up faster than it dissipates, the cable will eventually pose a fire hazard. The extent to which this is so depends on the nature of the cable insulation and, in AC circuits, on how many cables are bundled together.

Table 3-8 has been developed by the ABYC to indicate the maximum allowable current (ampacity) of different types of cable, both inside and outside engine spaces. *The correction factors at the bottom are to be applied when bundling current-carrying AC cables.* (Note that in a 120-volt circuit [240-volt UK circuit] the hot and neutral conductors are both current-carrying; in a 240-volt circuit [USA] the two hot conductors are current-carrying. In other words, regardless of the system voltage, there are normally two current-carrying conductors in each circuit.)

Table 3-4. Conductor Sizes for 10% Drop in Voltage

(Total current on circuit in amps)	(Length of conductor from source of current to device and back to source—feet) 10	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
12 volts																			
5	18	18	18	18	18	16	16	14	14	14	12	12	12	12	12	10	10	10	10
10	18	18	16	16	14	14	12	12	10	10	10	10	8	8	8	8	8	8	6
15	18	16	14	14	12	12	10	10	8	8	8	8	8	6	6	6	6	6	6
20	16	14	14	12	12	10	10	8	8	8	6	6	6	6	6	6	4	4	4
25	16	14	12	12	10	10	8	8	6	6	6	6	6	4	4	4	4	4	2
30	14	12	12	10	10	8	8	6	6	6	6	4	4	4	4	2	2	2	2
40	14	12	10	10	8	8	6	6	6	4	4	4	2	2	2	2	2	2	2
50	12	10	10	8	8	6	6	4	4	4	2	2	2	2	2	1	1	1	1
60	12	10	8	8	6	6	4	4	2	2	2	2	2	1	1	1	0	0	0
70	10	8	8	6	6	6	4	2	2	2	2	1	1	1	0	0	0	2/0	2/0
80	10	8	8	6	6	4	4	2	2	2	1	1	0	0	0	2/0	2/0	2/0	2/0
90	10	8	6	6	6	4	2	2	2	1	1	0	0	0	2/0	2/0	2/0	3/0	3/0
100	10	8	6	6	4	4	2	2	1	1	0	0	0	2/0	2/0	2/0	3/0	3/0	3/0
24 volts																			
5	18	18	18	18	18	18	18	18	16	16	16	16	14	14	14	14	14	14	12
10	18	18	18	18	18	16	16	14	14	14	12	12	12	12	12	10	10	10	10
15	18	18	18	16	16	14	14	12	12	12	10	10	10	10	10	8	8	8	8
20	18	18	16	16	14	14	12	12	10	10	10	10	8	8	8	8	8	8	6
25	18	16	16	14	14	12	12	10	10	10	8	8	8	8	8	6	6	6	6
30	18	16	14	14	12	12	10	10	8	8	8	8	8	6	6	6	6	6	6
40	16	14	14	12	12	10	10	8	8	8	6	6	6	6	6	6	4	4	4
50	16	14	12	12	10	10	8	8	6	6	6	6	6	4	4	4	4	4	2
60	14	12	12	10	10	8	8	6	6	6	6	4	4	4	4	2	2	2	2
70	14	12	10	10	8	8	6	6	6	6	4	4	4	2	2	2	2	2	2
80	14	12	10	10	8	8	6	6	6	4	4	4	2	2	2	2	2	2	2
90	12	10	10	8	8	6	6	6	4	4	4	2	2	2	2	2	2	1	1
100	12	10	10	8	8	6	6	4	4	4	2	2	2	2	2	1	1	1	1

Table 3-5. Conductor Sizes for 3% Drop in Voltage

(Total current on circuit in amps)	(Length of conductor from source of current to device and back to source—feet) 10	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
12 volts																			
5	18	16	14	12	12	10	10	10	8	8	8	6	6	6	6	6	6	6	6
10	14	12	10	10	10	8	6	6	6	6	4	4	4	4	2	2	2	2	2
15	12	10	10	8	8	6	6	6	4	4	2	2	2	2	2	1	1	1	1
20	10	10	8	6	6	6	4	4	2	2	2	2	1	1	1	0	0	0	2/0
25	10	8	6	6	6	4	4	2	2	2	1	1	0	0	0	2/0	2/0	2/0	3/0
30	10	8	6	6	4	4	2	2	1	1	0	0	0	2/0	2/0	3/0	3/0	3/0	3/0
40	8	6	6	4	4	2	2	1	0	0	2/0	2/0	3/0	3/0	3/0	4/0	4/0	4/0	4/0
50	6	6	4	4	2	2	1	0	2/0	2/0	3/0	3/0	4/0	4/0	4/0				
60	6	4	4	2	2	1	0	2/0	3/0	3/0	4/0	4/0	4/0						
70	6	4	2	2	1	0	2/0	3/0	3/0	4/0	4/0								
80	6	4	2	2	1	0	3/0	3/0	4/0	4/0									
90	4	2	2	1	0	2/0	3/0	4/0	4/0										
100	4	2	2	1	0	2/0	3/0	4/0											
24 volts																			
5	18	18	18	16	16	14	12	12	12	10	10	10	10	10	8	8	8	8	8
10	18	16	14	12	12	10	10	10	8	8	8	6	6	6	6	6	6	6	6
15	16	14	12	12	10	10	8	8	6	6	6	6	6	4	4	4	4	4	2
20	14	12	10	10	10	8	6	6	6	6	4	4	4	4	2	2	2	2	2
25	12	12	10	10	8	6	6	6	4	4	4	4	2	2	2	2	2	2	1
30	12	10	10	8	8	6	6	4	4	4	2	2	2	2	2	1	1	1	1
40	10	10	8	6	6	6	4	4	2	2	2	2	1	1	1	0	0	0	2/0
50	10	8	6	6	6	4	4	2	2	2	1	1	0	0	0	2/0	2/0	2/0	3/0
60	10	8	6	6	4	4	2	2	1	1	0	0	0	2/0	2/0	3/0	3/0	3/0	3/0
70	8	6	6	4	4	2	2	1	1	0	0	2/0	2/0	3/0	3/0	3/0	3/0	4/0	4/0
80	8	6	6	4	4	2	2	1	0	0	2/0	2/0	3/0	3/0	3/0	4/0	4/0	4/0	4/0
90	8	6	4	4	2	2	1	0	0	2/0	2/0	3/0	3/0	4/0	4/0	4/0	4/0	4/0	
100	6	6	4	4	2	2	1	0	2/0	2/0	3/0	3/0	4/0	4/0	4/0				

Notes: These tables are based on SAE wiring sizes. SAE-rated cables are typically 10% to 12% smaller than AWG-rated cables of the same nominal size (see Table 3-6, columns 2 and 3). Consequently, if a cable is sized by reference to these tables, and then AWG-rated wire of the same nominal size is substituted for SAE, the cable will be somewhat oversized for the application, which is all to the good. Although SAE-rated wiring can be used in DC circuits, *AWG-rated wiring must be used in AC circuits* (If you find this confusing, blame the ABYC and not me!).

Table 3-6. Conversion of American Wire Sizes to European Standards

1	2	3	4	5	6		
Conductor Size	Minimum Acceptable Circular Mil[1] (CM) Area (SAE specs and ABYC for DC Wiring)	Minimum Acceptable Circular Mil[1] (CM) Area (UL specs [AWG] and ABYC for AC Wiring)	Conductor Diameter (mm)	Conductor Cross-sectional Area (mm^2)	Minimum Number of Strands		
					Type 1	Type 2	Type 3
25			0.455	0.163			
24			0.511	0.205			
23			0.573	0.259			
22			0.644	0.325			
21			0.723	0.412			
20			0.812	0.519			
19			0.992	0.653			
18	1537	1620	1.024	0.823	7	16	
17			1.15	1.04			
16	2336	2580	1.29	1.31	7	19	26
15			1.45	1.65			
14	3702	4110	1.63	2.08	7	19	41
13			1.83	2.63			
12	5833	6530	2.05	3.31	7	19	65
11			2.30	4.15			
10	9343	10380	2.59	5.27	7	19	105
9			2.91	6.62			
8	14810	16510	3.26	8.35	7	19	168
7			3.67	10.6			
6	25910	26240	4.11	13.3		37	266
5			4.62	16.8			
4	37360	41740	5.19	21.2		49	420
3			5.83	26.7			
2	62450	66360	6.54	33.6		127	665
1	77790	83690	7.35	42.4		127	836
0 (1/0)	98980	105600	8.25	53.4		127	1064
00 (2/0)	125100	133100	9.27	67.5		127	1323
000 (3/0)	158600	167800	10.40	85.0		259	1666
0000 (4/0)	205500	211600	11.68	107.2		418	2107
00000 (5/0)	250000		13.12	135.1			
000000 (6/0)	300000		14.73	170.3			

1. 1 circular mil (CM) = 0.0005067 mm^2, and 1 MCM = 1,000 CM = 0.5067 mm^2

NOTES:
Type 1 no longer accepted in boat wiring by ABYC.
The lesser ABYC requirements for DC circuits reflects the fact that much of the industry is using SAE-rated cable. Using the UL specs for both DC and AC is preferable.

USA Cable-Sizing Formula

The ABYC tables have been developed by the application of the following formula:

$CM = (K \times I \times L) \div E$ where:

CM = Circular Mil area of the conductor (a measure of its cross-sectional area)

K = 10.75 (a constant representing the mil-foot resistance of copper)

I = the maximum current (amps) on the circuit

L = the length in feet of the conductors in the circuit

E = the maximum allowable voltage drop (in volts) at full load

Use the formula to calculate wire sizes for loads and voltage drops not covered by the tables. For example, if voltage drop is to be limited to 3%, what size cables would be required for a 12-volt electric windlass that pulls 200 amps at full load and which will be situated 25 feet from its battery?

3% of 12 volts is 0.36 volts.

$CM = (10.75 \times 200 \times 50) \div 0.36 = 298611$ Circular mils.

Table 3-6 converts Circular Mils to AWG. In our example a humongous, and totally impractical, 6/0 cable is required. Two 3/0 cables could be run in parallel, but in all probability we would settle for a 10% voltage drop at full load, which can be met with a 2/0 cable (still big!).

Column 2 of Table 3-6 gives minimum SAE (Society of Automotive Engineers) cable specifications, which the ABYC considers adequate for DC wiring, and column 3 gives minimum UL (Underwriters Laboratories) cable specifications (AWG), which the ABYC considers necessary for AC wiring. For a given cable size, UL cables (AWG) are larger than SAE (wiring is one of those confusing areas where there are several different standards). Using the UL standards (AWG) for both DC and AC wiring will ensure the best results.

UK Cable-Sizing Procedures

In the UK a slightly more involved procedure is used to determine cable sizes. The allowable volt-drop-per-amp-per-meter must be calculated. Taking the windlass example, a 3% volt drop on a 12-volt circuit is 0.36 volts. At a maximum current of 200 amps, this gives an allowable volt-drop-per-amp of:

$0.36 \div 200 = 0.0018$ volts (1.8 millivolts [mV, thousandths of a volt]).

Now we have a hitch. Some UK volt-drop tables are based on the *total length of the circuit* (as in the ABYC tables), but other tables are constructed on the basis of the *meter run* of the circuit, which means it is necessary to measure only the distance *in one direction* in order to enter the table. Table 3-7 is a *meter-run* table. The circuit is 7.5 meters (25 feet) in one direction, so the allowable volt-drop-per-amp-per-*meter run* is:

$0.0018 \div 7.5 = 0.00024$ volts (0.24 mVolts).

Table 3-7 is entered in the DC millivolt (mV) column. Reading down we find 0.25mV, which is very close to the 0.24 mV we are looking for. Reading across to the left-hand side, we find we need a cable with a cross-sectional area of 185 mm^2 (which is pretty close to AWG 6/0—see Table 3-6). If we decide to accept a 10% volt drop on the circuit, the allowable volt-drop-per-amp-per-meter run is now:

$1.2 \div (200 \times 7.5) = 0.0008$ volts (0.8 mV).

Entering Table 3-7, we find the nearest mV readings are 0.67 and 0.96. When we cannot find an exact correlation, we always use the *larger* cable which in this case is 70 mm^2. This is pretty close to AWG 2/0—the formula worked again! (Unless precise electrical engineering is needed, UK readers can use the ABYC tables to determine an American Wire Gauge size for a cable, and then use Table 3-6 to convert this to mm^2, but remember that the American tables require measurements in *feet,* both *to and from* the load.)

Table 3-7. Continuous Current Ratings for Cables

Conductor nominal cross-sectional area	Current rating DC or single-phase AC or 3-phase AC	Volt-drop-per-ampere-per-meter		
		DC	Single-phase AC	3-phase AC
1	2	3	4	5
mm²	A	mV	mV	mV
1.0	17	53	53	46
1.5	21	34	34	29
2.5	30	18	18	16
4	40	12	12	10
6	51	7.6	7.6	6.6
10	71	4.5	4.5	3.9
16	95	2.7	2.7	2.3
25	125	1.7	1.7	1.5
35	155	1.2	1.2	1.2
50	190	0.96	0.98	0.87
70	240	0.67	0.69	0.63
95	290	0.48	0.52	0.49
120	340	0.38	0.42	0.43
150	385	0.31	0.36	0.38
185	440	0.25	0.32	0.34
240	520	0.19	0.27	0.31
300	590	0.15	0.24	0.29
	DC / AC			
400	690 / 670	0.12	0.23	0.28
500	780 / 720	0.093	0.22	0.27
630	890 / 780	0.071	0.21	0.26

NOTES:

1. There are different tables for different types of cable in different ambient temperatures. This is a conservative table based on insulation rated for 60°C (140°F). A cable with insulation rated for higher temperatures will be able to carry higher currents. Since any good-quality boat cable should exceed the 60°C (140°F) temperature rating, this table can be safely used to size just about any cable.
2. This table is based upon distances measured in *meter-runs*—i.e., it is necessary to measure only the circuit *in one direction*. See the text for an explanation of how to use it.

Table 3-8. Allowable Ampacity of Conductors

CONDUCTOR SIZE AWG	Temperature Rating of Conductor Insulation													
	60°C (140°F)		75°C (167°F)		80°C (176°F)		90°C (194°F)		105°C (221°F)		125°C (257°F)		200°C (392°F)
	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE ENGINE SPACES	INSIDE ENGINE SPACES	OUTSIDE OR INSIDE ENGINE SPACES
18 (0.8)	10	5.8	10	7.5	15	11.7	20	16.4	20	17.0	25	22.3	25
16 (1)	15	8.7	15	11.3	20	15.6	25	20.5	25	21.3	30	26.7	35
14 (2)	20	11.6	20	15.0	25	19.5	30	24.6	35	29.8	40	35.6	45
12 (3)	25	14.5	25	18.8	35	27.3	40	32.8	45	38.3	50	44.5	55
10 (5)	40	23.2	40	30.0	50	39.0	55	45.1	60	51.0	70	62.3	70
8 (8)	55	31.9	65	48.8	70	54.6	70	57.4	80	68.0	90	80.1	100
6 (13)	80	46.4	95	71.3	100	78.0	100	82.0	120	102.0	125	111.3	135
4 (19)	105	60.9	125	93.8	130	101.4	135	110.7	160	136.0	170	151.3	180
2 (32)	140	81.2	170	127.5	175	136.5	180	147.6	210	178.5	225	200.3	240
1 (40)	165	95.7	195	146.3	210	163.8	210	172.2	245	208.3	265	235.9	280
0 (50)	195	113.1	230	172.5	245	191.1	245	200.9	285	242.3	305	271.5	325
00 (62)	225	130.5	265	198.8	285	222.3	285	233.7	330	280.5	355	316.0	370
000 (81)	260	150.8	310	232.5	330	257.4	330	270.6	385	327.3	410	364.9	430
0000 (103)	300	174.0	360	270.0	385	300.3	385	315.7	445	378.3	475	422.8	510

Maximum Allowable Amperage

Correction Factors for Bundling of AC Cables

No. of current-carrying conductors	Correction factor
3	0.70
4-6	0.60
7-24	0.50
25+	0.40

(ABYC)

This table, and these correction factors, are used to double-check the adequacy of cables selected by using the voltage-drop tables. For example, a 2/0 cable on a 200-amp circuit: If this is to be run through an engine space, Table 3-8 tells us the cable insulation must be rated for 167°F/75°C; if the only cable available has a 140°F/60°C rating, the 2/0 cable cannot be used to carry 200 amps in the engine room, but would be adequate outside it.

Table 3-9 converts American wire gauge sizes to European specifications.

Connections and Terminals

Poor connections are the bane of many an otherwise excellent electrical installation. The keys to success are using the proper terminals, installing them with the proper tools, and keeping moisture out of the terminal.

Proper terminals. Crimp-on connectors and terminals have gained almost universal acceptance in marine wiring. However, it should be noted that every one is a potential source of trouble: The exposed end of the cable core, protruding from the terminal, provides an entry path for moisture to wick up into the wiring, causing corrosion and resistance; the terminal forms a hard spot in the wiring so that any vibration will tend to cause the wire to fracture where it enters the terminal; and the terminal itself will be fastened to a terminal block or piece of equipment that may use a screw of a dissimilar metal, opening up the possibility of galvanic corrosion.

It makes sense to use the very best terminals available, and as usual there is more to this than meets the eye. A quality terminal will include the following features (none of which are likely to be found on the cheap terminals available at auto parts stores!):

- an *annealed, tin-plated,* copper terminal end. The annealing softens the copper so that the retaining screw will bite into it for maximum conductivity. The tin plating enhances conductivity and corrosion resistance.
- a *seamless* tin-plated brass or bronze sleeve to crimp onto the cable, preferably with a serrated inside surface to enhance its mechanical grip. A seamless sleeve can be crimped from any angle and will hold the wire better than a seamed sleeve.

Table 3-9. Comparison of Conductor Cross-Sections

AWG Ga.	AWG mm^2	ISO mm^2	Ampacity AWG	Ampacity ISO
18	0.82	0.75	20	12
		1.0		18
16	1.31		25	
		1.5		21
14	2.08		35	
		2.5		30
12	3.31		45	
		4.0		40
10	5.26		60	
		6.0		50
8	8.39		80	
		10.0		70
6	13.3		120	
		16.0		100
4	21.2		160	
3	26.6	25.0	180	140
2	33.6	35.0	210	185
1	42.4		245	
0	53.5	50.0	285	230
2/0	67.7	70.0	330	285
3/0	85.2		385	
		95.0		330
4/0	107		445	
250 kcm	127	120	500	400
300 kcm	152	150	550	430

ISO = International Standards Organization, the governing body for European standards.

(ABYC)

- *a long, nylon insulating sleeve*, extending up over the wire insulation. Nylon will not crack or punch through when crimping, and is UV-, diesel-, and oil-resistant (unlike the PVC found on cheap terminals). If the long sleeve contains an extra brass sleeve, a double crimp can be made—once on the terminal barrel, and once on the sleeve around the wire insulation—to provide maximum strain relief.

On wire sizes larger than 4 AWG, uninsulated *lugs* are used to terminate cables. Key features to look for in such lugs are once again an annealed terminal end, tin plating, and a seamless construction. In addition, *the lower end of the barrel should be closed to prevent water entry*. A long barrel will enable a double crimp to be made.

A terminal must be matched to both its cable and its retaining screw or stud. Terminals are given a simple color code: red for 22-18 gauge wire (0.5 to $1.0mm^2$); blue for 16-14 gauge (1.5 to $2.5mm^2$); and yellow for 12-10 gauge (3.0 to $6.0mm^2$).

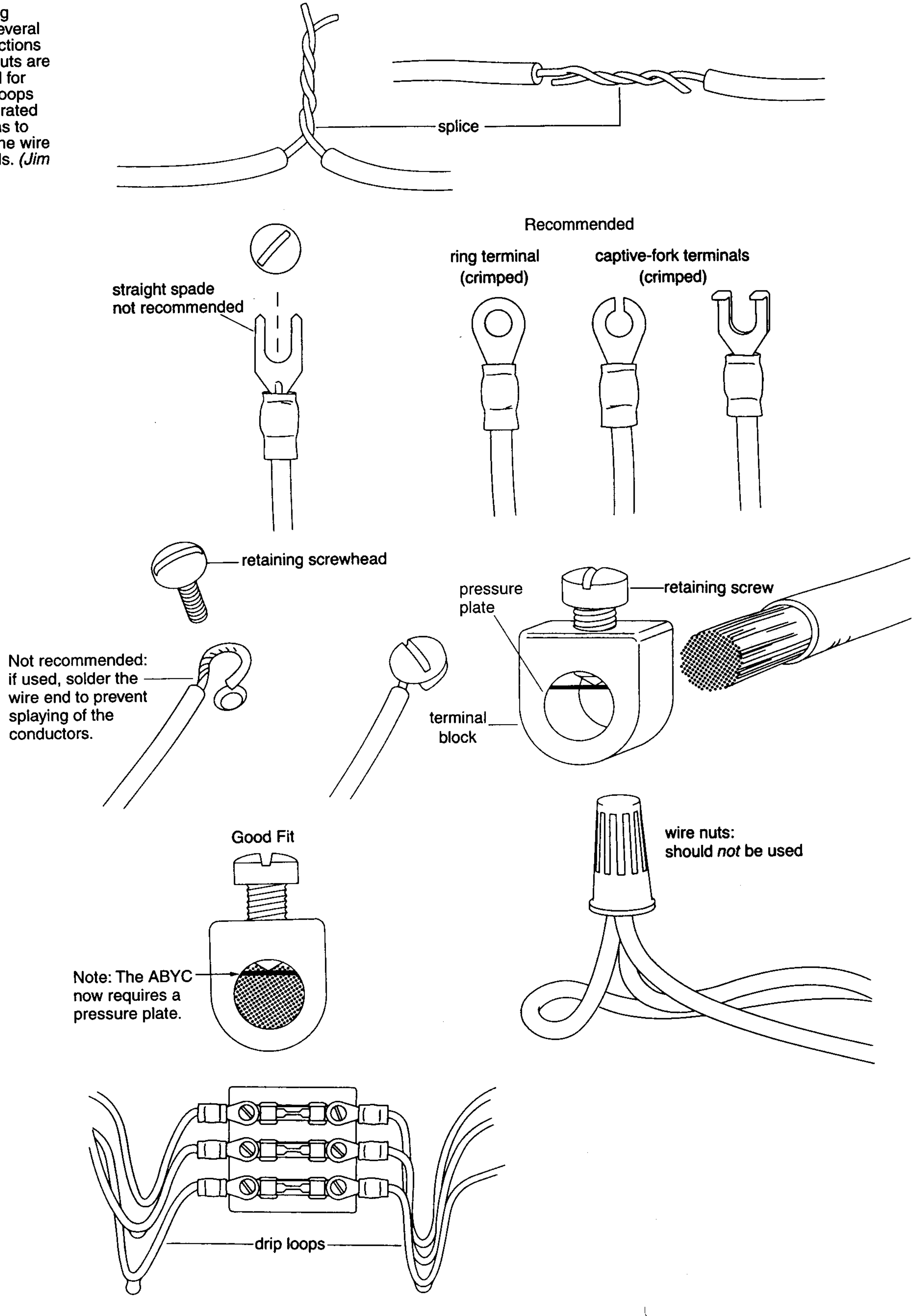
Ring-type terminals are preferred to spade, since they cannot pull off a loose screw. Locking spades are preferred to straight spades (Figure 3-43).

Wire nuts are frequently used to make connections in household circuits in the USA, though not in the UK. They are not suitable for marine use since the threaded metal insert is made of steel and will rust; what is more, the lower end of the nut is open to the atmosphere. If used, wire nuts should always be installed with the open end down so that the nut does not become a water trap. It is a good practice then to seal the nut with polyurethane sealant (it is a better practice to "just say no").

Proper tools. *It is simply not possible to turn out successful crimps without the right tools.* This means a *properly sized* insulation stripper (not a pocket knife, see Figure 3-44), and a *properly sized* crimper.

There are two types of crimp: an indented crimp, in which a deep slot is made in the terminal, and an elliptical crimp, in which the terminal is compressed around its circumference.

Figure 3-43. Wiring installation tips. Several acceptable connections are shown. Wire nuts are *not* recommended for marine use. Drip loops should be incorporated into all connections to keep water from the wire ends and terminals. *(Jim Sollers)*



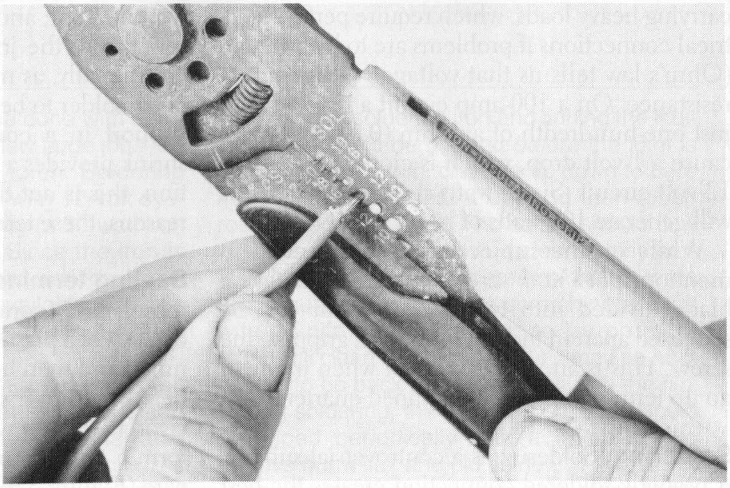


Figure 3-44. Wire stripper in use on a cheap multipurpose crimping and stripping tool. Note that the stripping holes are numbered with their AWG sizes—the numbers on the left-hand side are for stranded cable; those on the right-hand side for solid cable. The threaded holes in the tool (top left) are for cutting terminal retaining screws to length. The screws are threaded in from the numbered side, cut to length, and backed out. This tool has both indent and elliptical crimping slots (not shown).

Figure 3-45. A ratcheting-type crimper that does a perfect job every time. This one makes a double crimp (see Figure 3-46).

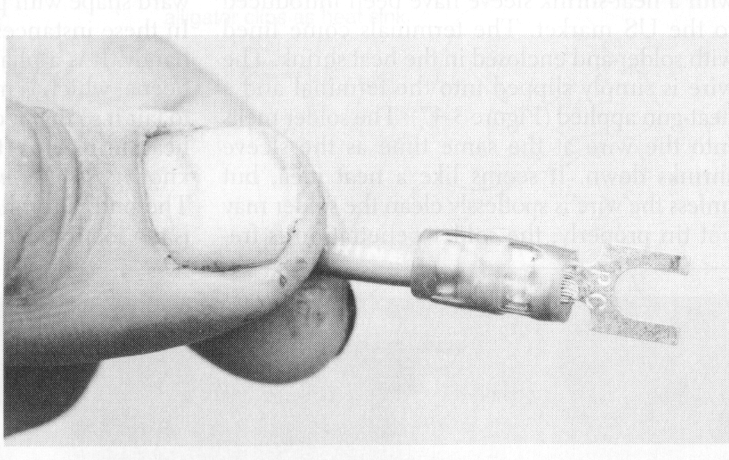


Figure 3-46. Double crimp, once on the terminal barrel and once on the insulated sleeve. Note that these are elliptical crimps, not indent crimps, because this is an insulated terminal (although in point of fact, an indent crimp could have been used in this case since this is a nylon sleeve).

To avoid the risk of cutting through any insulation, *an indent crimp is normally made only on an uninsulated terminal* (although it is permissible to use it on *nylon-sleeved* terminals, since the nylon resists cracking); for insulated terminals it is important to use an *elliptical* crimp (most cheap crimping tools will do both—its simply a matter of choosing the right slot).

But rather than use a cheap crimping tool, every maintenance-conscious boatowner should have a ratcheting-type crimper in the toolbox (Figures 3-45 and 3-46). These will assure a perfect crimp every time.

Special crimping tools are needed for larger cable sizes, but these need not be expensive (the Ancor catalog is an excellent source for marine-grade wiring products and installation tools: Ancor, Cotati, CA). These large cables will be carrying heavy loads, which require perfect electrical connections if problems are to be avoided. (Ohm's law tells us that voltage = amperage × resistance. On a 100-amp circuit a resistance of just one-hundredth of an ohm (0.01 ohm) will cause a 1-volt drop, which is close to 10% on a 12-volt circuit. Since watts = volts × amps, this will generate 100 watts of heat.)

While on the subject of tools, let me also mention *split-shank* screwdrivers. These have a blade divided into two sections that can be squeezed apart in the slot of a screw, gripping the screw. This is an invaluable tool when trying to do up terminal screws in cramped quarters.

Soldering. Soldering is a controversial subject. A properly soldered connection creates the best electrical connection, but all too often the soldering is not done properly. In any case, ABYC regulations require that every joint have a *mechanical* means of connection other than solder. The reason for this is that if the joint gets hot (through excessive resistance or a high current flow) the solder may melt and the joint fall apart. So soldering frequently becomes just an adjunct to a crimped connection, but in this case the solder wicking up the cable creates a hard spot, which is then liable to fail from vibration. *The consensus among professionals is that a properly made crimp, done with the proper tools, is frequently a more reliable termination than soldering.*

Recently low-temperature solder connections with a heat-shrink sleeve have been introduced to the US market. The terminals come lined with solder and enclosed in the heat shrink. The wire is simply slipped into the terminal and a heat-gun applied (Figure 3-47). The solder melts into the wire at the same time as the sleeve shrinks down. It seems like a neat idea, but unless the wire is spotlessly clean the solder may not tin properly; the solder penetration is frequently poor; and the solder melting point is so low that if the joint heats up it may well fail. Additionally, as mentioned, the ABYC does not allow solder to be the sole means of mechanical support in a connection. Although the heat shrink provides a degree of mechanical connection, this is not the same as a crimp. For these reasons, these terminals are not recommended.

Sealing terminals. In recent years heat-shrink tubing has become widely available. Heat shrink consists of a plastic tube that is slipped over a terminal and then heated, preferably with a proper heat gun, but a small propane torch or even a cigarette lighter will do. The tubing contracts to form a tight fit around the terminal barrel and wire (Figures 3-49A, 3-49B and 3-49C).

There are three types of heat shrink: *thin wall*; *dual wall* (which is thin wall lined with an adhesive); and *heavy wall with sealant*. The thin wall (which is commonly found at Radio Shack in the USA) provides insulation, but *not weatherproofing*; the adhesive in the dual wall and heavy wall is squeezed out of both ends of the tubing as it contracts, *forming an extremely effective barrier to moisture penetration*. The heavy wall provides an added margin of abrasion resistance over the dual wall. One or two companies now have a line of "waterproof" terminals that have a length of heat shrink tubing already built onto the terminal sleeve.

Some joints that need insulating are an awkward shape with protruding corners and screws. In these instances, electricians' putty comes in handy. It is a pliable substance, similar to plasticene, which is molded around the connection to fair it so that it can be wrapped smoothly with heat shrink tape (this can be bought in rolls; it is known as *self-amalgamating tape* in the UK). The putty itself has a high insulating value but is too soft to be left uncovered.

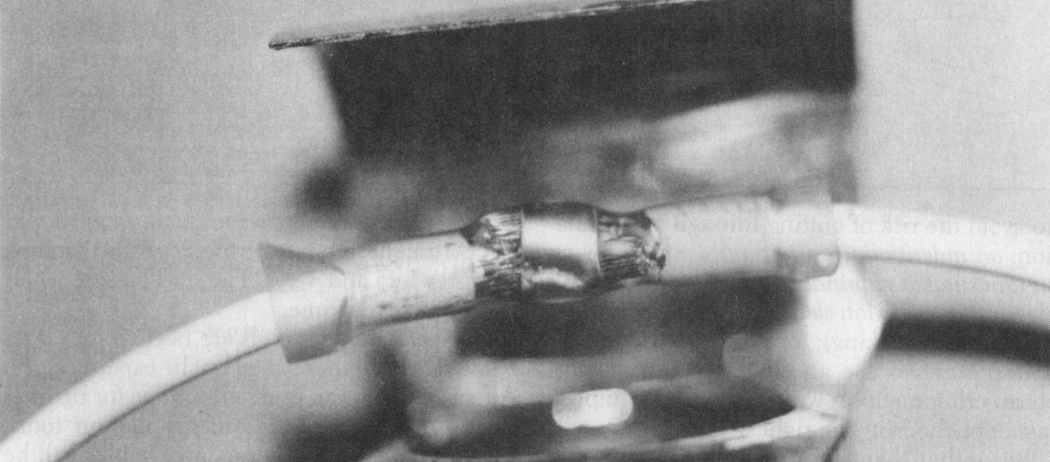


Figure 3-47. Low-temperature solder connection with built-in heat shrink tubing. The solder sleeve is just beginning to melt into the lay of the two cables. At the same time the heat shrink sleeve is starting to clamp down around the cables.

Most soldering aboard can be done with a 50- to 100-watt soldering iron; a few large jobs are best done with a propane torch. Soldering irons can be bought for use with 12-volt systems but are electrically greedy (a 50-watt iron will draw close to 5 amps). Since the iron is used intermittently and for short periods, this is not a great problem. Also available now are small, pocket-sized temperature-controllable butane soldering torches.

Solder is always used with a *flux,* an agent that helps to keep the metal surfaces clean while being soldered. Fluxes are either acid based or rosin based. Only rosin-based fluxes can be used in electrical work, acid fluxes will corrode copper wire.

There are numerous grades of solder, rated by their percentage of tin, lead, or silver. The best all-around solder for electrical work is 60/40 (60% tin; 40% lead). Avoid cheap solders with higher percentages of lead. Solder comes in rolls of either solid or rosin-cored wire, the latter having a hollow center with flux already in it whereas solid solder requires an external application of flux. The rosin-cored solder is suitable for most marine uses and is much more convenient.

The keys to successful soldering are having a well-tinned soldering iron and tinning the individual pieces to be bonded *before* the joint is made. To tin the iron, clean its tip down to bare metal with a file, heat it up, and then touch rosin-cored solder to it. The solder should flow over the whole tip to form a clean, shiny surface. If it will not adhere to areas of the tip, there are impurities. Sometimes scratching around with a knife and the solder (to lay on more rosin) will clean these areas, but it may be necessary to go back and start again with the file. During soldering, the tip of the hot iron should be wiped periodically with a damp rag to remove burnt flux and old solder.

To tin wire ends and terminals, clean them down to bare, shiny metal and then hold the iron to the part to heat it. Touch the solder *to the part,* not to the iron. When the part is hot enough, the solder will flow over and into it, at which point the iron can be withdrawn—the tinning is complete. Once again, if the solder will not adhere to certain areas, they are not clean enough. To speed the heating of the part, place a drop of solder on the iron itself where it is in contact with the part; the actual tinning should always be done by applying the solder as described above.

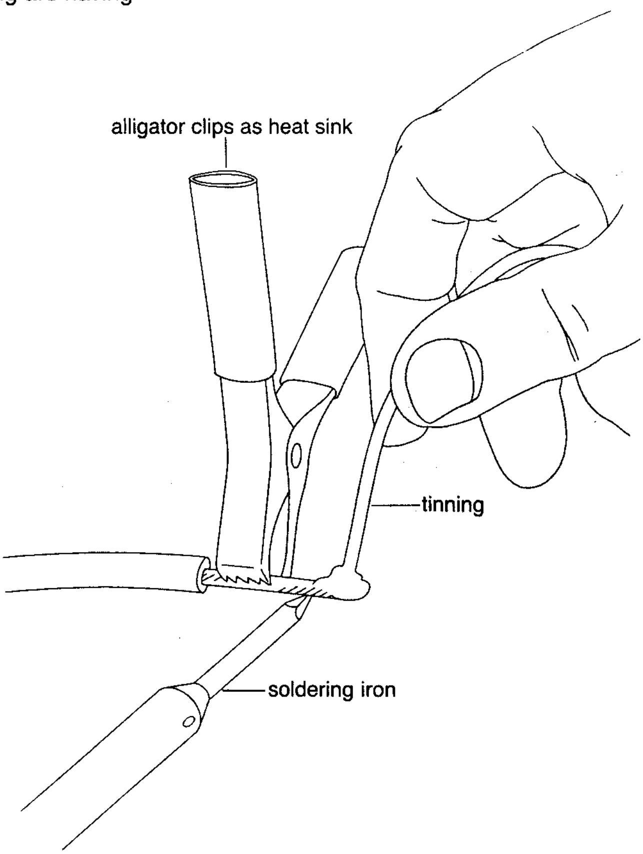


Figure 3-48. Soldering practices. Note that an alligator clip or a strip of aluminum used as a heat sink will protect the insulation from melting. When tinning (applying solder to the wire—not necessary on tinned wire), touch the solder to the wire, not to the iron. As a preparatory step, sandpaper or file the tip of the iron to a pyramid-shaped point of bright metal, then heat the iron, file it bright again, and, working fast, run on a little solder. Try to achieve a good coating of solder over the entire point and ½ inch or so down the tip. Before making a joint, scrape the wire clean and bright. Place the parts to be soldered in firm contact. Use enough heat, but don't overheat. Keep the joint and wire immobile while the solder cools. *(Jim Sollers)*

APPENDIX B

CURRENT CARRYING CAPACITY OF COPPER WIRE

The ratings in the following tabulations are those permitted by the National Electrical Code for flexible cords and for interior wiring of houses, hotels, office buildings, industrial plants, and other buildings.

The values are for copper wire. For aluminum wire the allowable carrying capacities shall be taken as 84% of those given in the table for the respective sizes of copper wire with the same kind of covering.

Size A.W.G.	Area Circular (mils)	Diameter of Solid Wires (mils)	Rubber Insulation (amperes)	Varnished Cambric Insulation (amperes)	Other Insulations and Bare Conductors (amperes)
24	404	20.1	–	–	1.5
22	642	25.3	–	–	2.5
20	1,022	32.0	–	–	4
18	1,624	40.3	3*	–	6**
16	2,583	50.8	6*	–	10**
14	4,107	64.1	15	18	20
12	6,530	80.8	20	25	30
10	10,380	101.9	25	30	35
8	16,510	128.5	35	40	50
6	26,250	162.0	50	60	70
5	33,100	181.9	55	65	80
4	41,740	204.3	70	85	90
3	52,630	229.4	80	95	100
2	66,370	257.6	90	110	125

Note: 1 mil = 0.001 inch.

*The allowable carrying capacities of No. 18 and 16 are 5 and 7 amperes, respectively, when in flexible cords.

**The allowable carrying capacities of No. 18 and 16 are 10 and 15 amperes, respectively, when in cords for portable heaters. Types AFS, AFSI, HC, HPD, and HSJ.

G. Voltage Drop in Conductors

Where the permissible voltage drop is greater than 1 percent, multiply the distance values below by the total percentage of voltage drop. For example, if a 2 percent voltage drop is acceptable, double the distance values in the following table.

Table G

One-Way Distance (Feet) to Load for 1 Percent Voltage Drop in Copper and Aluminum Wire in the United States

Approx. Gen. Size (kW)	Max. Current (amps)	Wire Size (AWG) 10		8		6		4		3		2		1		0		00		000	
		(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)	(Cu)	(Al)
12 volts																					
0.01	1	48	30	74	47	118	74	187	118	236	149	299	188	375	237	472	299	594	377	753	476
0.06	5	10	6	15	9	24	15	37	24	47	30	60	38	75	47	94	60	119	75	151	95
0.12	10	5	3	7	5	12	7	19	12	24	15	30	19	38	24	47	30	59	38	75	48
0.24	20	2	2	4	2	6	4	9	6	12	7	15	9	19	12	24	15	30	19	38	24
0.48	40	1	1	2	1	3	2	5	3	6	4	7	5	9	6	12	7	15	9	19	12
24 volts																					
0.24	10	10	6	15	9	24	15	37	24	47	30	60	38	75	47	94	60	119	75	151	95
0.48	20	5	3	7	5	12	7	19	12	24	15	30	19	38	24	47	30	59	38	75	48
0.7	30	3	2	5	3	8	5	12	8	16	10	20	13	25	16	31	20	40	25	50	32
1	40	2	2	4	2	6	4	9	6	12	7	15	9	19	12	24	15	30	19	38	24
1.4	60	2	1	2	2	4	2	6	4	8	5	10	6	13	8	16	10	20	13	25	16
1.9	80	1	1	2	1	3	2	5	3	6	4	7	5	9	6	12	7	15	9	19	12
2.4	100	1	1	1	1	2	1	4	2	5	3	6	4	8	5	9	6	12	8	15	10
2.9	120	1	1	1	1	2	1	3	2	4	2	5	3	6	4	8	5	10	6	13	8
3.4	140	1	0	1	1	2	1	3	2	3	2	4	3	5	3	7	4	8	5	11	7
36 volts																					
0.7	20	7	5	11	7	18	11	28	18	35	22	45	28	56	36	71	45	89	57	113	71
1.4	40	4	2	6	4	9	6	14	9	18	11	22	14	28	18	35	22	45	28	56	36
2.2	60	2	2	4	2	6	4	9	6	12	7	15	9	19	12	24	15	30	19	38	24
2.9	80	2	1	3	2	4	3	7	4	9	6	11	7	14	9	18	11	22	14	28	18
3.6	100	1	1	2	1	4	2	6	4	7	4	9	6	11	7	14	9	18	11	23	14
48 volts																					
1	20	10	6	15	9	24	15	37	24	47	30	60	38	75	47	94	60	119	75	151	95
1.4	30	6	4	10	6	16	10	25	16	31	20	40	25	50	32	63	40	79	50	100	63
1.9	40	5	3	7	5	12	7	19	12	24	15	30	19	38	24	47	30	59	38	75	48
2.4	50	4	2	6	4	9	6	15	9	19	12	24	15	30	19	38	24	48	30	60	38
2.9	60	3	2	5	3	8	5	12	8	16	10	20	13	25	16	31	20	40	25	50	32
3.4	70	3	2	4	3	7	4	11	7	13	9	17	11	21	14	27	17	34	22	43	27

One-Way Distance (Feet) to Load for 1 Percent Voltage Drop in Copper and Aluminum Wire, con't.

Approx. Gen. Size (kW)	Max. Current (amps)	Wire Size (AWG) 10 (Cu)	10 (Al)	8 (Cu)	8 (Al)	6 (Cu)	6 (Al)	4 (Cu)	4 (Al)	3 (Cu)	3 (Al)	2 (Cu)	2 (Al)	1 (Cu)	1 (Al)	0 (Cu)	0 (Al)	00 (Cu)	00 (Al)	000 (Cu)	000 (Al)
120 volts																					
1.2	10	48	30	74	47	118	74	187	118	236	149	299	188	375	237	472	299	594	377	753	476
1.8	15	32	20	49	31	78	50	125	79	157	99	199	125	250	158	315	199	396	252	502	317
2.4	20	24	15	37	23	59	37	93	59	118	74	149	94	188	119	236	149	297	189	376	238
3	25	19	12	30	19	47	30	75	47	94	60	119	75	150	95	189	119	238	151	301	190
3.6	30	16	10	25	16	39	25	62	39	79	50	100	63	125	79	157	100	198	126	251	159
4.2	35	14	9	21	13	34	21	53	34	67	43	85	54	107	68	135	85	170	108	215	136
4.8	40	12	8	19	12	29	19	47	30	59	37	75	47	94	59	118	75	149	94	188	119
7.2	60	8	5	12	8	20	12	31	20	39	25	50	31	63	40	79	50	99	63	125	79
10	80	6	4	9	6	15	9	23	15	30	19	37	24	47	30	59	37	74	47	94	60
12	100	5	3	7	5	12	7	19	12	24	15	30	19	38	24	47	30	59	38	75	48
240 volts																					
2	10	95	60	148	94	235	149	374	236	472	298	597	376	750	474	945	597	1188	755	1506	952
5	20	48	30	74	47	118	74	187	118	236	149	299	188	375	237	472	299	594	377	753	476
10	40	24	15	37	23	59	37	93	59	118	74	149	94	188	119	236	149	297	189	376	238
14	60	16	10	25	16	39	25	62	39	79	50	100	63	125	79	157	100	198	126	251	159
19	80	12	8	19	12	29	19	47	30	59	37	75	47	94	59	118	75	149	94	188	119
24	100	10	6	15	9	24	15	37	24	47	30	60	38	75	47	94	60	119	75	151	95

Wire

Low voltage power systems often operate at rather high current levels. If the interconnecting cables are too small, a large proportion of the power available will be wasted in the cable itself. This loss can be reduced by using a larger cable, but this increases costs. The chart and the formula on this page are provided to help you in selecting the best cost / power loss compromise.

WIRE CHART

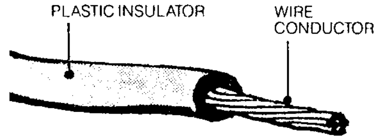
Voltage lost per 10 metres of route length of twin cable.

	Wire Size					
Amps	.4	2	3.2	5	7.5	15
.5	.43	.09	.05	.03	.02	.01
1	.85	.17	.11	.07	.05	.02
1.5	1.3	.26	.16	.10	.07	.03
2	1.7	.34	.21	.14	.09	.05
2.5	2.1	.43	.27	.17	.11	.06
3	2.6	.51	.32	.20	.14	.07
4	3.4	.68	.43	.27	.18	.09
5	4.3	.85	.53	.34	.23	.11
7.5	6.4	1.3	.80	.51	.34	.17
10		1.7	1.1	.68	.45	.23
15		2.6	1.6	1.0	.68	.34
20		3.4	2.1	1.4	.91	.45
25		4.3	2.7	1.7	1.1	.57
30	DO NOT		3.2	2.0	1.4	.68
40	use cable			2.7	1.8	.91
50	sizes and currents				2.3	1.1
75	in this section as					1.7
100	overheating will occur					2.3

Power loss in watts per 10 m of route length of twin cable

	Wire Size					
Amps	.4	2	3.2	5	7.5	15
.5	.21	.04	.03	.02	.01	.01
1	.85	.17	.11	.07	.05	.02
1.5	1.9	.38	.24	.15	.10	.05
2	3.4	.68	.43	.27	.18	.09
2.5	5.3	1.1	.66	.43	.28	.14
3	7.7	1.5	.96	.61	.41	.20
4	14	2.7	1.7	1.1	.73	.36
5	21	4.3	2.7	1.7	1.1	.57
7.5	48	9.6	6.0	3.8	2.6	1.3
10		17	11	6.8	4.5	2.3
15		38	24	15	10	5.1
20		68	43	27	18	9.1
25		106	66	43	28	14
30	DO NOT		96	61	41	20
40	use cable			109	73	36
50	sizes and currents				113	57
75	in this section as					128
100	overheating will occur.					227

NOTE: The above distances are route length. The table takes the total conductor length into account. If the positive and negative leads are different lengths an average must be taken.



Metric cables are specified by the copper area (in square millimetres), the number of strands of wire and the number of conductors or cores in each sheath. The voltage drop is the same regardless of voltage, assuming that amps, distance and cross sectional areas are the same. If the wattage remains the same for different voltages, the amps can be calculated by dividing watts by volts.

The Formula

To calculate amps for 0.5 volt drop, divide above figures by 2.

To calculate amps for a 2 volt drop, multiply above figures by 2.

If you need to calculate the voltage drop under a given set of circumstances, there is a formula by which it can be determined.

Let:

A = cross sectional area of cable in (mm^2)
L = length of cable in metres
(twice distance to complete circuit)
I = current measured in amps
R = resistance of cable (Ω)
resistance of copper = 0.017 Ω
aluminium = 0.028 Ω
steel = 0.18 Ω

Voltage Drop = $L \times I \times R \div A$

Example:

You have a power point connected to a power source. The distance of the positive wire is greater than the distance of the negative wire. The total distance that the current must flow is obtained by adding both these distances together. If the length of the positive cable is 6 metres and the negative is 4 metres, then the total distance that the current must flow is 10 metres. If the wire is 5 mm^2 multi-stranded copper cable and the expected current is expected to be 20 amps, we have:

A = 5   L = 10   I = 20   R = 0.017

Voltage drop can then be calculated to be 0.68 volts. If this figure is considered to be acceptable it would avoid spending more money on larger wire.

Catalog Numbers

mm^2		per metre	30 m roll	100 m roll
0.4	twin	WIR-M01	WIR-301	WIR-101
2.0	twin	WIR-M03	WIR-303	WIR-103
2.0	double	WIR-M04	WIR-304	WIR-104
2.5	twin+earth	WIR-M12	WIR-312	WIR-112
3.2	double	WIR-M06	WIR-306	WIR-106
5.0	double	WIR-M05	WIR-305	WIR-105
7.5	single	WIR-M09	WIR-309	WIR-109
15.0	single	WIR-M10	WIR-310	WIR-110

Power for Water Pumping

The power required to pump water is proportional to the flow rate and to the pressure against which the pump is working. This pressure is usually expressed in terms of the "head," which has two contributions: (1) the height that the water must be pumped from groundwater level, and (2) an extra contribution, called the "friction head," due to friction in the pipes retarding the flow of water. A fairly accurate value for the power required can be calculated using the formula:

$$\text{Power} = 0.00025 \times \frac{G}{E_p} \times (WH + FH),$$

where

- G = *water flow rate in gallons per minute;*
- E_p = *mechanical efficiency of the water pump;*
- WH = *water head—the vertical height in feet from groundwater level to tank inlet; and*
- FH = *friction head in feet.*

This formula gives you the power in units of horsepower; to get the answer in watts, multiply by 746.

This equation is meant to work with the average flow rate and to give you the average power required by the pump. One simple way to establish an average flow rate is to estimate your need for water, expressed in gallons, and divide this need by the number of hours you expect the wind to produce usable power during the same time period. Do this on a daily, weekly or monthly basis—depending on the results of your wind survey. To get the flow rate in gallons per minute, then, use the formula:

$$G = \frac{\text{Gallons Needed}}{60 \times \text{hours of wind}} .$$

Friction losses depend on the pipe length L (in feet), the pipe diameter D (in inches), the number N of pipe joints and corners, and the flow rate G. The formula for friction head FH is:

$$FH = \frac{L \times G^2}{1000 \times D^5} + 2.3 \times N .$$

The pipe length L includes all pipes down in the well, across the pasture, and up the hill or into the tank. If pipe diameter changes along the way, as it usually does, this formula must be used separately for each different length of pipe, and the results added together to get the total friction head.

Example: *Suppose the depth of water in a well is 100 feet below the ground level. A 3-inch pipe brings this water to the surface. The water passes through one elbow joint and into a 1-inch diameter pipe running 200 feet along the ground, then through a second elbow joint and up 14 feet before passing through a third elbow and into the tank. Suppose the farmer needs 2700 gallons of water per day and there are an average of 6 hours of usable wind per day. How many watts of wind power must be supplied to a water pump with 75 percent efficiency?*

Solution: *The average flow rate needed is*

$$G = \frac{2700}{60 \times 6} = 7.5 \text{ gallons/min} .$$

The friction head in the 3-inch pipe is

$$FH = \frac{100 \times 7.5^2}{1000 \times 3^5} + (2.3 \times 1)$$

$$= 2.3 \text{ feet} .$$

The friction head in the 1-inch pipe is

$$FH = \frac{214 \times 7.5^2}{1000 \times 1^5} + (2.3 \times 2)$$

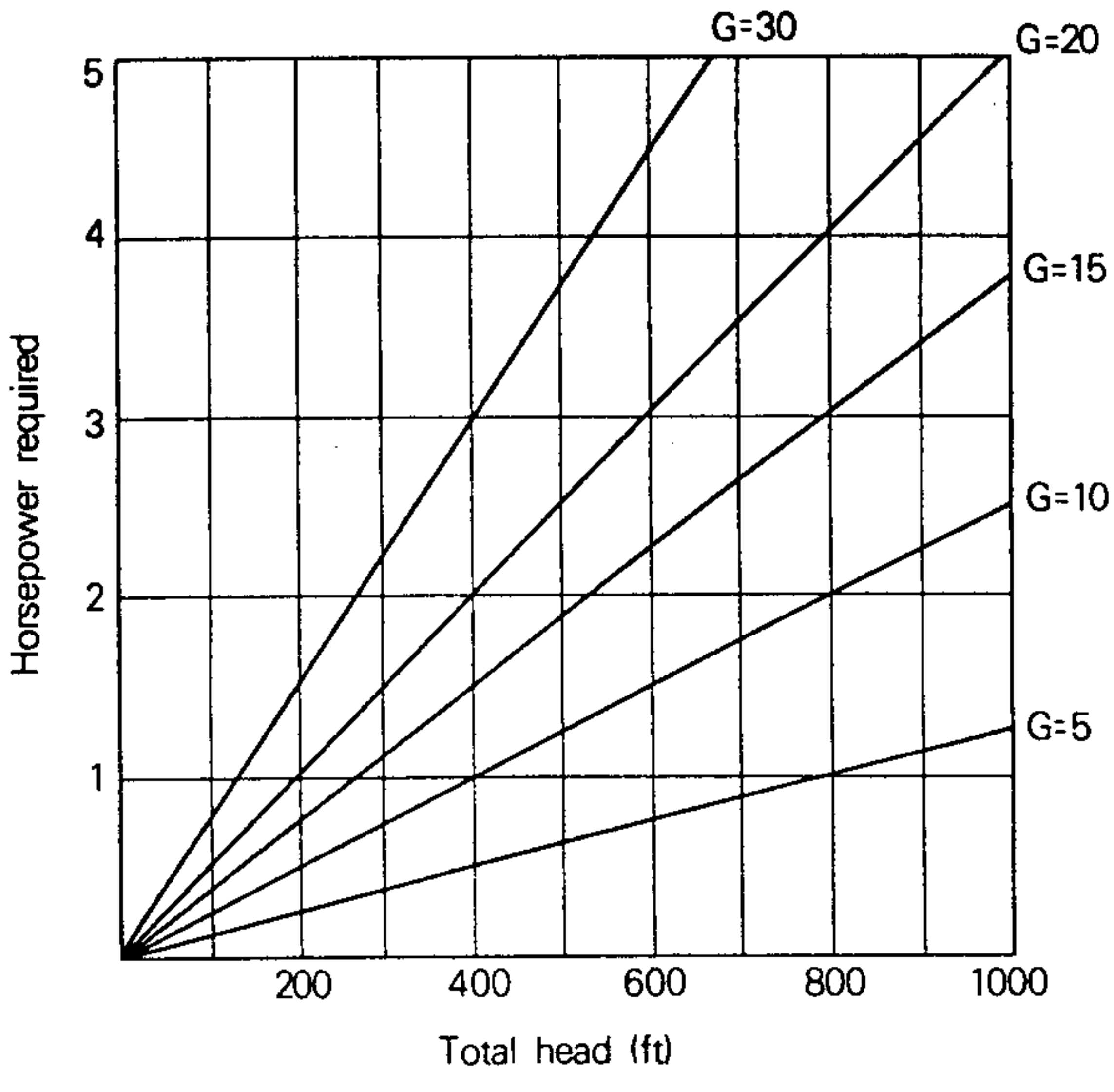
$$= 16.6 \text{ feet} .$$

The total friction head is the sum of these two contributions or FH = 18.9 feet. Then the pump power required is

$$\text{Power} = 0.00025 \times \frac{7.5}{0.75} \times (114 + 18.9)$$

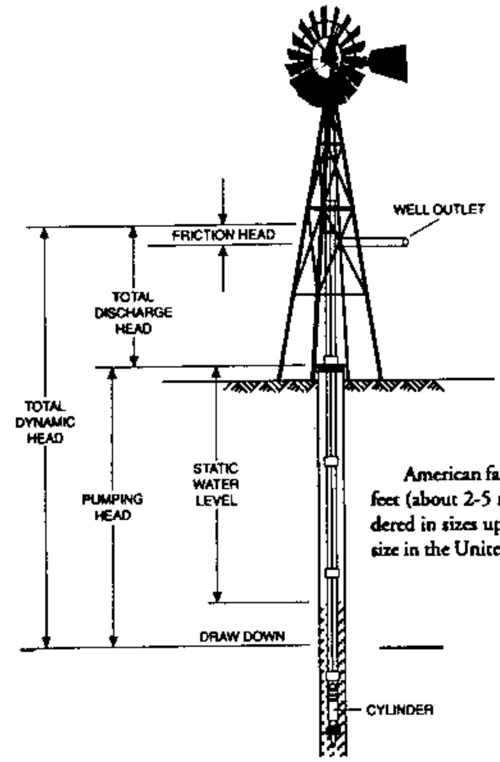
$$= 0.33 \text{ hp} .$$

To get the answer, you just multiply by 746, so the power requirement is 246 watts.

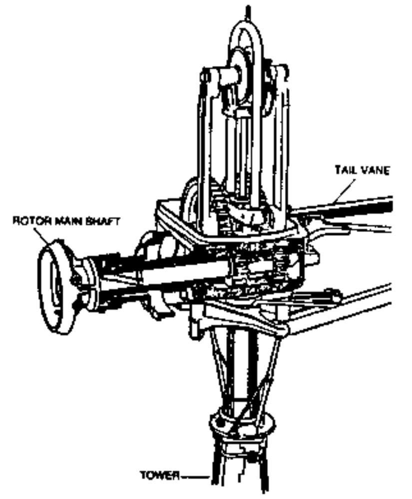


Pump power needed to lift water at a flow rate G, in gallons per minute. To get the wind power needed to drive the pump, divide by the pump efficiency—about 70 percent.

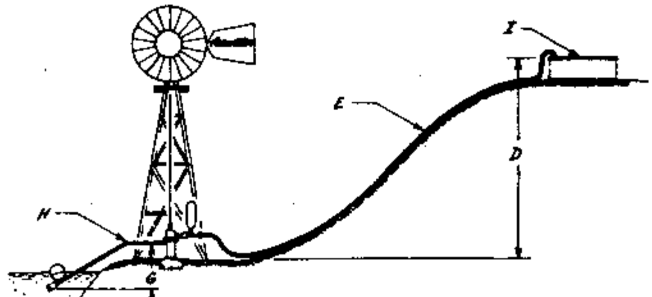
CHOOSING A WINDMILL

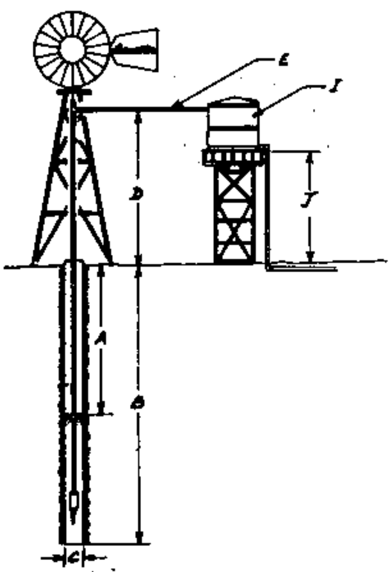


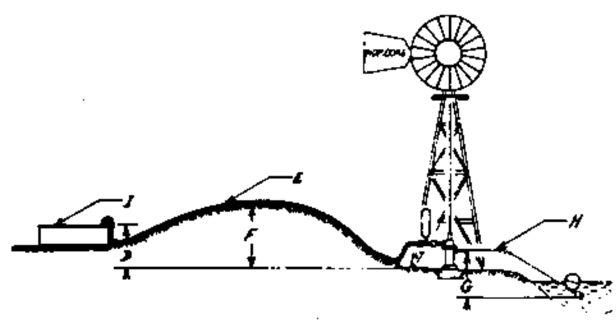
American farm windmills are available in sizes ranging from 6 feet to 16 feet (about 2-5 meters) in diameter. Australia's Southern Cross can be ordered in sizes up 25 feet (about 8 meters) in diameter. The most common size in the United States is the 8-foot mill,

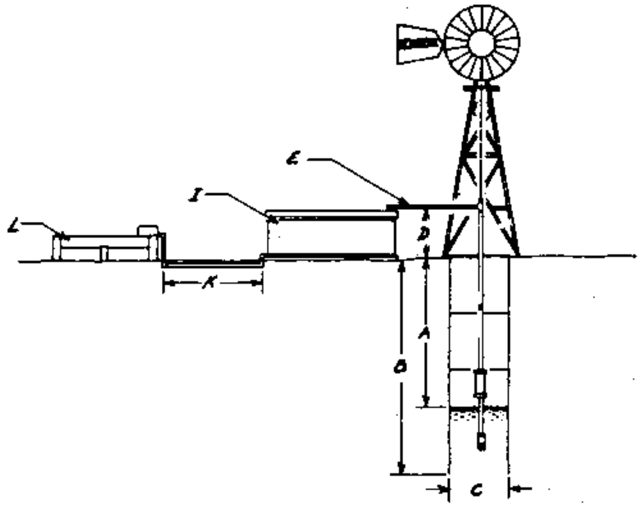


Most farm windmills are back-geared, that is, the rotor turns several revolutions per pump stroke. (Aermotor Co.)









CHOOSING THE CORRECT WINDMILL

Use this pamphlet as a guide of your proposed installation.

1. What size tower is required to place your Aeromotor windmill at least 20 feet above all surrounding obstructions . . . .
2. What quantity of water is required per day. . . . .
3. What quantity of water is the bore, well or soak expected to yield per day . . . .
4. Are the average wind conditions, light, moderate or strong . . . .
5. Which of the sample pumping installations is similar to your proposed system. . . . .
6. Are there any piping, pump rod, or pumps already on the job . . . . (Give particulars regarding sizes and types). . . . .

INFORMATION FROM SAMPLE PUMPING INSTALLATIONS

A. What is the depth from ground level to the low water mark . . . .
B. What is the total depth of the bore or well . . . .
C. What is the outside diameter of the bore casing or the size of the well . . . .
D. How high is the point of delivery above the ground level at the mill base. . . . .
E. What is the length of the delivery pipeline . . . .
F. The vertical height of any rise or depression in the delivery pipeline from the ground level at the mill base, is . . . .
G. What is the height of suction (note: it is not recommended for suction to exceed 18'). . . . .
H. How long is the suction pipeline. . . . .
I. What type and capacity storage tank do you require. . . . .
J. How high do you want your tankstand . . . .
K. What is the length of the pipeline from the tank to the trough . . . .
L. What size and type of trough do you require. . . . .

THE WATER PUMP

To estimate power needed to pump water, you need to know how high you intend to raise the water, and how fast you intend to raise it. See Figure 1. The result of your calculation will be horsepower required. This is different from horsepower available from the wind. The difference lies in the efficiency, or inefficiency (depending on how you look at it) of all the devices used to do the work. If everything were like the textbooks always say (frictionless perfectly balanced, etc.) power required would be equal to power available. But, this is not the case. Estimate power required to pump water by using CHART A.

EXAMPLE

You intend to pump water from a well 150 feet down to a tank on a 50 foot high hill -thus total height equals 200 feet.

You figure that a flow rate of 400 gallons per hour will tend all needs. Horsepower required is found by locating 200 feet on the horizontal line, then looking up to the 400 gallon per hour line, then across to the vertical line to read horsepower equals 0.94.

Data supplied for commercially available windmill pumps may be used for comparison with power estimates. One should remember that CHART A allows estimation. Conservative windmill design will call for increasing the power requirement estimate by a factor for safety, for eventual growth, or both. A factor like half-again, or even twice the estimate is not unreasonable.

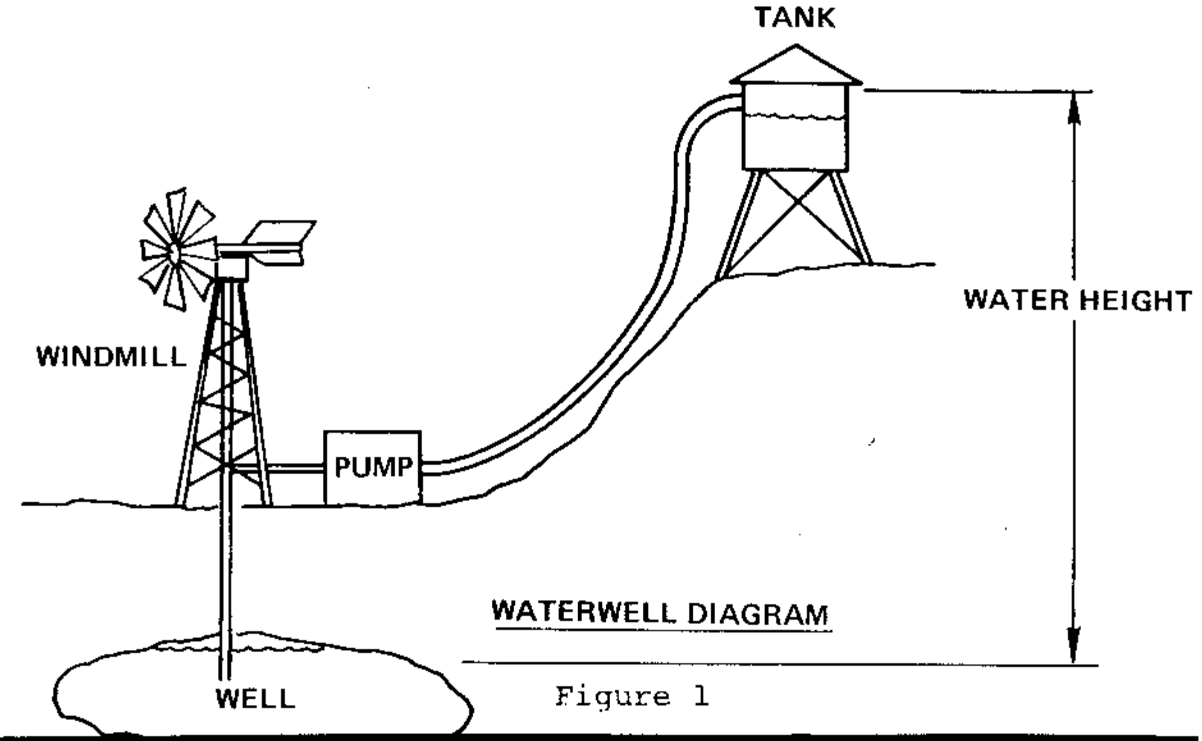


Figure 1

		f=(1.1)	(1.2)	(1.3)	(1.4)
	FLOW RATE	100	200	300	400
HEIGHT	50	.05	.10	.16	.24
	100	.09	.20	.33	.47
	200	.18	.40	.66	.94
	400	.36	.80	1.3	1.9
	600	.54	1.2	1.9	2.8
	800	.72	1.6	2.6	3.8
	1000	.90	2.0	3.3	4.7

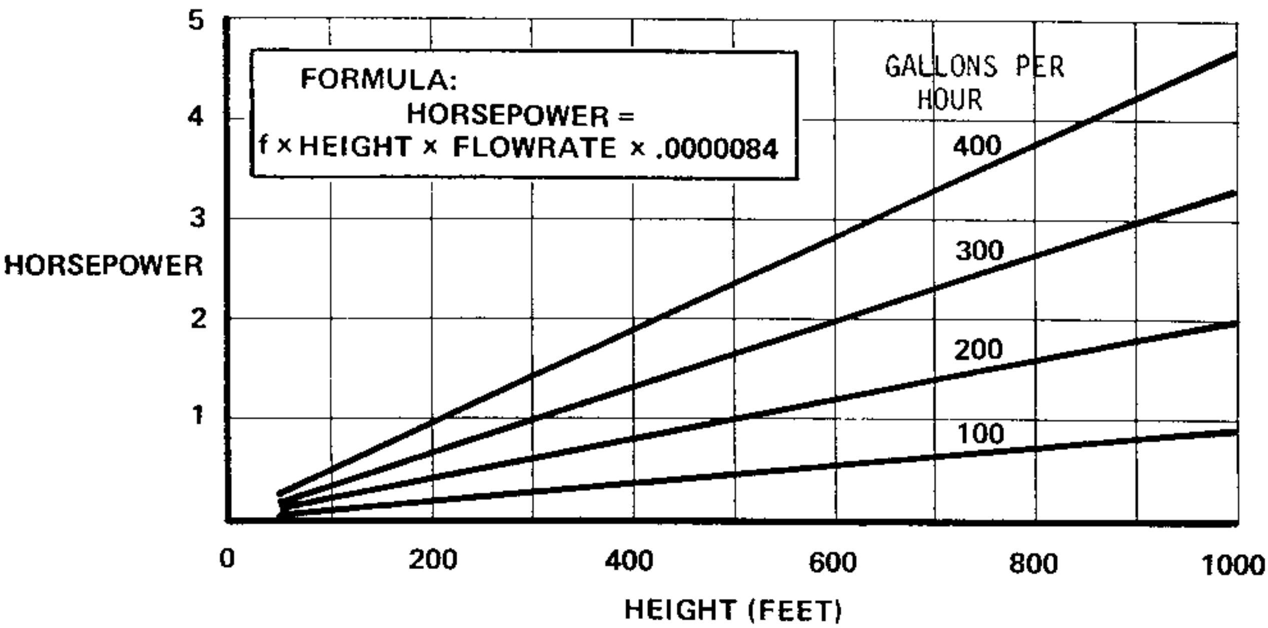


CHART A

F. Estimates of Water Pumping Capacity of Farm Windmills

The following tables estimate the amount of water a traditional American windmill of a given diameter will pump daily from a given depth within different wind regimes. The tables assume that the overall efficiency of the windmill is 5% in a Rayleigh wind speed distribution. Actual performance may vary depending on the windmill and whether it's properly matched to the well pump.

To use the tables, first find the total dynamic head in the left most column. Then find the average annual wind speed at hub height. For example, if the total pumping head is about 100 feet (30 meters) at a site with an 11 mph (5 m/s) average wind speed, a farm windmill with an 8-foot windwheel will pump about 2600 gallons (10 m³) per day.

Table F-1

Approximate Daily Output, American Farm Windmill

8-foot (2.4-meter) Diameter Rotor, in cubic meters/day and gallons/day

Pumping Head		Average Annual Wind Speed, m/s (approximate mph) 3 (7)		4 (9)		5 (11)		6 (13)		7 (16)	
(m)	(ft)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)
10	30	6	1700	15	4000	30	7900	51	13,600	82	21,600
20	70	3	800	8	2000	15	3900	26	6800	41	10,800
30	100	2	600	5	1300	10	2600	17	4500	27	7200
40	130	2	400	4	1000	7	2000	13	3400	20	5400

Source: Center for International Development, Research Triangle Institute.

Table F-2

Approximate Daily Output, American Farm Windmill

10-foot (3.05-meter) Diameter Rotor, in cubic meters/day and gallons/day

Pumping Head		Average Annual Wind Speed, m/s (approximate mph) 3 (7)		4 (9)		5 (11)		6 (13)		7 (16)	
(m)	(ft)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)	(m³)	(gals.)
10	30	10	2700	24	6300	47	12,300	80	21,200	128	33,700
20	70	5	1300	12	3100	23	6100	40	10,600	64	16,800
30	100	3	900	8	2100	16	4100	27	7100	43	11,200
40	130	3	700	6	1600	12	3100	20	5300	32	8400

Source: Center for International Development, Research Triangle Institute.

Table F-3

Approximate Daily Output, American Farm Windmill

12-foot (3.7-meter) Diameter Rotor, in cubic meters/day and gallons/day

Pumping Head		Average Annual Wind Speed, m/s (approximate mph) 3 (7)		4 (9)		5 (11)		6 (13)		7 (16)	
(m)	(ft)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)
10	30	14	3800	34	9100	67	17,700	116	30,600	184	48,500
20	70	7	1900	17	4500	33	8800	58	15,300	92	24,300
30	100	5	1300	11	3000	22	5900	39	10,200	61	16,200
40	130	4	1000	9	2300	17	4400	29	7600	46	12,100

Source: Center for International Development, Research Triangle Institute.

Table F-4

Approximate Daily Output, American Farm Windmill

14-foot (4.3-meter) Diameter Rotor, in cubic meters/day and gallons/day

Pumping Head		Average Annual Wind Speed, m/s (approximate mph) 3 (7)		4 (9)		5 (11)		6 (13)		7 (16)	
(m)	(ft)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)
10	30	20	5200	47	12,300	91	24,100	158	41,600	250	66,000
20	70	10	2600	23	6200	46	12,000	79	20,800	125	33,000
30	100	7	1700	16	4100	30	8000	53	13,900	83	22,000
40	130	5	1300	12	3100	23	6000	39	10,400	63	16,500

Source: Center for International Development, Research Triangle Institute.

Table F-5

Approximate Daily Output, American Farm Windmill

16-foot (4.9-meter) Diameter Rotor, in cubic meters/day and gallons/day

Pumping Head		Average Annual Wind Speed, m/s (approximate mph) 3 (7)		4 (9)		5 (11)		6 (13)		7 (16)	
(m)	(ft)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)	(m^3)	(gals.)
10	30	26	6800	61	16,100	119	31,400	206	54,300	327	86,300
20	70	13	3400	30	8000	60	15,700	103	27,200	163	43,100
30	100	9	2300	20	5400	40	10,500	69	18,100	109	28,800
40	130	6	1700	15	4000	30	7900	51	13,600	82	21,600

Source: Center for International Development, Research Triangle Institute.

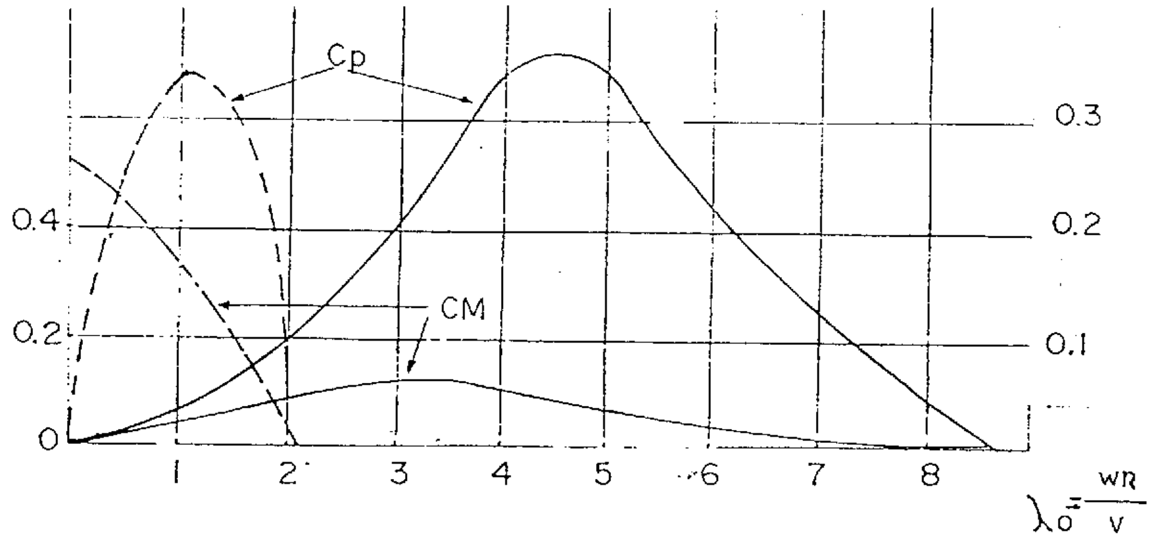


fig.1 - Caracteristicas aerodinámicas de un rotor lento de 18 palas (linea de puntos) y un rotor rápido de 3 palas (linea continua).

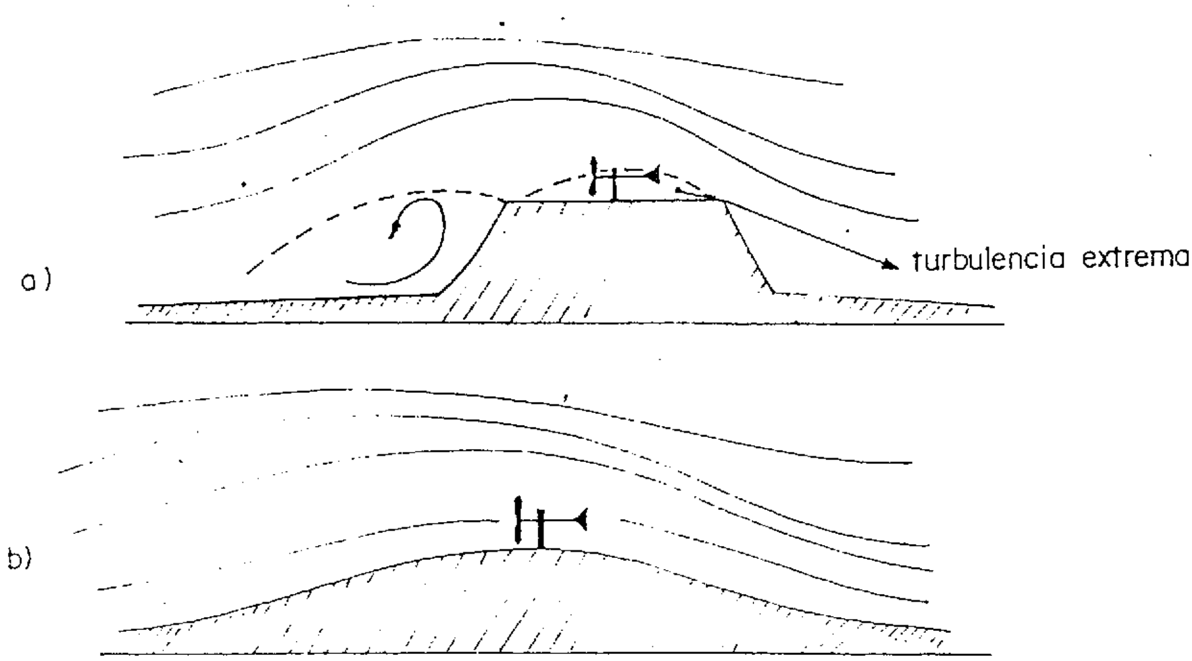


fig.2 - Efecto de la forma del perfil de la loma sobre el viento.

a) - Sobre un acantilado (de pendiente abrupta).

b) - Pendiente suave.

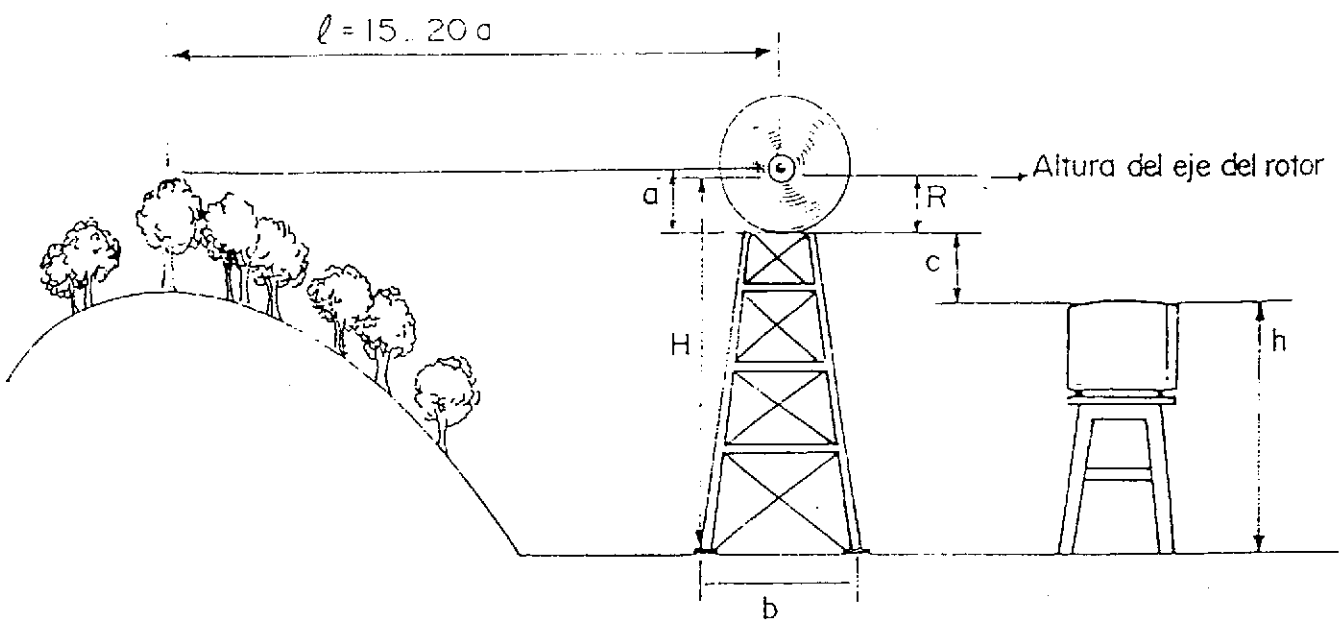


Fig. 3 Ubicacion de un molino de viento

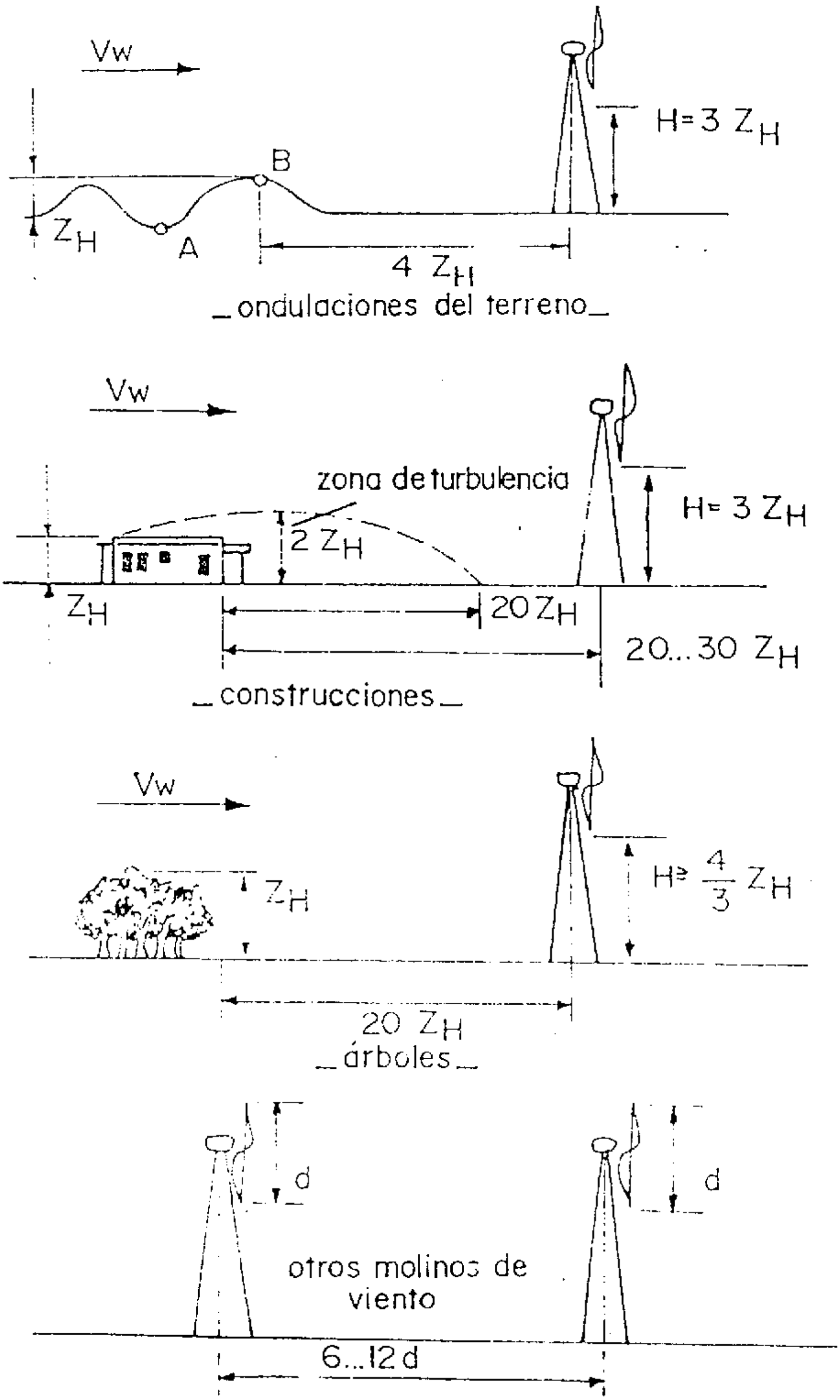


fig.4- Ubicación de las máquinas eólicas según las características del terreno.

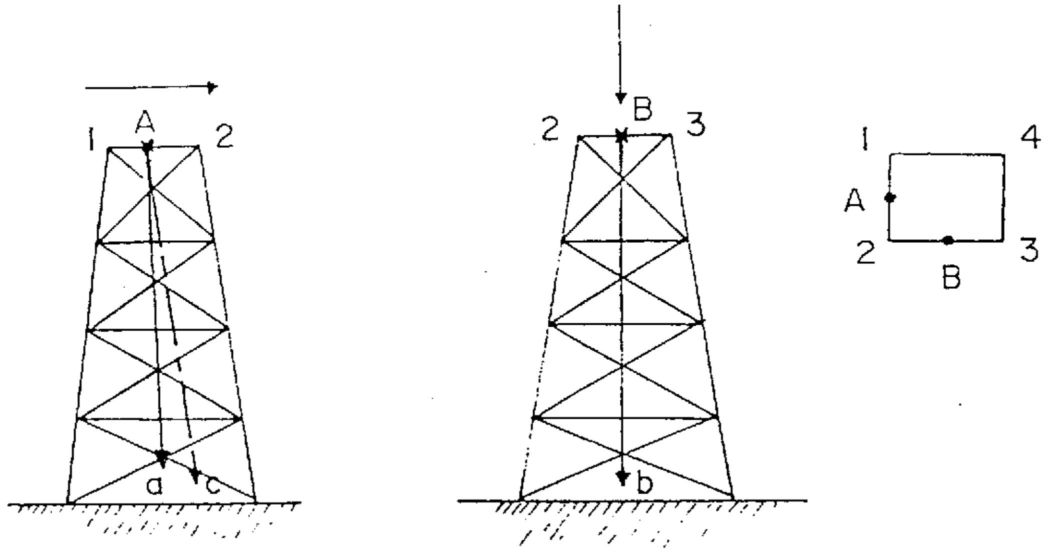


fig.5 - Esquema del centrado de la torre, para ubicarla en posición vertical.

. Cuando la plomada se encuentra en "a" y en "b" __ la torre está vertical.
. Cuando la plomada se encuentra en "c" __ la torre está inclinada en la dirección de la flecha.

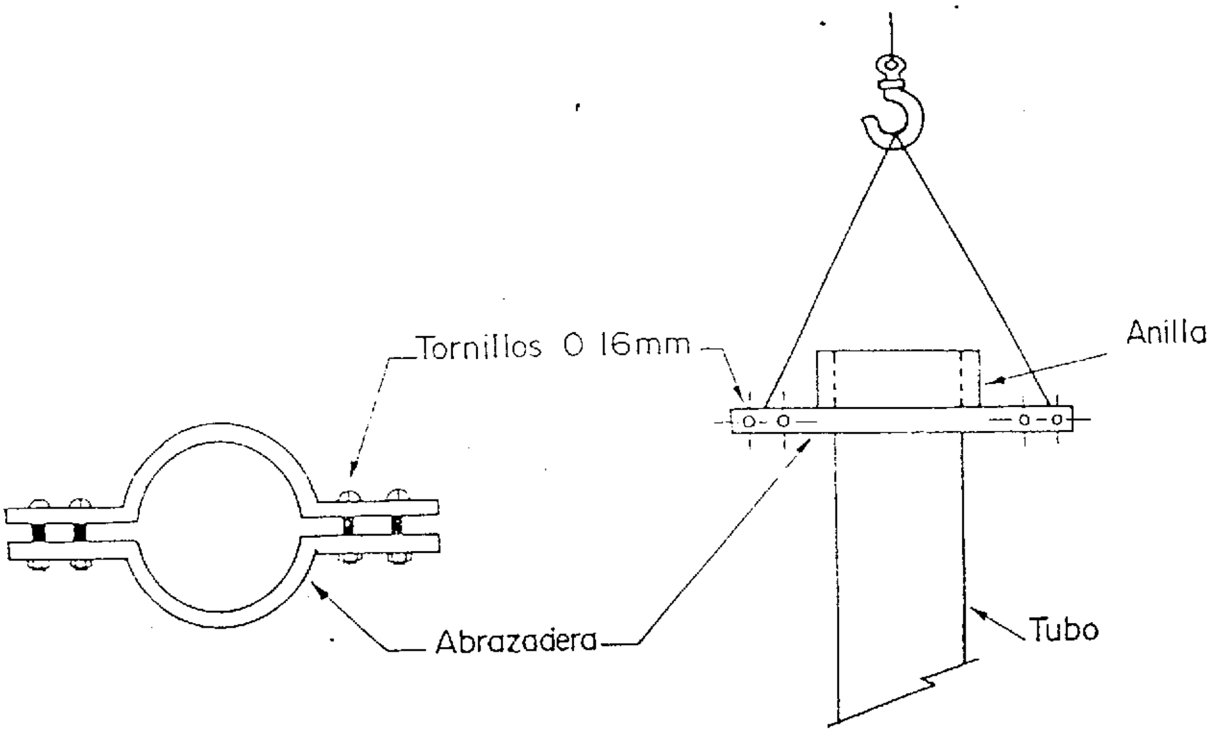


Fig. 6 - Abrazadera

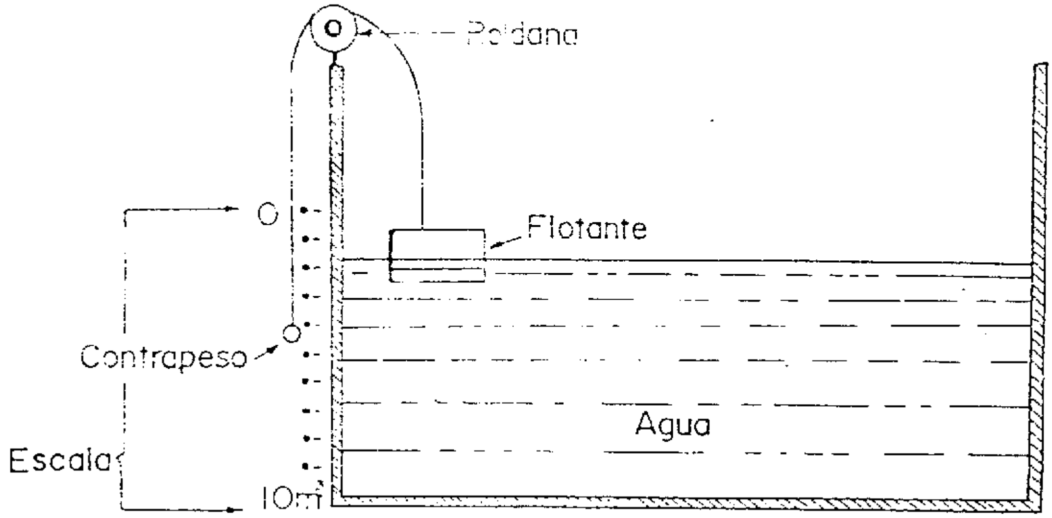


Fig.-7- Marcador del nivel de agua en el tanque

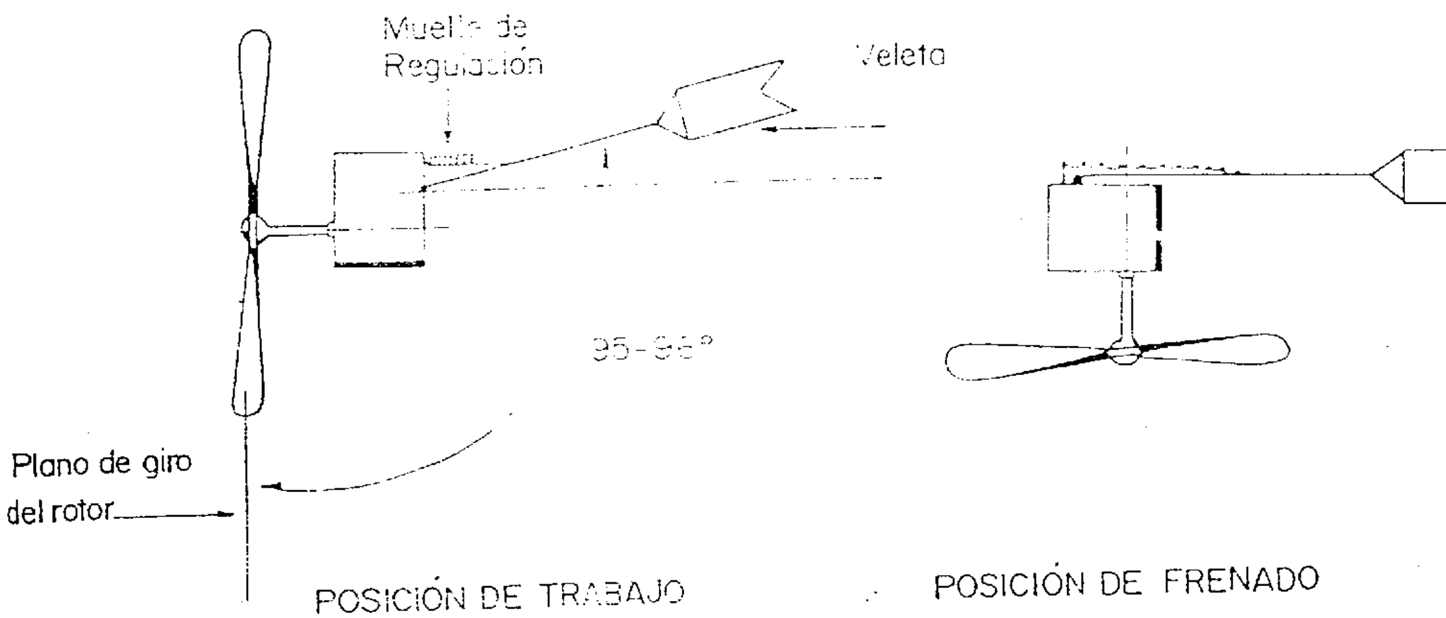


Fig.-8- Sistema de regulación del molino tradicional.

Basic SI units, prefixes, and most common derived SI units used

Basic SI units

Quantity	*Basic unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampère	A
Temperature	kelvin	K

SI prefixes

Prefix	*Symbol*	*Factor*	*Prefix*	*Symbol*	*Factor*
exa	E	10^{18}	deci	d	10^{-1}
peta	P	10^{15}	centi	c	10^{-2}
tera	T	10^{12}	milli	m	10^{-3}
giga	G	10^{9}	micro	μ	10^{-6}
mega	M	10^{6}	nano	n	10^{-9}
kilo	k	10^{3}	pico	p	10^{-12}
hecto	h	10^{2}	femto	f	10^{-15}
deca	da	10^{1}	atto	a	10^{-18}

Most common derived SI units

Quantity	*Unit*	*Symbol*
Area	square metre	m^2
Volume (contents)	cubic metre	m^3
Speed	metre per second	m/s
Acceleration	metre per second, squared	m/s^2
Frequency	hertz	Hz (= s^{-1})
Pressure	pascal	Pa (= N/m^2)
Volume flow	cubic metre per second	m^3/s
Mass flow	kilogram per second	kg/s
Density (specific mass)	kilogram per cubic metre	kg/m^3
Force	newton	N (= $kg.m/s^2$)
Energy/heat/work	joule	J (= N.m)*
Power/energy flow	watt	W (J/s)
Energy flux	watt per square metre	W/m^2
Calorific value (heat of combustion)	joule per kilogram	J/kg
Specific heat capacity	joule per kilogram kelvin	J/kg K
Voltage	volt	V (= W/A)

* NB The joule can also be written in the form watt second (1J = 1W.s)

Conversion of non-SI units to SI units

Although academic scientists and engineers may be strict in their use of SI units for their calculations, a number of non-SI units are still in everyday use. For example, engines are still sold by cc (cubic centimetres) and hp (horse power), and water-pumping windmill manufacturers often quote in terms of cubic feet of the same type of equipment there is not always consistency. In order to be able to compare different manufacturers' products, therefore, it is important to be able convert the different data to a common unit. The following tables give some useful conversion factors for many of the common non-SI units.

Length

Unit (symbol)	millimetre (mm)	metre (m)	kilometre (km)	inch (in.)	foot (ft)	mile (m.)
	1	0.001	10^{-6}	0.0394	0.0033	5.4×10^{-7}
	1000	1	0.001	39.4	3.28	5.4×10^{-4}
	10^6	1000	1	39 360	3280	0.5392
	25.4	0.025	2.5×10^{-5}	1	0.083	1.4×10^{-5}
	305	0.305	3.0×10^{-4}	12	1	1.9×10^{-4}
	1.6×10^6	1609	1.609	63 360	5280	1

Area

Unit (symbol)	square metre (m^2)	hectare (ha)	square kilometre (km^2)	square foot (ft^2)	acre –	square mile (sq. m.)
	1	10^{-4}	10^{-6}	10.76	2.5×10^{-4}	3.9×10^{-7}
	10 000	1	0.01	1.1×10^5	2.471	3.9×10^{-3}
	10^6	100	1	1.1×10^7	247.1	0.386
	0.0929	9.3×10^{-6}	9.3×10^{-8}	1	2.3×10^{-5}	3.6×10^{-8}
	4047	0.4047	4×10^{-3}	43 560	1	1.6×10^{-3}
	2.6×10^6	259	2.590	2.8×10^7	640	1

Volume

Unit (symbol)	litre (l)*	cubic metre (m^3)	cubic inch (in^3)	US gallon (gal)	Imperial gallon (gal)	cubic foot (ft^3)
	1	10^{-3}	61.02	0.264	0.220	0.0353
	1000	1	6102	264	220	35.31
	0.0164	1.6×10^{-5}	1	4.3×10^{-3}	3.6×10^{-3}	5.8×10^{-4}
	3.785	3.8×10^{-3}	231.1	1	0.833	0.134
	4.546	4.5×10^{-3}	277.4	1.201	1	0.160
	28.32	0.0283	1728	7.47	6.23	1

* L in some countries

Mass

Unit (symbol)	gram (g)	kilogram (kg)	tonne (t)	pound (lb)	ton –
	1	0.001	10^{-6}	2.2×10^{-3}	9.8×10^{-7}
	1000	1	0.001	2.205	9.8×10^{-4}
	10^6	1000	1	2205	0.984
	453.6	0.4536	4.5×10^{-4}	1	4.5×10^{-4}
	10^6	1016	1.016	2240	1

Velocity

Unit (symbol)	metres per second (m/s)	kilometres per hour (km/h)	feet per second (ft/s)	miles per hour (mph)	knots (kt)
	1	3.60	3.28	2.237	1.942
	0.278	1	0.912	0.621	0.539
	0.305	1.097	1	0.682	0.592
	0.447	1.609	1.467	1	0.868
	0.566	1.853	1.689	1.152	1

Frequency

Unit (symbol)	hertz (Hz)	revolutions per minute (rpm)	radians per second (rad/s)
	1	60	6.283
	0.0167	1	0.1047
	0.159	9.549	1

Flow rate

Unit (symbol)	litres per minute (l/min)	cubic metres per second (m^3/s)	Imperial gallons per minute (gal(Imp)/min)	cubic feet per second (ft^3/s)
	1	1.7×10^{-5}	0.220	5.9×10^{-4}
	60 000	1	13 206	35.315
	4.546	7.6×10^{-5}	1	2.7×10^{-3}
	1699	0.0283	373.7	1

Force

Unit (symbol)	newton (N)	kilonewton (kN)	kilogram force (kgf)	tonne force (t)	pound force (lbf)	ton force –
	1	0.001	0.102	1×10^{-4}	0.225	1×10^{-4}
	1000	1	102	0.102	225	0.100
	9.807	0.010	1	0.001	2.205	9.8×10^{-4}
	9807	9.807	1000	1	2205	0.984
	4.448	0.004	0.5436	4.5×10^{-4}	1	4.5×10^{-4}
	9964	9.964	1016	1.1016	2240	1

Torque

Unit (symbol)	newton-metre (Nm)	kilonewton-metre (kNm)	foot-pound (ft.lb)
	1	0.001	0.738
	1000	1	738
	1.365	1.4×10^{-3}	1

Work/heat/energy (smaller quantities)

Unit (symbol)	calorie (cal)	joule (J)	watt-hour (Wh)	British Thermal Unit (BTU)	footpound force (ft.lbf)	horsepower-hour (hp.h)
	1	4.182	1.2×10^{-3}	3.9×10^{-3}	3.088	1.6×10^{-6}
	0.239	1	2.8×10^{-4}	9.4×10^{-4}	0.7376	3.7×10^{-7}
	860.4	3600	1	3.414	2655	1.3×10^{-3}
	252	1055	2.93	1	778	3.9×10^{-4}
	0.324	1.356	3.8×10^{-4}	1.3×10^{-3}	1	5.0×10^{-7}
	6.4×10^{5}	2.6×10^{6}	745.7	2546	2.0×10^{6}	1

Work/heat/energy (larger quantities)

Unit (symbol)	kilocalorie (kcal)	megajoule (MJ)	kilowatt hour (kWh)	British Thermal Unit (BTU)	horsepower-hour (hp.h)
	1	4.2×10^{-3}	1.2×10^{-3}	3.968	1.6×10^{-3}
	239	1	0.2887	947.8	0.3725
	860.4	3.600	1	3414	1.341
	0.252	1.1×10^{-3}	2.9×10^{-4}	1	3.9×10^{-4}
	641.6	2.685	0.7457	2546	1

Power

Unit (symbol)	watt (W or J/s)	kilowatt (kW)	metric horse-power (CV)	foot-pound per second (ft.lbf/s)	horse-power (hp)	British Thermal Units per minute (BTU/min)
	1	0.001	1.4×10^{-3}	0.7376	1.3×10^{-3}	0.0569
	1000	1	1.360	737.6	1.341	56.9
	735	0.735	1	558	1.014	41.8
	1.356	1.4×10^{-3}	1.8×10^{-3}	1	1.8×10^{-3}	0.077
	746	0.746	0.9860	550	1	42.44
	17.57	0.0176	0.0239	12.96	0.0236	1

Power flux

Unit (symbol)	watts per square metre (W/m^2)	kilowatts per square metre (kW/m^2)	horsepower per square foot (hp/ft^2)
	1	0.001	1.2×10^{-4}
	1000	1	0.1246
	8023	8.023	1

Calorific value (heat of combustion)

Unit (symbol)	calories per gram (cal/g)	megajoules per kilogram (MJ/kg)	British thermal units per pound (BTU/lb)
	1	4.2×10^{-3}	1.8
	239	1	430
	0.556	2.3×10^{-3}	1

Density (specific mass) and (net) calorific value (heat of combustion) of fuels

	Density (kg/m^3)	Calorific value (MJ/kg)
LPG	560	45.3
Gasoline (petrol)	720	44.0
Kerosene	806	43.1
Diesel oil	850	42.7
Fuel oil	961	40.1
Wood, oven-dried	varies	16–20
Natural gas	—	$103 m^3$ at 1013 mbar, 0°C = 39.36×10^9 J

NB These values are approximate since the fuels vary in composition and this affects both the density and calorific value.

Replacement values

When trying to compare different fuel options, energy planners often use replacement values, which indicate in a specific situation how much fuel it would take to replace another one. For example, the tonne coal equivalent (tce) would be used to say how much coal it would take to replace a given quanity of oil or natural gas. The table below gives some of the most common equivalence values.

Fuel	Unit	Tonnes of coal equivalent (tce)	Tonnes of oil equivalent (toe)	Barrels of oil equivalent (boe)	GJ*
Coal	tonne	1.00	0.70	5.05	29.3**
Firewood (air-dried)	tonne	0.46	0.32	2.34	13.6
Kerosene	tonne	1.47	1.03	7.43	43.1
Natural gas	$1000 m^3$	1.19	0.83	6.00	34.8
Gasoline (petrol)	barrel***	0.18	0.12	0.90	5.2
Gasoil/diesel	barrel***	0.20	0.14	1.00	5.7

* GJ/tonne is numerically equivalent to MJ/kg
** The energy content of 1 tce and 1 toe varies. The values used here are the European Community norms: 1 tce = 29.31×10^9 J and 1 toe = 41.868×10^9 J
*** 1 barrel of oil = 42 US gallons = $0.158987 m^3$

Power equivalents

	Mtoe/yr	*Mbd*	*Mtce/yr*	*GW_{th}*	*PJ/yr*
Mtoe/yr	1	0.02	1.55	1.43	45
Mbd	50	1	77	71	2235
Mtce/yr	0.65	0.013	1	0.92	29
GW_{th}	0.70	0.014	1.09	1	32
PJ/yr	0.02	4.5×10^{-4}	0.034	0.031	1

Mtoe/yr = Million tonnes of oil per year
Mbd = Million barrels of oil per day
Mtce/yr = Million tonnes of coal equivalent per year
GW_{th} = Gigawatts thermal (see page 203 for further information)
PJ/yr = Petrajoules per year

VII. Weights and Measures: Conversion Ratios

WEIGHTS AND MEASURES*

Tables of United States Customary Weights and Measures

Linear Measure

12 inches (in.)	= 1 foot (ft.)
3 feet	= 1 yard (yd.)
$5^1/_2$ yards	= 1 rod (rd.), pole, or perch ($16^1/_2$ ft.)
40 rods	= 1 furlong (fur.) = 220 yards = 660 feet
8 furlongs	= 1 statute mile (mi.) = 1760 yards = 5280 feet
3 miles	= 1 league = 5280 yards = 15,840 feet
5280 feet	= 1 statute or land mile
6076.11549 feet	= 1 international nautical mile

Area Measure

Squares and cubes of units are sometimes abbreviated by using "superior" figures. For example, ft^2 means square foot, and ft^3 means cubic foot.

144 square inches	= 1 square foot (sq. ft.)
9 square feet	= 1 square yard (sq. yd.) = 1296 square inches
$30^1/_4$ square yards	= 1 square rod (sq. rd.) = $272^1/_4$ square feet
160 square rods	= 1 acre = 4840 square yards = 43,560 square feet
640 acres	= 1 square mile (sq. mi.)
1 mile square	= 1 section (of land)
6 miles square	= 1 township = 36 sections = 36 square miles

Cubic Measure

1728 cubic inches (cu. in.)	= 1 cubic foot (cu. ft.)
27 cubic feet	= 1 cubic yard (cu. yd.)

Gunter's or Surveyor's Chain Measure

7.92 inches (in.)	= 1 link (li.)
100 links	= 1 chain (ch.) = 4 rods = 66 feet
80 chains	= 1 statute mile (mi.) = 320 rods = 5280 feet

Liquid Measure

When necessary to distinguish the liquid pint or quart from the dry pint or quart, the word "liquid" or the abbreviation "liq" should be used in combination with the name or abbreviation of the liquid unit.

4 gills (gi.)	= 1 pint (pt.) (= 28.875 cubic inches)
2 pints	= 1 quart (qt.) (= 57.75 cubic inches)
4 quarts	= 1 gallon (gal.) (= 231 cubic inches) = 8 pints = 32 gills

* Source: National Bureau of Standards, U.S. Department of Commerce.

Apothecaries' Fluid Measure

60 minims (min.)	= 1 fluid dram (fl. dr.) (= 0.2256 cubic inch)
8 fluid drams	= 1 fluid ounce (fl. oz.) (= 1.8047 cubic inches)
16 fluid ounces	= 1 pint (pt.) (= 28.875 cubic inches) = 128 fluid drams
2 pints	= 1 quart (qt.) (= 57.75 cubic inches) = 32 fluid ounces = 256 fluid drams
4 quarts	= 1 gallon (gal.) (= 231 cubic inches) = 128 fluid ounces = 1024 fluid drams

Dry Measure

When necessary to distinguish the dry pint or quart from the liquid pint or quart, the word "dry" should be used in combination with the name or abbreviation of the dry unit.

2 pints (pt.)	= 1 quart (qt.) (= 67.2006 cubic inches)
8 quarts	= 1 peck (pk.) (= 537.605 cubic inches) = 16 pints
4 pecks	= 1 bushel (bu.) (= 2150.42 cubic inches) = 32 quarts

Avoirdupois Weight

When necessary to distinguish the avoirdupois dram from the apothecaries' dram, or to distinguish the avoirdupois dram or ounce from the fluid dram or ounce, or to distinguish the avoirdupois ounce or pound from the troy or apothecaries' ounce or pound, the word "avoirdupois" or the abbreviation "avdp" should be used in combination with the name or abbreviation of the avoirdupois unit.

(The "grain" is the same in avoirdupois, troy, and apothecaries' weight.)

$27^{11}/_{32}$ grains	= 1 dram (dr.)
16 drams	= 1 ounce (oz.) = $437^1/_2$ grains
16 ounces	= 1 pound (lb.) = 256 drams = 7000 grains
100 pounds	= 1 hundredweight (cwt.)†
20 hundredweights	= 1 ton (tn.) = 2000 pounds†

In "gross" or "long" measure, the following values are recognized:

112 pounds	= 1 gross or long hundredweight†
20 gross or long hundredweights	= 1 gross or long ton = 2240 pounds†

† When the terms "hundredweight" and "ton" are used unmodified, they are commonly understood to mean the 100-pound hundredweight and the 2,000-pound ton, respectively; these units may be designated "net" or "short" when necessary to distinguish them from the corresponding units in gross or long measure.

Troy Weight

24 grains	= 1 pennyweight (dwt.)
20 pennyweights	= 1 ounce troy (oz. t.) = 480 grains
12 ounces troy	= 1 pound troy (lb. t.) = 240 pennyweights = 5760 grains

Apothecaries' Weight

20 grains	= scruple (s. ap.)
3 scruples	= 1 dram apothecaries' (dr. ap.) = 60 grains
8 drams apothecaries'	= 1 ounce apothecaries' (oz. ap.) = 24 scruples = 480 grains
12 ounces apothecaries'	= 1 pound apothecaries' (lb. ap.) = 96 drams apothecaries' = 288 scruples = 5760 grains

Tables of Metric Weights and Measures

Linear Measure

10 millimeters (mm.)	= 1 centimeter (cm.)
10 centimeters	= 1 decimeter (dm.) = 100 millimeters
10 decimeters	= 1 meter (m.) = 1000 millimeters
10 meters	= 1 dekameter (dkm.)
10 dekameters	= 1 hectometer (hm.) = 100 meters
10 hectometers	= 1 kilometer (km.) = 1000 meters

Area Measure

100 square millimeters (mm^2)	= 1 square centimeter (cm^2)
10,000 square centimeters	= 1 square meter (m^2) = 1,000,000 square millimeters
100 square meters	= 1 are (a.)
100 ares	= 1 hectare (ha.) = 10,000 square meters
100 hectares	= 1 square kilometer (km^2) = 1,000,000 square meters

Volume Measure

10 milliliters (ml.)	= 1 centiliter (cl.)
10 centiliters	= 1 deciliter (dl.) = 100 milliliters
10 deciliters	= 1 liter‡ (l.) = 1000 milliliters
10 liters	= 1 dekaliter (dkl.)
10 dekaliters	= 1 hectoliter (hl.) = 100 liters
10 hectoliters	= 1 kiloliter (kl.) = 1000 liters

‡ The liter is defined as the volume occupied, under standard conditions, by a quantity of pure water having a mass of 1 kilogram. This volume is very nearly equal to 1000 cubic centimeters or 1 cubic decimeter; the actual metric equivalent is, 1 liter = 1.000028 cubic decimeters. Thus the milliliter and the liter are larger than the cubic centimeter and the cubic decimeter, respectively, by 28 parts in 1,000,000.

Cubic Measure

1000 cubic millimeters (mm^3)	= 1 cubic centimeter (cm^3)
1000 cubic centimeters	= 1 cubic decimeter (dm^3) = 1,000,000 cubic millimeters
1000 cubic decimeters	= 1 cubic meter (m^3) = 1 stere = 1,000,000 cubic centimeters = 1,000,000,000 cubic millimeters

Weight

10 milligrams (mg.)	= 1 centigram (cg.)
10 centigrams	= 1 decigram (dg.) = 100 milligrams
10 decigrams	= 1 gram (g.) = 1000 milligrams
10 grams	= 1 dekagram (dkg.)
10 dekagrams	= 1 hectogram (hg.) = 100 grams
10 hectograms	= 1 kilogram (kg.) = 1000 grams
1000 kilograms	= 1 metric ton (t.)

Tables of Equivalents

When the name of a unit is enclosed in brackets thus: [1 hand], this indicates (1) that the unit is not in general current use in the United States, or (2) that the unit is believed to be based on "custom and usage" rather than on formal definition.

Equivalents involving decimals are, in most instances, rounded off to the third decimal place except where they are exact, in which cases these exact equivalents are so designated.

Lengths

1 Angstrom (A.)	0.1 millimicron (exactly) 0.0001 micron (exactly) 0.0000001 millimeter (exactly) 0.000000004 inch
1 cable's length	120 fathoms 720 feet 219.456 meters (exactly)
1 centimeter (cm.)	0.3937 inch
1 chain (ch.) (Gunter's or surveyor's)	66 feet 20.1168 meters (exactly)
1 chain (engineer's)	100 feet 30.48 meters (exactly)
1 decimeter (dm.)	3.937 inches
1 dekameter (dkm.)	32,808 feet
1 fathom	6 feet 1.8288 meters (exactly)
1 foot (ft.)	0.3048 meters (exactly)
1 furlong (fur.)	10 chains (surveyor's) 660 feet 220 yards 1/8 statute mile 201.168 meters
[1 hand]	4 inches
1 inch (in.)	2.54 centimeters (exactly)
1 kilometer (km.)	0.621 mile
1 league (land)	3 statute miles 4.828 kilometers
1 link (li.) (Gunter's or surveyor's)	7.92 inches 0.201 meter
1 link (li.) (engineer's)	1 foot 0.305 meter

1 meter (m.)	39.37 inches 1.094 yards
1 micron (μ [the Greek letter mu])	0.001 millimeter (exactly) 0.00003937 inch
1 mil	0.001 inch (exactly) 0.0254 millimeter (exactly)
1 mile (mi.) (statute or land)	5280 feet 1.609 kilometers
1 mile (mi.) (nautical, international, and new U.S. value)	1.852 kilometers (exactly) 1.150779 statute miles 6076.11549 feet
1 millimeter (mm.)	0.03937 inch
1 millimicron (mμ [the English letter *m* in combination with the Greek letter mu])	0.001 micron (exactly) 0.00000003937 inch (exactly)
1 point (typography)	0.013837 inch (exactly) 0.351 millimeter
1 rod (rd.), pole, or perch	$16\frac{1}{2}$ feet $5\frac{1}{2}$ yards 5.029 meters
1 yard (yd.)	0.9144 meter (exactly)

Areas or Surfaces

1 acre	43,560 square feet 4840 square yards 0.405 hectare
1 are (a.)	119.599 square yards 0.025 acre
1 hectare (ha.)	2.471 acres
[1 square (building)]	100 square feet
1 square centimeter (cm^2)	0.155 square inch
1 square decimeter (dm^2)	15.500 square inches
1 square foot (sq. ft.)	929.030 square centimeters
1 square inch (sq. in.)	6.452 square centimeters
1 square kilometer (km^2)	247.105 acres 0.386 square mile
1 square meter (m^2)	1.196 square yards 10.764 square feet
1 square mile (sq. mi.)	258.999 hectares
1 square millimeter (mm^2)	0.002 square inch
1 square rod (sq. rd.), sq. pole, or sq. perch	25.293 square meters
1 square yard (sq. yd.)	0.836 square meter

Capacities or Volumes

1 barrel (bbl.), liquid	31 to 42 gallons*
1 barrel (bbl.), standard, for fruits, vegetables, and other dry commodities except cranberries	7056 cubic inches 105 dry quarts 3.281 bushels, struck measure

* There are a variety of "barrels," established by law or usage. For example, federal taxes on fermented liquors are based on a barrel of 31 gallons; many state laws fix the "barrel for liquids" at $31\frac{1}{2}$ gallons; one state fixes a 36-gallon barrel for cistern measurement; federal law recognizes a 40-gallon barrel for "proof spirits"; by custom, 42 gallons comprise a barrel of crude oil or petroleum products for statistical purposes, and this equivalent is recognized "for liquids" by four states.

1 barrel (bbl.), standard, cranberry	5826 cubic inches $86\,^{45}/_{64}$ dry quarts 2.709 bushels, struck measure
1 bushel (bu.) (U.S.) (struck measure)	2150.42 cubic inches (exactly) 35.238 liters
[1 bushel, heaped (U.S.)]	2747.715 cubic inches 1.278 bushels, struck measure†

† Frequently recognized as $1\,^1/_4$ bushels, struck measure.

[1 bushel (bu.) (British Imperial) (struck measure)]	1.032 U.S. bushels, struck measure 2219.36 cubic inches
1 cord (cd.) (firewood)	128 cubic feet
1 cubic centimeter (cm^3)	0.061 cubic inch
1 cubic decimeter (dm^3)	61.023 cubic inches
1 cubic foot (cu. ft.)	7.481 gallons 28.317 cubic decimeters
1 cubic inch (cu. in.)	0.554 fluid ounce 4.433 fluid drams 16.387 cubic centimeters
1 cubic meter (m^3)	1.308 cubic yards
1 cubic yard (cu. yd.)	0.765 cubic meter
1 cup, measuring	8 fluid ounces $^1/_2$ liquid pint
1 dekaliter (dkl.)	2.642 gallons 1.135 pecks
1 dram, fluid (or liquid) (fl. dr.) (U.S.)	$^1/_8$ fluid ounce 0.226 cubic inch 3.697 milliliters
[1 dram, fluid (fl. dr.) (British)]	0.961 U.S. fluid dram 0.217 cubic inch 3.552 milliliters
1 gallon (gal.) (U.S.)	231 cubic inches 3.785 liters 0.833 British gallon 128 U.S. fluid ounces
[1 gallon (gal.) (British Imperial)]	277.42 cubic inches 1.201 U.S. gallons 4.546 liters 160 British fluid ounces
1 gill (gi.)	7.219 cubic inches 4 fluid ounces 0.118 liter
1 hectoliter (hl.)	26.418 gallons 2.838 bushels
1 liter	1.057 liquid quarts 0.908 dry quart 61.025 cubic inches
1 milliliter (ml.)	0.271 fluid dram 16.231 minims 0.061 cubic inch
1 ounce, fluid (or liquid) (fl. oz.) (U.S.)	1.805 cubic inches 29.573 milliliters 1.041 British fluid ounces

[1 ounce, fluid (fl. oz.) (British)]	0.961 U.S. fluid ounce 1.734 cubic inches 28.412 milliliters
1 peck (pk.)	8.810 liters
1 pint (pt.), dry	33.600 cubic inches 0.551 liter
1 pint (pt.), liquid	28.875 cubic inches (exactly) 0.473 liter
1 quart (qt.), dry (U.S.)	67.201 cubic inches 1.101 liters 0.969 British quart
1 quart (qt.), liquid (U.S.)	57.75 cubic inches (exactly) 0.946 liter 0.833 British quart
[1 quart (qt.) (British)]	69.354 cubic inches 1.032 U.S. dry quarts 1.201 U.S. liquid quarts
1 tablespoon	3 teaspoons‡ 4 fluid drams $^1/_2$ fluid ounce
1 teaspoon	$^1/_3$ tablespoon‡ $1^1/_3$ fluid drams‡

‡ The equivalent "1 teaspoon = $1^1/_3$ fluid drams" has been found by the Bureau to correspond more closely with the actual capacities of "measuring" and silver teaspoons than the equivalent "1 teaspoon = 1 fluid dram" which is given by a number of dictionaries.

Weights or Masses

1 assay ton* (AT)	29.167 grams

* Used in assaying. The assay ton bears the same relation to the milligram that a ton of 2000 pounds avoirdupois bears to the ounce troy; hence the weight in milligrams of precious metal obtained from one assay ton of ore gives directly the number of troy ounces to the net ton.

1 carat (c.)	200 milligrams 3.086 grains
1 dram, apothecaries' (dr. ap.)	60 grains 3.888 grams
1 dram, avoirdupois (dr. avdp.)	$27^{11}/_{32}$ (= 27.344) grains 1.772 grams
gamma, *see* microgram	
1 grain	64.799 milligrams
1 gram (g.)	15.432 grains 0.035 ounce, avoirdupois
1 hundredweight, gross or long† (gross cwt.)	112 pounds 50.802 kilograms

† The gross or long ton and hundredweight are used commercially in the United States to only a limited extent, usually in restricted industrial fields. These units are the same as the British "ton" and "hundredweight."

1 hundredweight, net or short (cwt. or net cwt.)	100 pounds 45.359 kilograms
1 kilogram (kg.)	2.205 pounds
1 microgram (γ [the Greek letter gamma])	0.000001 gram (exactly)
1 milligram (mg.)	0.015 grain
1 ounce, avoirdupois (oz. avdp.)	437.5 grains (exactly) 0.911 troy or apothecaries' ounce 28.350 grams
1 ounce, troy or apothecaries' (oz. t. or oz. ap.)	480 grains 1.097 avoirdupois ounces 31.103 grams
1 pennyweight (dwt.)	1.555 grams
1 pound, avoirdupois (lb. avdp.)	7000 grains 1.215 troy or apothecaries' pounds 453.59237 grams (exactly)
1 pound, troy or apothecaries' (lb. t. or lb. ap.)	5760 grains 0.823 avoirdupois pound 373.242 grams
1 scruple (s. ap.)	20 grains 1.296 grams
1 ton, gross or long† (gross tn.)	2240 pounds 1.12 net tons (exactly) 1.016 metric tons
1 ton, metric (t.)	2204.623 pounds 0.984 gross ton 1.102 net tons
1 ton, net or short (tn. or net tn.)	2000 pounds 0.893 gross ton 0.907 metric ton

Tables of Interrelation of Units of Measurement

Bold face type indicates exact values

Units of Length

Units	Inches	Links	Feet	Yards	Rods	Chains	Miles	Cm.	Meters
1 inch =	**1**	0.126 333	0.083 333	0.027 778	0.005 051	0.001 263	0.000 016	**2.54**	**0.025 4**
1 link =	**7.92**	**1**	**0.66**	**0.22**	**0.04**	**0.01**	**0.000 125**	20.117	**0.201 168**
1 foot =	**12**	1.515 152	**1**	0.333 333	0.060 606	0.015 152	0.000 189	**30.48**	**0.304 8**
1 yard =	**36**	4.545 45	**3**	**1**	0.181 818	0.045 455	0.000 568	**91.44**	**0.914 4**
1 rod =	**198**	**25**	**16.5**	**5.5**	**1**	**0.25**	**0.003 125**	**502.92**	**5.029 2**
1 chain =	**792**	**100**	**66**	**22**	**4**	**1**	**0.012 5**	**2011.68**	**20.116 8**
1 mile =	**63 360**	**8000**	**5280**	**1760**	**320**	**80**	**1**	**160 934.4**	**1609.344**
1 cm. =	0.3937	0.049 710	0.032 808	0.010 936	0.001 988	0.000 497	0.000 006	**1**	**0.01**
1 meter =	39.37	4.970 970	3.280 840	1.093 613	0.198 839	0.049 710	0.000 621	**100**	**1**

Units of Area

Units		Square inches	Square links	Square feet	Square yards	Square rods	Square chains
1 sq. inch	=	**1**	.015 942 3	0.006 944	0.000 771 605	0.000 025 5	0.000 001 594
1 sq. link	=	**62.726 4**	**1**	**0.435 6**	**0.0484**	**0.0016**	**0.000 1**
1 sq. foot	=	**144**	2.295 684	**1**	0.111 111 1	0.003 673 09	0.000 229 568
1 sq. yard	=	**1296**	20.661 16	**9**	**1**	0.033 057 85	0.002 066 12
1 sq. rod	=	**39 204**	**625**	**272.25**	**30.25**	**1**	**0.062 5**
1 sq. chain	=	**627 264**	**10 000**	**4356**	**484**	**16**	**1**
1 acre	=	**6 272 640**	**100 000**	**43 560**	**4840**	**160**	**10**
1 sq. mile	=	**4 014 489 600**	**64 000 000**	**27 878 400**	**3 097 600**	**102 400**	**6400**
1 sq. cm.	=	0.155 000 3	0.002 471 05	0.001 076	0.000 119 599	0.000 003 954	0.000 000 247
1 sq. meter	=	1550.003	24.710 54	10.763 91	1.195 990	0.039 536 86	0.002 471 054
1 hectare	=	15 500 031	247 105	107 639.1	11 959.90	395.368 6	24.710 54

Units		Acres	Square miles	Square centimeters	Square meters	Hectares
1 sq. inch	=	0.000 000 159 423	0.000 000 000 249 10	**6.451 6**	**0.000 645 16**	0.000 000 065
1 sq. link	=	**0.000 01**	**0.000 000 015 625**	**404.685 642 24**	0.040 468 56	0.000 004 047
1 sq. foot	=	0.000 022 956 84	0.000 000 035 870 06	**929.030 4**	**0.092 903 04**	0.000 009 290
1 sq. yard	=	0.000 206 611 6	0.000 000 322 830 6	**8 361.273 6**	**0.836 127 36**	0.000 083 613
1 sq. rod	=	**0.006 25**	**0.000 009 765 625**	**252 928.526 4**	**25.292 852 64**	0.002 529 285
1 sq. chain	=	**0.1**	**0.000 156 25**	4 046 856	**404.685 642 24**	0.040 468 564
1 acre	=	**1**	**0.001 562 5**	40 468 654	**4046.856 422 4**	0.404 685 642
1 sq. mile	=	**640**	**1**	25 899 881 103	2 589 988.11	258.998 811 034
1 sq. cm.	=	0.000 000 024 711	0.000 000 000 038 610	**1**	**0.0001**	**0.000 000 01**
1 sq. meter	=	0.000 247 105 4	0.000 000 386 102 2	**10 000**	**1**	**0.0001**
1 hectare	=	2.471 054	0.003 861 022	**100 000 000**	**10 000**	**1**

Units of Volume

Units		Cubic inches	Cubic feet	Cubic yards	Cubic centimeters	Cubic decimeters	Cubic meters
1 cubic inch	=	**1**	0.000 578 704	0.000 021 433	**16.387 064**	0.016 387	0.000 016 387
1 cubic foot	=	**1728**	**1**	0.037 037 04	**28 316.846 592**	28.316 847	0.028 316 847
1 cubic yard	=	**46 656**	**27**	**1**	**764 554.857 984**	764.554 858	0.764 554 858
1 cubic cm.	=	0.061 023 74	0.000 035 315	0.000 001 308	**1**	**0.001**	**0.000 001**
1 cubic dm.	=	61.023 74	0.035 314 67	0.001 307 951	**1000**	**1**	**0.001**
1 cubic meter	=	61 023.74	35.314 67	1.307 951	**1 000 000**	**1000**	**1**

Units of Capacity (Liquid Measure)

Units		Minims	Fluid drams	Fluid ounces	Gills	Liquid pints
1 minim	=	**1**	0.016 666 7	0.002 083 33	0.000 520 833	0.000 130 208
1 fluid dram	=	**60**	**1**	**0.125**	**0.031 25**	**0.007 812 5**
1 fluid ounce	=	**480**	**8**	**1**	**0.25**	**0.062 5**
1 gill	=	**1920**	**32**	**4**	**1**	**0.25**
1 liquid pint	=	**7680**	**128**	**16**	**4**	**1**
1 liquid quart	=	**15 360**	**256**	**32**	**8**	**2**
1 gallon	=	**61 440**	**1024**	**128**	**32**	**8**
1 milliliter	=	16.231	0.270 519 8	0.033 814 97	0.008 453 742	0.002 113 436
1 liter	=	16 231.19	270.519 8	33.814 97	8.453 742	2.113 436
1 cubic inch	=	265.974	4.432 900	0.554 112 6	0.138 528 1	0.034 632 03
1 cubic foot	=	459 603.1	7660.052	957.506 5	239.376 6	59.844 16

Units of Capacity (Liquid Measure) Continued. Bold face type indicates exact values

Units		Liquid quarts	Gallons	Milliliters	Liters	Cubic inches	Cubic feet
1 minim	=	0.000 065 104	0.000 016 276	0.061 610	0.000 061 610	0.003 760	0.000 002 176
1 fluid dram	=	**0.003 906 25**	0.000 976 562	3.696 588	0.003 696 588	0.225 586	0.000 130 547
1 fluid ounce	=	**0.031 25**	**0.007 812 5**	29.572 70	0.029 572 7	1.804 687	0.001 044 379
1 gill	=	**0.125**	**0.031 25**	118.290 8	0.118 290 8	**7.218 75**	0.004 177 517
1 liquid pint	=	**0.5**	**0.125**	473.163 2	0.473 163 2	**28.875**	0.016 710 07
1 liquid quart	=	**1**	**0.25**	946.326 4	0.946 326 4	**57.75**	0.033 420 14
1 gallon	=	**4**	**1**	3785.306	3.785 306	**231**	0.133 680 6
1 milliliter	=	0.001 056 718	0.000 264 179	**1**	**0.001**	0.061 025	0.000 035 316
1 liter	=	1.056 718	0.264 179 4	**1000**	**1**	61.025 45	0.035 315 66
1 cubic inch	=	0.017 316 02	0.004 329 004	16.386 61	0.016 386 61	**1**	0.000 578 704
1 cubic foot	=	29.922 08	7.480 519	28 316.05	28.316 05	**1728**	**1**

Units of Capacity (Dry Measure)

Units		Dry pints	Dry quarts	Pecks	Bushels	Liters	Dekaliters	Cubic inches
1 dry pint	=	**1**	**0.5**	**0.062 5**	**0.015 625**	0.550 595	0.055 060	**33.600 312 5**
1 dry quart	=	**2**	**1**	**0.125**	**0.031 25**	1.101 190	0.110 119	**67.200 625**
1 peck	=	**16**	**8**	**1**	**0.25**	8.809 521	0.880 952	**537.605**
1 bushel	=	**64**	**32**	**4**	**1**	35.238 08	3.523 808	**2150.42**
1 liter	=	1.816 217	0.908 108	0.113 514	0.028 378	**1**	**0.1**	61.025 45
1 dekaliter	=	18.162 17	9.081 084	1.135 136	0.283 784	**10**	**1**	610.254 5
1 cubic inch	=	0.029 762	0.014 881	0.001 860	0.000 465	0.016 386	0.001 639	**1**

Units of Mass not Greater than Pounds and Kilograms

Units		Grains	Apothecaries' scruples	Pennyweights	Avoirdupois drams	Apothecaries' drams	Avoirdupois ounces
1 grain	=	1	0.05	0.041 666 67	0.036 571 43	0.016 666 67	0.002 285 71
1 scruple	=	20	1	0.833 333 3	0.731 428 6	0.333 333 3	0.045 714 29
1 pennyweight	=	24	1.2	1	0.877 714 3	0.4	0.054 857 14
1 dram avdp.	=	27.343 75	1.367 187 5	1.139 323	1	0.455 729 2	0.062 5
1 dram ap.	=	60	3	2.5	2.194 286	1	0.137 142 9
1 oz. avdp.	=	437.5	21.875	18.229 17	16	7.291 667	1
1 oz. ap. or t.	=	480	24	20	17.554 29	8	1.097 143
1 lb. ap. or t.	=	5760	288	240	210.651 4	96	13.165 71
1 lb. avdp.	=	7000	350	291.666 7	256	116.666 7	16
1 milligram	=	0.015 432	0.000 771 618	0.000 643 015	0.000 564 383	0.000 257 206	0.000 035 274
1 gram	=	15.432 36	0.771 617 9	0.643 014 9	0.564 383 4	0.257 206 0	0.035 273 96
1 kilogram	=	15 432.36	771.617 9	643.014 9	564.383 4	257.206 0	35.273 96

Units		Apothecaries' or troy ounces	Apothecaries' or troy pounds	Avoirdupois pounds	Milligrams	Grams	Kilograms
1 grain	=	0.002 083 33	0.000 173 611	0.000 142 857	64.798 91	0.064 798 91	0.000 064 799
1 scruple	=	0.041 666 67	0.003 472 222	0.002 857 143	1295.978 2	1.295 978 2	0.001 295 978
1 pennyweight	=	0.05	0.004 166 667	0.003 428 571	1555.173 84	1.555 173 84	0.001 555 174
1 dram avdp.	=	0.056 966 15	0.004 747 179	0.003 906 25	1771.845 195	1.771 845 195	0.001 771 845
1 dram ap.	=	0.125	0.010 416 67	0.008 571 429	3887.934 6	3.887 934 6	0.003 887 935
1 oz. avdp.	=	0.911 458 3	0.075 954 86	0.062 5	28 349.523 125	28.349 523 125	0.028 349 52
1 oz. ap. or t.	=	1	0.083 333 333	0.068 571 43	31 103.476 8	31.103 476 8	0.031 103 47
1 lb. ap. or t.	=	12	1	0.822 857 1	373 241.721 6	373.241 721 6	0.373 241 722
1 lb. avdp.	=	14.583 33	1.215 278	1	453 592.37	453.592 37	0.453 592 37
1 milligram	=	0.000 032 151	0.000 002 679	0.000 002 205	1	0.001	0.000 001
1 gram	=	0.032 150 75	0.002 679 229	0.002 204 623	1000	1	0.001
1 kilogram	=	32.150 75	2.679 229	2.204 623	1 000 000	1000	1

Units of Mass not Less than Avoirdupois Ounces

Units		Avoirdupois ounces	Avoirdupois pounds	Short hundredweights	Short tons	Long tons	Kilograms	Metric tons
1 oz. avdp.	=	**1**	**0.0625**	**0.000 625**	**0.000 031 25**	0.000 027 902	0.028 349 523	0.000 028 350
1 lb. avdp.	=	**16**	**1**	**0.01**	**0.0005**	0.000 446 429	**0.453 592 37**	0.000 453 592
1 short cwt.	=	**1600**	**100**	**1**	**0.05**	0.044 642 86	**45.359 237**	**0.045 359 237**
1 short ton	=	**32 000**	**2000**	**20**	**1**	0.892 857 1	**907.184 74**	**0.907 184 74**
1 long ton	=	**35 840**	**2240**	**22.4**	**1.12**	**1**	**1016.046 908 8**	1.016 046 909
1 kilogram	=	35.273 96	2.204 623	0.022 046 23	0.001 102 311	0.000 094 207	**1**	**0.001**
1 metric ton	=	35 273.96	2204.623	22.046 23	1.102 311	0.984 206 5	**1000**	**1**

VIII. Decimal Equivalents of Common Fractions

8ths	16ths	32ds	64ths		8ths	16ths	32ds	64ths	
			1	.015625				33	.515625
		1	2	.03125			17	34	.53125
			3	.046875				35	.546875
	1	2	4	.0625		9	18	36	.5625
			5	.078125				37	.578125
		3	6	.09375			19	38	.59375
			7	.109375				39	.609375
1	2	4	8	.125	5	10	20	40	.625
			9	.140625				41	.640625
		5	10	.15625			21	42	.65625
			11	.171875				43	.671875
	3	6	12	.1875		11	22	44	.6875
			13	.203125				45	.703125
		7	14	.21875			23	46	.71875
			15	.234375				47	.734375
2	4	8	16	.25	6	12	24	48	.75
			17	.265625				49	.765625
		9	18	.28125			25	50	.78125
			19	.296875				51	.796875
	5	10	20	.3125		13	26	52	.8125
			21	.328125				53	.828125
		11	22	.34375			27	54	.84375
			23	.359375				55	.859375
3	6	12	24	.375	7	14	28	56	.875
			25	.390625				57	.890625
		13	26	.40625			29	58	.90625
			27	.421875				59	.921875
	7	14	28	.4375		15	30	60	.9375
			29	.453125				61	.953125
		15	30	.46875			31	62	.96875
			31	.484375				63	.984375
4	8	16	32	.5	8	16	32	64	1

Conversions: length

Use of the tables: the number to be converted, which is made up by adding the unit at the side of a line to the unit at the head of a column, is converted to the number in the position where line and column meet. For example, 11 in = 10 in + 1 in = 27.940 cm

Inches to Centimetres   1 in = 2.54 cm

in → ↓	0	1	2	3	4	5	6	7	8	9	← in ↓
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	
0	0.000	2.540	5.080	7.620	10.160	12.700	15.240	17.780	20.320	22.860	0
10	25.400	27.940	30.480	33.020	35.560	38.100	40.640	43.180	45.720	48.260	10
20	50.800	53.340	55.880	58.420	60.960	63.500	66.040	68.580	71.120	73.660	20
30	76.200	78.740	81.280	83.820	86.360	88.900	91.440	93.980	96.520	99.060	30
40	101.600	104.140	106.680	109.220	111.760	114.300	116.840	119.380	121.920	124.460	40
50	127.000	129.540	132.080	134.620	137.160	139.700	142.240	144.780	147.320	149.860	50
60	152.400	154.940	157.480	160.020	162.560	165.100	167.640	170.180	172.720	175.260	60
70	177.800	180.340	182.880	185.420	187.960	190.500	193.040	195.580	198.120	200.660	70
80	203.200	205.740	208.280	210.820	213.360	215.900	218.440	220.980	223.520	226.060	80
90	228.600	231.140	233.680	236.220	238.760	241.300	243.840	246.380	248.920	251.460	90
100	254.000										100

in → ↓	0	10	20	30	40	50	60	70	80	90	← in ↓
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	0
100	254.000	279.400	304.800	330.200	355.600	381.000	406.400	431.800	457.200	482.600	100
200	508.000	533.400	558.800	584.200	609.600	635.000	660.400	685.800	711.200	736.600	200
300	762.000	787.400	812.800	838.200	863.600	889.000	914.400	939.800	965.200	990.600	300
400	1016.000	1041.400	1066.800	1092.200	1117.600	1143.000	1168.400	1193.800	1219.200	1244.600	400
500	1270.000	1295.400	1320.800	1346.200	1371.600	1397.000	1422.400	1447.800	1473.200	1498.600	500
600	1524.000	1549.400	1574.800	1600.200	1625.600	1651.000	1676.400	1701.800	1727.200	1752.600	600
700	1778.000	1803.400	1828.800	1854.200	1879.600	1905.000	1930.400	195[illegible].800	1981.200	2006.600	700
800	2032.000	2057.400	2082.800	2108.200	2133.600	2159.000	2184.400	2209.800	2235.200	2260.600	800
900	2286.000	2311.400	2336.800	2362.200	2387.600	2413.000	2438.400	2463.800	2489.200	2514.600	900
1000	2540.000										1000

Centimetres to Inches   1 cm = 0.393 701 in

cm → ↓	0	1	2	3	4	5	6	7	8	9	← cm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.394	0.787	1.181	1.575	1.969	2.362	2.756	3.150	3.543	0
10	3.937	4.331	4.724	5.118	5.512	5.906	6.299	6.693	7.087	7.480	10
20	7.874	8.268	8.661	9.055	9.449	9.843	10.236	10.630	11.024	11.417	20
30	11.811	12.205	12.598	12.992	13.386	13.780	14.173	14.567	14.961	15.354	30
40	15.748	16.142	16.535	16.929	17.323	17.717	18.110	18.504	18.898	19.291	40
50	19.685	20.079	20.472	20.866	21.260	21.654	22.047	22.441	22.835	23.228	50
60	23.622	24.016	24.409	24.803	25.197	25.591	25.984	26.378	26.772	27.165	60
70	27.559	27.953	28.346	28.740	29.134	29.528	29.921	30.315	30.709	31.102	70
80	31.496	31.890	32.283	32.677	33.071	33.465	33.858	34.252	34.646	35.039	80
90	35.433	35.827	36.220	36.614	37.008	37.402	37.795	38.189	38.583	38.976	90
100	39.370										100

cm → ↓	0	10	20	30	40	50	60	70	80	90	← cm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	3.937	7.874	11.811	15.748	19.685	23.622	27.559	31.496	35.433	0
100	39.370	43.307	47.244	51.181	55.118	59.055	62.992	66.929	70.866	74.803	100
200	78.740	82.677	86.614	90.551	94.488	98.425	102.362	106.299	110.236	114.173	200
300	118.110	122.047	125.984	129.921	133.858	137.795	141.732	145.669	149.606	153.543	300
400	157.480	161.417	165.354	169.291	173.228	177.165	181.102	185.039	188.976	192.913	400
500	196.850	200.787	204.724	208.661	212.598	216.535	220.472	224.409	228.346	232.283	500
600	236.220	240.157	244.094	248.031	251.969	255.906	259.843	263.780	267.717	271.654	600
700	275.591	279.528	283.465	287.402	291.339	295.276	299.213	303.150	307.087	311.024	700
800	314.961	318.898	322.835	326.772	330.709	334.646	338.583	342.520	346.457	350.394	800
900	354.331	358.268	362.205	366.142	370.079	374.016	377.953	381.890	385.827	389.764	900
1000	393.701										1000

Use of the tables: the number to be converted, which is made up by adding the unit at the side of a line to the unit at the head of a column, is converted to the number in the position where line and column meet.
For example, 11 in = 10 in + 1 in = 279.400 mm

Inches to Millimetres 1 in = 25.4 mm

Note. This table can also be used for converting milli-inches (mils or 'thou') to micrometres ('microns')

in → ↓	0	1	2	3	4	5	6	7	8	9	← in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	0
10	254.000	279.400	304.800	330.200	355.600	381.000	406.400	431.800	457.200	482.600	10
20	508.000	533.400	558.800	584.200	609.600	635.000	660.400	685.800	711.200	736.600	20
30	762.000	787.400	812.800	838.200	863.600	889.000	914.400	939.800	965.200	990.600	30
40	1016.000	1041.400	1066.800	1092.200	1117.600	1143.000	1168.400	1193.800	1219.200	1244.600	40
50	1270.000	1295.400	1320.800	1346.200	1371.600	1397.000	1422.400	1447.800	1473.200	1498.600	50
60	1524.000	1549.400	1574.800	1600.200	1625.600	1651.000	1676.400	1701.800	1727.200	1752.600	60
70	1778.000	1803.400	1828.800	1854.200	1879.600	1905.000	1930.400	1955.800	1981.200	2006.600	70
80	2032.000	2057.400	2082.800	2108.200	2133.600	2159.000	2184.400	2209.800	2235.200	2260.600	80
90	2286.000	2311.400	2336.800	2362.200	2387.600	2413.000	2438.400	2463.800	2489.200	2514.600	90
100	2540.000										100

in → ↓	0	10	20	30	40	50	60	70	80	90	← in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	254.000	508.000	762.000	1016.000	1270.000	1524.000	1778.000	2032.000	2286.000	0
100	2540.000	2794.000	3048.000	3302.000	3556.000	3810.000	4064.000	4318.000	4572.000	4826.000	100
200	5080.000	5334.000	5588.000	5842.000	6096.000	6350.000	6604.000	6858.000	7112.000	7366.000	200
300	7620.000	7874.000	8128.000	8382.000	8636.000	8890.000	9144.000	9398.000	9652.000	9906.000	300
400	10160.000	10414.000	10668.000	10922.000	11176.000	11430.000	11684.000	11938.000	12192.000	12446.000	400
500	12700.000	12954.000	13208.000	13462.000	13716.000	13970.000	14224.000	14478.000	14732.000	14986.000	500
600	15240.000	15494.000	15748.000	16002.000	16256.000	16510.000	16764.000	17018.000	17272.000	17526.000	600
700	17780.000	18034.000	18288.000	18542.000	18796.000	19050.000	19304.000	19558.000	19812.000	20066.000	700
800	20320.000	20574.000	20828.000	21082.000	21336.000	21590.000	21844.000	22098.000	22352.000	22606.000	800
900	22860.000	23114.000	23368.000	23622.000	23876.000	24130.000	24384.000	24638.000	24892.000	25146.000	900
1000	25400.000										1000

Millimetres to Inches 1 mm = 0.039 370 in

Note. This table can also be used for converting micrometres ('microns') to milli-inches (mils or 'thou')

mm → ↓	0	1	2	3	4	5	6	7	8	9	← mm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.039	0.079	0.118	0.157	0.197	0.236	0.276	0.315	0.354	0
10	0.394	0.433	0.472	0.512	0.551	0.591	0.630	0.669	0.709	0.748	10
20	0.787	0.827	0.866	0.906	0.945	0.984	1.024	1.063	1.102	1.142	20
30	1.181	1.220	1.260	1.299	1.339	1.378	1.417	1.457	1.496	1.535	30
40	1.575	1.614	1.654	1.693	1.732	1.772	1.811	1.850	1.890	1.929	40
50	1.969	2.008	2.047	2.087	2.126	2.165	2.205	2.244	2.283	2.323	50
60	2.362	2.402	2.441	2.480	2.520	2.559	2.598	2.638	2.677	2.717	60
70	2.756	2.795	2.835	2.874	2.913	2.953	2.992	3.031	3.071	3.110	70
80	3.150	3.189	3.228	3.268	3.307	3.346	3.386	3.425	3.465	3.504	80
90	3.543	3.583	3.622	3.661	3.701	3.740	3.780	3.819	3.858	3.898	90
100	3.937										100

mm → ↓	0	10	20	30	40	50	60	70	80	90	← mm ↓
	in	in	in	in	in	in	in	in	in	in	
0	0.000	0.394	0.787	1.181	1.575	1.969	2.362	2.756	3.150	3.543	0
100	3.937	4.331	4.724	5.118	5.512	5.906	6.299	6.693	7.087	7.480	100
200	7.874	8.268	8.661	9.055	9.449	9.843	10.236	10.630	11.024	11.417	200
300	11.811	12.205	12.598	12.992	13.386	13.780	14.173	14.567	14.961	15.354	300
400	15.748	16.142	16.535	16.929	17.323	17.717	18.110	18.504	18.898	19.291	400
500	19.685	20.079	20.472	20.866	21.260	21.654	22.047	22.441	22.835	23 228	500
600	23.622	24.016	24.409	24.803	25.197	25.591	25.984	26.378	26.772	27.165	600
700	27.559	27.953	28.346	28.740	29.134	29.528	29.921	30.315	30.709	31.102	700
800	31.496	31.890	32.283	32.677	33.071	33.465	33.858	34.252	34.646	35.039	800
900	35.433	35.827	36.220	36.614	37.008	37.402	37.795	38.189	38.583	38.976	900
1000	39.370										1000

Conversions: length

Use of the table: the number of inches to be converted, which is made up by the number of inches at the head of a column and the fraction at the side of a line, is converted to the number in the position where line and column meet.
For example, 1 1/64 in = 1 in + 1/64 in = 25.797 mm

Inches and fractions of an inch to Millimetres   1 in = 25.4 mm

in → ↓	0	1	2	3	4	5	6	7	8	9	10	11	← in ↓
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
0	0.000	25.400	50.800	76.200	101.600	127.000	152.400	177.800	203.200	228.600	254.000	279.400	0
1/64	0.397	25.797	51.197	76.597	101.997	127.397	152.797	178.197	203.597	228.997	254.397	279.797	1/64
1/32	0.794	26.194	51.594	76.994	102.394	127.794	153.194	178.594	203.994	229.394	254.794	280.194	1/32
3/64	1.191	26.591	51.991	77.391	102.791	128.191	153.591	178.991	204.391	229.791	255.191	280.591	3/64
1/16	1.588	26.988	52.388	77.788	103.188	128.588	153.988	179.388	204.788	230.188	255.588	280.988	1/16
5/64	1.984	27.384	52.784	78.184	103.584	128.984	154.384	179.784	205.184	230.584	255.984	281.384	5/64
3/32	2.381	27.781	53.181	78.581	103.981	129.381	154.781	180.181	205.581	230.981	256.381	281.781	3/32
7/64	2.778	28.178	53.578	78.978	104.378	129.778	155.178	180.578	205.978	231.378	256.778	282.178	7/64
1/8	3.175	28.575	53.975	79.375	104.775	130.175	155.575	180.975	206.375	231.775	257.175	282.575	1/8
9/64	3.572	28.972	54.372	79.772	105.172	130.572	155.972	181.372	206.772	232.172	257.572	282.972	9/64
5/32	3.969	29.369	54.769	80.169	105.569	130.969	156.369	181.769	207.169	232.569	257.969	283.369	5/32
11/64	4.366	29.766	55.166	80.566	105.966	131.366	156.766	182.166	207.566	232.966	258.366	283.766	11/64
3/16	4.762	30.162	55.562	80.962	106.362	131.762	157.162	182.562	207.962	233.362	258.762	284.162	3/16
13/64	5.159	30.559	55.959	81.359	106.759	132.159	157.559	182.959	208.359	233.759	259.159	284.559	13/64
7/32	5.556	30.956	56.356	81.756	107.156	132.556	157.956	183.356	208.756	234.156	259.556	284.956	7/32
15/64	5.953	31.353	56.753	82.153	107.553	132.953	158.353	183.753	209.153	234.553	259.953	285.353	15/64
1/4	6.350	31.750	57.150	82.550	107.950	133.350	158.750	184.150	209.550	234.950	260.350	285.750	1/4
17/64	6.747	32.147	57.547	82.947	108.347	133.747	159.147	184.547	209.947	235.347	260.747	286.147	17/64
9/32	7.144	32.544	57.944	83.344	108.744	134.144	159.544	184.944	210.344	235.744	261.144	286.544	9/32
19/64	7.541	32.941	58.341	83.741	109.141	134.541	159.941	185.341	210.741	236.141	261.541	286.941	19/64
5/16	7.938	33.338	58.738	84.138	109.538	134.938	160.338	185.738	211.138	236.538	261.938	287.338	5/16
21/64	8.334	33.734	59.134	84.534	109.934	135.334	160.734	186.134	211.534	236.934	262.334	287.734	21/64
11/32	8.731	34.131	59.531	84.931	110.331	135.731	161.131	186.531	211.931	237.331	262.731	288.131	11/32
23/64	9.128	34.528	59.928	85.328	110.728	136.128	161.528	186.928	212.328	237.728	263.128	288.528	23/64
3/8	9.525	34.925	60.325	85.725	111.125	136.525	161.925	187.325	212.725	238.125	263.525	288.925	3/8
25/64	9.922	35.322	60.722	86.122	111.522	136.922	162.322	187.722	213.122	238.522	263.922	289.322	25/64
13/32	10.319	35.719	61.119	86.519	111.919	137.319	162.719	188.119	213.519	238.919	264.319	289.719	13/32
27/64	10.716	36.116	61.516	86.916	112.316	137.716	163.116	188.516	213.916	239.316	264.716	290.116	27/64
7/16	11.112	36.512	61.912	87.312	112.712	138.112	163.512	188.912	214.312	239.712	265.112	290.512	7/16
29/64	11.509	36.909	62.309	87.709	113.109	138.509	163.909	189.309	214.709	240.109	265.509	290.909	29/64
15/32	11.906	37.306	62.706	88.106	113.506	138.906	164.306	189.706	215.106	240.506	265.906	291.306	15/32
31/64	12.303	37.703	63.103	88.503	113.903	139.303	164.703	190.103	215.503	240.903	266.303	291.703	31/64
1/2	12.700	38.100	63.500	88.900	114.300	139.700	165.100	190.500	215.900	241.300	266.700	292.100	1/2
33/64	13.097	38.497	63.897	89.297	114.697	140.097	165.497	190.897	216.297	241.697	267.097	292.497	33/64
17/32	13.494	38.894	64.294	89.694	115.094	140.494	165.894	191.294	216.694	242.094	267.494	292.894	17/32
35/64	13.891	39.291	64.691	90.091	115.491	140.891	166.291	191.691	217.091	242.491	267.891	293.291	35/64
9/16	14.288	39.688	65.088	90.488	115.888	141.288	166.688	192.088	217.488	242.888	268.288	293.688	9/16
37/64	14.684	40.084	65.484	90.884	116.284	141.684	167.084	192.484	217.884	243.284	268.684	294.084	37/64
19/32	15.081	40.481	65.881	91.281	116.681	142.081	167.481	192.881	218.281	243.681	269.081	294.481	19/32
39/64	15.478	40.878	66.278	91.678	117.078	142.478	167.878	193.278	218.678	244.078	269.478	294.878	39/64
5/8	15.875	41.275	66.675	92.075	117.475	142.875	168.275	193.675	219.075	244.475	269.875	295.275	5/8
41/64	16.272	41.672	67.072	92.472	117.872	143.272	168.672	194.072	219.472	244.872	270.272	295.672	41/64
21/32	16.669	42.069	67.469	92.869	118.269	143.669	169.069	194.469	219.869	245.269	270.669	296.069	21/32
43/64	17.066	42.466	67.866	93.266	118.666	144.066	169.466	194.866	220.266	245.666	271.066	296.466	43/64
11/16	17.462	42.862	68.262	93.662	119.062	144.462	169.862	195.262	220.662	246.062	271.462	296.862	11/16
45/64	17.859	43.259	68.659	94.059	119.459	144.859	170.259	195.659	221.059	246.459	271.859	297.259	45/64
23/32	18.256	43.656	69.056	94.456	119.856	145.256	170.656	196.056	221.456	246.856	272.256	297.656	23/32
47/64	18.653	44.053	69.453	94.853	120.253	145.653	171.053	196.453	221.853	247.253	272.653	298.053	47/64
3/4	19.050	44.450	69.850	95.250	120.650	146.050	171.450	196.850	222.250	247.650	273.050	298.450	3/4
49/64	19.447	44.847	70.247	95.647	121.047	146.447	171.847	197.247	222.647	248.047	273.447	298.847	49/64
25/32	19.844	45.244	70.644	96.044	121.444	146.844	172.244	197.644	223.044	248.444	273.844	299.244	25/32
51/64	20.241	45.641	71.041	96.441	121.841	147.241	172.641	198.041	223.441	248.841	274.241	299.641	51/64
13/16	20.638	46.038	71.438	96.838	122.238	147.638	173.038	198.438	223.838	249.238	274.638	300.038	13/16
53/64	21.034	46.434	71.834	97.234	122.634	148.034	173.434	198.834	224.234	249.634	275.034	300.434	53/64
27/32	21.431	46.831	72.231	97.631	123.031	148.431	173.831	199.231	224.631	250.031	275.431	300.831	27/32
55/64	21.828	47.228	72.628	98.028	123.428	148.828	174.228	199.628	225.028	250.428	275.828	301.228	55/64
7/8	22.225	47.625	73.025	98.425	123.825	149.225	174.625	200.025	225.425	250.825	276.225	301.625	7/8
57/64	22.622	48.022	73.422	98.822	124.222	149.622	175.022	200.422	225.822	251.222	276.622	302.022	57/64
29/32	23.019	48.419	73.819	99.219	124.619	150.019	175.419	200.819	226.219	251.619	277.019	302.419	29/32
59/64	23.416	48.816	74.216	99.616	125.016	150.416	175.816	201.216	226.616	252.016	277.416	302 816	59/64
15/16	23.812	49.212	74.612	100.012	125.412	150.812	176.212	201.612	227.012	252.412	277.812	303.212	15/16
61/64	24.209	49.609	75.009	100.409	125.809	151.209	176.609	202.009	227.409	252.809	278.209	303.609	61/64
31/32	24.606	50.006	75.406	100.806	126.206	151.606	177.006	202.406	227.806	253.206	278.606	304.006	31/32
63/64	25.003	50.403	75.803	101.203	126.603	152.003	177.403	202.803	228.203	253.603	279.003	304.403	63/64

Fractions to Decimals

Fraction	Decimal equivalent	Fraction	Decimal equivalent
1/2	0.5	1/32	0.031 25
1/3	0.333 333	1/33	0.030 303
1/4	0.25	1/34	0.029 412
1/5	0.2	1/35	0.028 571
1/6	0.166 667	1/36	0.027 778
1/7	0.142 857	1/37	0.027 027
1/8	0.125	1/38	0.026 316
1/9	0.111 111	1/39	0.025 641
1/10	0.1	1/40	0.025
1/11	0.090 909	1/41	0.024 390
1/12	0.083 333	1/42	0.023 810
1/13	0.076 923	1/43	0.023 256
1/14	0.071 429	1/44	0.022 727
1/15	0.066 667	1/45	0.022 222
1/16	0.062 5	1/46	0.021 739
1/17	0.058 824	1/47	0.021 277
1/18	0.055 556	1/48	0.020 833
1/19	0.052 632	1/49	0.020 408
1/20	0.05	1/50	0.02
1/21	0.047 619	1/51	0.019 608
1/22	0.045 455	1/52	0.019 231
1/23	0.043 478	1/53	0.018 868
1/24	0.041 667	1/54	0.018 519
1/25	0.04	1/55	0.018 182
1/26	0.038 462	1/56	0.017 857
1/27	0.037 037	1/57	0.017 544
1/28	0.035 714	1/58	0.017 241
1/29	0.034 483	1/59	0.016 949
1/30	0.033 333	1/60	0.016 667
1/31	0.032 258		

Note. For the decimal equivalent of other fractions with 1 as numerator, and a number from 0.01 to 100.9 as denominator, see reciprocals, pages 144–147.

Fractions 3rds	6ths	12ths	24ths	Decimal equivalent
			1	0.041 667
		1	2	0.083 333
			3	0.125
	1	2	4	0.166 667
			5	0.208 333
		3	6	0.25
			7	0.291 667
1	2	4	8	0.333 333
			9	0.375
		5	10	0.416 667
			11	0.458 333
	3	6	12	0.5
			13	0.541 667
		7	14	0.583 333
			15	0.625
2	4	8	16	0.666 667
			17	0.708 333
		9	18	0.75
			19	0.791 667
	5	10	20	0.833 333
			21	0.875
		11	22	0.916 667
			23	0.958 333
3	6	12	24	1

Fractions 1/2's	1/4's	8ths	16ths	32nds	64ths	Decimal equivalent (all figures are exact)
					1	0.015 625
				1	2	0.031 25
					3	0.046 875
			1	2	4	0.062 5
					5	0.078 125
				3	6	0.093 75
					7	0.109 375
		1	2	4	8	0.125
					9	0.140 625
				5	10	0.156 25
					11	0.171 875
			3	6	12	0.187 5
					13	0.203 125
				7	14	0.218 75
					15	0.234 375
	1	2	4	8	16	0.25
					17	0.265 625
				9	18	0.281 25
					19	0.296 875
			5	10	20	0.312 5
					21	0.328 125
				11	22	0.343 75
					23	0.359 375
		3	6	12	24	0.375
					25	0.390 625
				13	26	0.406 25
					27	0.421 875
			7	14	28	0.437 5
					29	0.453 125
				15	30	0.468 75
					31	0.484 375
1	2	4	8	16	32	0.5
					33	0.515 625
				17	34	0.531 25
					35	0.546 875
			9	18	36	0.562 5
					37	0.578 125
				19	38	0.593 75
					39	0.609 375
		5	10	20	40	0.625
					41	0.640 625
				21	42	0.656 25
					43	0.671 875
			11	22	44	0.687 5
					45	0.703 125
				23	46	0.718 75
					47	0.734 375
	3	6	12	24	48	0.75
					49	0.765 625
				25	50	0.781 25
					51	0.796 875
			13	26	52	0.812 5
					53	0.828 125
				27	54	0.843 75
					55	0.859 375
		7	14	28	56	0.875
					57	0.890 625
				29	58	0.906 25
					59	0.921 875
			15	30	60	0.937 5
					61	0.953 125
				31	62	0.968 75
					63	0.984 375
2	4	8	16	32	64	1

IX. Greek Alphabet; Roman Numerals

GREEK ALPHABET

Α	α	alpha	Ι	ι	iota	Ρ	ρ	rho
Β	β	beta	Κ	κ	kappa	Σ	σ	sigma
Γ	γ	gamma	Λ	λ	lambda	Τ	τ	tau
Δ	δ	delta	Μ	μ	mu	Υ	υ	upsilon
Ε	ϵ	epsilon	Ν	ν	nu	Φ	ϕ	phi
Ζ	ζ	zeta	Ξ	ξ	xi	Χ	χ	chi
Η	η	eta	Ο	o	omicron	Ψ	ψ	psi
Θ	θ	theta	Π	π	pi	Ω	ω	omega

ROMAN NUMERALS

I	1	XI	11	XXX	30	CD	400
II	2	XII	12	XL	40	D	500
III	3	XIII	13	L	50	DC	600
IV	4	XIV	14	LX	60	DCC	700
V	5	XV	15	LXX	70	DCCC	800
VI	6	XVI	16	LXXX	80	CM	900
VII	7	XVII	17	XC	90	M	1,000
VIII	8	XVIII	18	C	100	MCM	1,900
IX	9	XIX	19	CC	200	MM	2,000
X	10	XX	20	CCC	300	$\overline{\mathrm{V}}$	5,000

A dash line over a numeral multiplies the value by 1,000: thus, $\overline{\mathrm{X}}$ = 10,000; $\overline{\mathrm{L}}$ = 50,000; $\overline{\mathrm{C}}$ = 100,000; $\overline{\mathrm{D}}$ = 500,000; $\overline{\mathrm{M}}$ = 1,000,000; $\overline{\mathrm{CLIX}}$ = 159,000; $\overline{\mathrm{DLIX}}$ = 559,000.

Other general rules for Roman numerals are as follows: (1) Repeating a letter repeats its value: XX = 20; CCC = 300. (2) A letter placed after one of greater value adds thereto: VI = 6; DC = 600. (3) A letter placed before one of greater value subtracts therefrom: IV = 4.

TABLE 2–5

Conversion factors between the British FPSR (foot, pound, second, rankine) system and SI (Système International) units

Quantity	FPSR Units	Multiply by	To obtain SI Units	Multiply by	To obtain FPSR Units
Mass (M)	slug	1.459×10	kg	6.852×10^{-2}	slug
Length (L)	ft	3.048×10^{-1}	m	3.281	ft
Density (ρ)	slug/ft^3	5.155×10^{2}	kg/m^3	1.940×10^{-3}	slug/ft^3
Temperature (T)	°F + 460	5.56×10^{-1}	°C + 273	1.8	°F + 460
	°R		°K		°R
Velocity (V)	ft/sec	3.048×10^{-1}	m/sec	3.281	ft/sec
	mph	1.609	kph	6.214×10^{-1}	mph
	knot	1.853	kph	5.396×10^{-1}	knot
		0.515	m/sec	1.942	
Force (F)	lbf	4.448	N (newton)	2.248×10^{-1}	lbf
	slug ft/sec^2		kg m/sec^2		slug ft/sec^2
Work	slug ft^2/sec^2	1.356	Nm	7.376×10^{-1}	slug ft^2/sec^2
Energy (J)	BTU		(joule)		BTU
Power (W)	slug ft^2/sec^3	1.356	Nm/sec	7.376×10^{-1}	slug ft^2/sec^3
	hp (550 ft lbf/sec)	7.456×10^{2}	(Watt)	1.341×10^{-3}	hp (550 ft lbf/sec)
Pressure (p)	slug/ft sec^2	4.788×10	N/m^2	2.088×10^{-2}	slug/ft sec^2
	lbf/ft^2		(pascal)		lbf/ft^2
		4.788×10^{-4}	bar	2.088×10^{3}	
Specific Energy, etc	ft lbf/slug	9.290×10^{-2}	Nm/kg	1.076×10	ft lbf/slug
Gas Constant	ft lbf/slug° R	1.672×10^{-1}	Nm/kg° K	5.981	ft lbf/slug° R
Coef of Viscosity (μ)	slug/ft sec	4.788×10	kg/m sec	2.088×10^{-2}	slug/ft sec
Kinematic Viscosity (ν)	ft^2/sec	9.290×10^{-2}	m^2/sec	1.076×10	ft^2/sec
Thermal Conductivity (k)	lbf/sec° R	8.007	N/sec° K	1.249×10^{-1}	lbf/sec° R
Heat Transfer Coefficient	lbf/ft sec° R	2.627×10	N/m sec° K	3.807×10^{-2}	lbf/ft sec° R
Frequency	c/sec	1.0	Hz (hertz)	1.0	c/sec

TABLE 2-6

Conversion Factors (mixed FPSR, metric and SI)

Multiply	By	To obtain
acres	0.4047	ha (= 10^4 m^2)
	43560	ft^2
	0.0015625	mi^2
standard atmospheres (atm)	76	cm Hg
	29.92	in Hg
	1.01325	bar (= 10^5 N/m^2)
	1.033	kgf/cm^2
	14.70	lbf/in^2
	2116	lbf/ft^2
	101325	N/m^2
bars (bar)	0.98692	atm
	14.5038	lbf/in^2
British Thermal Unit (BTU)	0.5556	CHU
	1055	J
	0.2520	kcal (kilocalorie)
centimetres (cm)	0.3937	in
	0.032808	ft
centimetres of mercury at 0° C (cm Hg)	0.01316	atm
	0.3937	in Hg
	0.1934	lbf/in^2
	27.85	lbf/ft^2
	135.95	kgf/m^2
centimetres per second (cm/s)	0.032808	ft/s
	1.9685	ft/min
	0.02237	mph
cubic centimetres (cm^3)	0.06102	in^3
	3.531×10^{-5}	ft^3
	0.001	litre
	2.642×10^{-4}	US gal
cubic feet (ft^3)	28317	cm^3
	0.028317	m^3
	1728	in^3
	0.037037	yd^3
	7.481	US gal
	28.32	litre
cubic feet per minute (ft^3/min)	0.472	litre/s
	0.028317	m^3/min
cubic inches (in^3)	16.39	cm^3
	1.639×10^{-5}	m^3
	5.787×10^{-4}	ft^3
	0.5541	fl oz
	0.01639	litre
	4.329×10^{-3}	US gal
	0.01732	US qt
cubic metres (m^3)	61024	in^3
	1.308	yd^3
	35.3147	ft^3
	264.2	US gal

TABLE 2-6 – *continued*

Multiply	By	To obtain
cubic metres per minute (m^3/min)	35.3147	ft^3/min
cubic yards (yd^3)	27	ft^3
	0.7646	m^3
	202	US gal
degrees (arc)	0.01745	radians
degrees per second (deg/s)	0.01745	radians/s
erg	1.0×10^{-7}	J
feet (ft)	30.48	cm
	0.3048	m
	12	in
	0.33333	yd
	0.0606061	rod
	1.894×10^{-4}	stm
	1.646×10^{-4}	nm (international)
feet per minute (ft/min)	0.01136	mph
	0.01829	km/h
	0.508	cm/s
	0.00508	m/s
feet per second (ft/s)	0.6818	mph
	1.097	km/h
	30.48	cm/s
	0.5925	knot (international)
foot–pounds (ft lbf)	0.138255	kgf m
	3.24×10^{-4}	kcal
	1.356	Nm (J)
foot-pounds per minute (ft lbf/min)	3.030×10^{-5}	hp
foot–pounds per second (ft lbf/s)	1.818×10^{-3}	hp
gallons, Imperial (Imp gal)	277.4	in^3
	1.201	US gal
	4.546	litre
	153.707	fl oz
gallons, US dry (US gal dry)	268.8	in^3
	1.556×10^{-1}	ft^3
	1.164	US gal
	4.405	litre
gallons, US liquid (US gal)	231	in^3
	0.1337	ft^3
	4.951×10^{-3}	yd^3
	3785.4	cm^3
	3.785×10^{-3}	m^3
	3.785	litre
	0.83267	Imp gal
	133.227	fl oz
US gallons per acre (gal/acre)	9.353	litre/ha
grams (g)	0.001	kg
	2.205×10^{-3}	lb
grams per centimetre (g/cm)	0.1	kg/m
	6.720×10^{-2}	lb/ft
	5.600×10^{-3}	lb/in
grams per cubic centimetre (g/cm^3)	1000	kg/m^3
	0.03613	lb/in^3
	62.43	lb/ft^3

TABLE 2-6 – *continued*

Multiply	By	To obtain
hectares (ha)	2.471	acres
	107639	ft^2
	10000	m^2
horsepower (hp)	33000	ft lbf/min
	550	ft lbf/s
	0.7457	kW
	76.04	kgf m/s
	1.014	metric hp
	745.70	Nm/s (W)
horsepower, metric	75	kgf m/s
	0.9863	hp
inches (in)	25.40	mm
	2.540	cm
	0.0254	m
	0.08333	ft
	0.027777	yd
inches of mercury at 0°C (in Hg)	0.033421	atm
	0.4912	lb/in^2
	70.73	lb/ft^2
	345.3	kg/m^2
	2.540	cm Hg
	25.40	mm Hg
	3.386×10^3	N/m^2
inch-pounds (in lbf)	0.011521	kgf m
J (joule)	0.27778×10^{-6}	kWh
	1	Nm
	1	Ws
kilograms (kg)	2.204623	lb
	35.27	oz avdp
	1000	g
kilogram-calories (kcal) (kilocalories)	3.9683	BTU
	3088	ft lbf
	426.9	kgf m
kilogram-metre² (kg m²)	3417	lb in^2
	23.729	lb ft^2
	0.7376	slug ft^2
kilograms per cubic metre (kg/m^3)	0.06243	lb/ft^3
	0.001	g/cm^3
kilograms per hectare (kg/ha)	0.892	lb/acre
kilograms per square centimetre (kg/cm^2)	0.9678	atm
	28.96	in Hg
	14.22	lbf/in^2
	2048	lbf/ft^2
kilograms per square metre (kg/m^2)	2.896×10^{-3}	in Hg
	1.422×10^{-3}	lb/in^2
	0.2048	lb/ft^2
kilometres (km)	1×10^5	cm
	3280.8	ft
	0.6214	stm
	0.53996	nm (international)
kilometers per hour (kph)	0.9113	ft/s
	58.68	ft/min

TABLE 2–6 – *continued*

Multiply	By	To obtain
	0.53996	knot (international)
	0.6214	mph
	0.27778	m/s
	16.67	m/min
kilowatt	1.34	hp
knots (knot) (international)	1	nm/h
	1.688	ft/s
	1.1508	mph
	1.852	km/h
	0.5144	m/s
litres (litre)	1000	cm^3
	61.02	in^3
	0.03531	ft^3
	33.814	fl oz
	0.2642	US gal
	0.2200	Imp gal
	1.0568	US qt
litres per hectare (litre/ha)	13.69	fl oz/acre
	0.107	US gal/acre
litres per second (litre/s)	2.12	ft^3/min
metres (m)	39.37	in
	3.280840	ft
	1.0936	yd
	0.198839	rod
	6.214×10^{-4}	stm
	5.3996×10^{-4}	nm (international)
metre-kilogram (kgf/m)	7.23301	ft lbf
	86.798	in lbf
metres per minute (m/min)	0.06	km/h
metres per second (m/sec)	3.280840	ft/s
	196.8504	ft/min
	2.237	mph
	3.6	km/h
microns	3.937×10^{-5}	in
miles (stm)	5280	ft
	1.6093	km
	1609.3	m
	0.8690	nm (international)
miles per hour (mph)	44.704	cm/s
	0.4470	m/s
	1.467	ft/s
	88	ft/min
	1.6093	km/h
	0.8690	knot (international)
millibars	2.953×10^{-2}	in Hg
	0.1	kN/m^2
millimetres (mm)	0.03937	in
millimetres of mercury at 0°C (mm Hg)	0.03937	in Hg
international nautical miles (nm)	6076	ft
	1.1508	stm
	1852	m
	1.852	km

TABLE 2-6 – *continued*

Multiply	By	To obtain
Newton (N)	0.2248	lbf
ounces, fluid (fl oz)	8	dr fl
	29.57	cm^3
	1.805	in^3
	0.0296	litre
	0.0078	US gal
ounces, fluid per acre (fl oz/acre)	0.073	litre/ha
pounds (lb): mass	453.6	g
	0.453592	kg
	3.108×10^{-2}	slug
pounds force (lbf)	4.4482	N
	0.45359	kgf
pounds-feet (lbf ft)	1.356	Nm
pounds-feet^2 (lb ft^2)	0.421	kg m^2
	144	lb in^2
	0.0311	slug ft^2
pounds per acre (lb/acre)	1.121	kg/ha
pounds per cubic foot (lb/ft^3)	16.02	kg/m^3
pounds per cubic inch (lb/in^3)	1728	lb/ft^3
	27.68	g/cm^3
pounds per hour per pound force (lb/h/lbf)	28.3	mg/Ns
pounds per hour per horsepower (lb/h/hp)	169	μg/J
pounds-force per square foot (lbf/ft^2)	0.1414	in Hg
	4.88243	kgf/m^2
	4.725×10^{-4}	atm
	0.048	kN/m^2
pounds per square inch (psi or lbf/in^2)	5.1715	cm Hg
	2.036	in Hg
	0.06805	atm
	0.0689476	bar
	703.1	kg/m^2
	6.89476	kN/m^2
quart, US (qt)	0.94635	litre
	57.750	in^3
	3.342×10^{-2}	ft^3
radians	57.30	deg (arc)
	0.1592	rev
radians per second (radians/s)	57.296	deg/s
	0.1592	rev/s
	9.549	rpm
revolutions (rev)	6.283	radians
revolutions per minute (rpm or rev/min)	0.1047	radians/s
revolutions per second (rev/s)	6.283	radians/s
rod	16.5	ft
	5.5	yd
	5.0292	m
slug	14.594	kg
	32.174	lb
slug feet^2 (slug ft^2)	1.3559	kg m^2
	4633.1	lb in^2
	32.174	lb ft^2

TABLE 2-6 – *continued*

Multiply	By	To obtain
square centimetres (cm^2)	0.1550	in^2
	0.001076	ft^2
square feet (ft^2)	929.03	cm^2
	0.092903	m^2
	144	in^2
	0.1111	yd^2
	2.296×10^{-5}	acres
square inches (in^2)	6.4516	cm^2
	6.944×10^{-3}	ft^2
square kilometres (km^2)	0.3861	stm^2
square metres (m^2)	10.76391	ft^2
	1.196	yd^2
	0.0001	ha
square miles (mi^2)	2.590	km^2
	640	acres
square rods (rod^2)	30.25	yd^2
square yards (yd^2)	0.8361	m^2
	9	ft^2
	0.0330579	rod^2
ton	2240	lb
	1016	kg
	1.016	t (tonne)
ton-force (tonf)	9.964×10^3	N
tons per square foot (tonf/ft^2)	107.252×10^3	kN/m^2
watt (W)	1.34×10^{-3}	hp
	10^{-3}	kW
yards (yd)	0.9144	m
	3	ft
	36	in
	0.181818	rod

TABLE 2–7

General Notation*

Axes	OX	OY	OZ
Aerodynamic forces	X	Y	Z
Angular motions	ϕ (bank)	θ (pitch)	Ψ (yaw)
Linear velocities	u	v	w
Angular velocities	p	q	r
Moments of forces	L (roll)	M (pitch)	N (yaw)
Moments of inertia	A	B	C
	(Note: $A + B \approx C$)		

Energy and other mechanical concepts
Aeronautics is mainly a mechanical subject. To fly, forces must be applied to cause action, and work is done. Energy, inertia, momentum, power, work and similar terms are of such fundamental importance that they must be swept under one common heading. For simplicity and ease of reading, speed is preferred to velocity when explaining something. Strictly speaking, velocity contains both direction and speed.
Centre of gravity (*see* under *Performance and operational terms*).
Energy and work. Energy is the capacity for doing work and it can adopt a variety of exchangeable forms when given the right conditions, i.e., mechanical, thermal (heat), chemical, electrical, atomic; and it seems impossible to destroy it. Even so, usable energy can be more easily lost than gained. Work is done when energy is expended by applying a force to a mass of any substance so as to make it move.

$$\text{work done} = \text{force applied} \times \text{distance moved} \qquad (2\text{–}15)$$

The types of energy in which we are interested are:

□ *Kinetic energy (KE).* A result of motion. Imagine an aeroplane flying at a constant speed as measured between two fixed points on the ground. We know from eq (2–12) that as the aeroplane has accelerated at different rates from take-off, and as the mass of the machine has varied with fuel consumed, then the product of the *average* mass of the aeroplane × *average* acceleration gives the *average* force doing the work:

$$\begin{aligned} \text{force} &= \text{mass of aircraft} \times \text{speed attained/time taken} \\ \text{While:}\quad \text{kinetic energy} &= \text{force} \times \text{distance moved} \\ &= \text{mass} \times \text{acceleration} \times \tfrac{1}{2}\text{(i.e. average) speed attained} \\ \text{i.e. } KE &= \tfrac{1}{2}MV^2 \qquad (2\text{–}16) \end{aligned}$$

This equation should be compared with eq (2–9) which shows that the dynamic pressure on the nose of an aircraft, $q = \frac{1}{2}\rho V^2$, has exactly the same form, except that the symbol ρ is used for the mass per unit volume of air. Thus dynamic pressure q is a measure of the kinetic energy per unit volume of the air in motion.
Note: We can arrive at the same result using *dimensional analysis*, generally writing mass = M, distance = L and time = T, so that:

force = $M(L/T)/T = ML/T^2$, where L/T = speed, V
distance = $\frac{1}{2}(L/T)T = \frac{1}{2}L$
KE = force × distance = $\frac{1}{2}(ML/T^2)\,L = \frac{1}{2}M(L/T^2) = \frac{1}{2}MV^2$ (2–16a)

See Appendix C.

□ *Potential energy.* Is derived by virtue of position in space, raising the mass of a body through a change of height in a gravitational field. Thus, applying eq (2–15), if an aeroplane weighing 2200 lb (1000 kg) climbs 1000 ft (305 m) above the airfield:

$$\begin{aligned} \text{potential energy gained} &= 2200 \times 1000 \\ &= 2.2 \times 10^6 \text{ft lb } (2.98 \times 10^6 \text{ Nm or J}) \end{aligned}$$

which is obtained by burning fuel within the engine.
□ *Thermal or heat energy.* This is a measure of the kinetic energy of molecules in a solid, liquid or gas by *specific heat*, i.e. the quantity of heat needed to raise the temperature of a defined mass of water by a given amount. Common units are:
British Thermal Unit, BTU. The heat required to raise the temperature of 1 lb of water through 1° F is equivalent to 778 ft lbf work (1055 Nm or J) (2–17a)

Centigrade Heat Unit, CHU. The heat required to raise the temperature of 1 lb water through 1°C is equivalent to 1400 ft lbf work (1900 Nm or J) (2–17b)

Joule, J. (after James Prescott Joule (1818–89) an English physicist). The unit of work in the SI system (table 2–5), when a force of one newton acts for one metre.

$$1 \text{ joule} = 0.736 \text{ BTU} \qquad (2\text{–}17c)$$

An important quantity in aerodynamics is:

$$\frac{\text{specific heat of air at constant pressure}}{\text{specific heat of air at constant volume}} = \gamma = 1.4 \qquad (2\text{–}18)$$

□ *Pressure energy.* The capacity of a compressed gas to do work. When air is compressed within a cylinder by a piston the pressure rises directly with compression. The mean value of the pressure during the process is called the *mean effective pressure, MEP.* Consider the pressure energy during one stroke of a reciprocating engine:

$$\begin{aligned} \text{pressure energy} &= \text{work done} = \text{force on piston} \times \text{distance moved} \\ &= \text{mean effective pressure} \times \text{piston area} \times \text{stroke} \\ &= MEP \times \text{swept volume (capacity) of cylinder} \qquad (2\text{–}19) \end{aligned}$$

Efficiency. The effectiveness with which useful work is done for a given working input:

$$\begin{aligned} \text{efficiency} &= \text{output of work/input of energy} \\ &= \text{output/input} \qquad (2\text{–}20) \end{aligned}$$

Force and mass (*see slug* and eq (2–12)).

Inertia. A property possessed by all masses. If an aeroplane is at rest on the ground we have to push hard at first to make it move. Inertia of the mass resists the force, in an attempt to remain inertly in a state of rest. Once steady motion is established we have an equally hard job stopping it again. This time the inertia of the mass causes it to remain in uniform motion. Inertia therefore is experienced as resistance to a change of velocity..

Moment. If a force acts at a distance from a point to which it is connected by a lever, the moment of the force about the point is a measure of the *torque* applied:

$$\text{Moment} = \text{force} \times \text{length of lever} = \text{torque} \qquad (2\text{–}21)$$

To distinguish dimensionally between moment and work, a moment is measured in *lbf ft*, work in *ft lbf* in the FPSR system or Nm (joule) in the SI system (table 2–5).

Moment of inertia. A measure of the work that would be needed to impart kinetic energy of rotation to a body about an axis. The moment of inertia depends upon the shape and distribution of mass about the axis of rotation, fig. 2.7a. The clearest picture is that of a flywheel: when stationary it is in balance about its axis, regardless of angular position. But to make it rotate involves work and to stop it also requires work. Every little particle of the flywheel has a different mass Δm, the centre of gravity of which is located on a moment arm, r, from the axis of rotation. We know from eq (2–16) that, taking just one little bit of the flywheel,

$$\text{kinetic energy, } KE_{bit} = \tfrac{1}{2} \times \Delta m \times \text{linear speed}^2$$

where the linear speed of the bit, whirling around at ω radians per second is shown in fig. 2.7b and:

$$\text{linear velocity, } v = r_{\omega} \qquad (2\text{–}22)$$

so that $$KE_{bit} = (\Delta mr^2)\ \omega^2$$

and the kinetic energy of the whole, which is the work done in causing the total mass of the body M to rotate at a rate ω, is the sum of the individual kinetic energies of all of its bits:

$$KE_{whole} = \Sigma_0^M (\Delta mr^2)\omega^2 \tag{2-23}$$

Here Σ_0^M uses the Greek letter sigma (Σ) to mean 'the sum of all of the little bits from 0 to total mass M'.

$$\text{moment of inertia of the whole, } I = \Sigma_0^M \Delta mr^2 \tag{2-24}$$

Now, fig. 2.7a showed a body being rotated about two different axes. The total mass is the same, but the moment of inertia will be different depending upon which axis is used. We distinguish I_{XX} from I_{YY}, and imagine redistributing the total mass in the form of a spinning ring, a torus, with a *constant radius of gyration*, k, such that in the case of rotation about the X–X and Y–Y axes respectively:

$$\text{moment of inerita, } I_{XX} = Mk^2_{XX} \tag{2-25a}$$

$$I_{YY} = Mk^2_{YY} \tag{2-25b}$$

This is shown in fig. 2.7c.

Momentum. A fundamental property of a mass in motion, defined as:

$$\text{momentum} = \text{mass} \times \text{velocity}$$

$$M = mV \tag{2-26}$$

The Newtonian system of dynamics is based upon three axioms called Newton's laws of motion:

(i) Every body continues in a state of rest or of uniform motion in a straight line unless it is compelled to change that state by the action of a force upon it.
(ii) The rate of change of momentum per unit time is proportional to the force causing it and its direction is the same as that of the force.
(iii) To every action there is an equal and opposite reaction.

If we look back to eq (2–12) and Newton's second law:

$$\text{force} = \text{rate of exchange of momentum} = \text{mass} \times \text{rate of change of speed of time}$$

$$F = m\,\mathrm{d}V/\mathrm{d}t \tag{2-27}$$

(where $\mathrm{d}V/\mathrm{d}t$ is the ratio of a very small change in velocity ΔV with a small increment in time Δt, as the increments tend to zero).
But, *change of speed/time taken = acceleration*, a, which shows that eq (2–27) is identical to eq (2–12).
Power. The rate of doing work, which is the same as the rate at which energy is expended:

$$\text{power} = \text{force} \times \text{distance through which it is applied/time taken}$$

$$= \text{force} \times \text{velocity}$$

$$\text{i.e., } P = FV \tag{2-28}$$

Conventionally power is measured in horsepower, or watts (1 watt = 1 joule per second) which are related by:

$$1 \text{ horsepower} = 550 \text{ ftlb/s } (33000 \text{ ftlb/min})$$

$$= 746 \text{ watts} \tag{2-29}$$

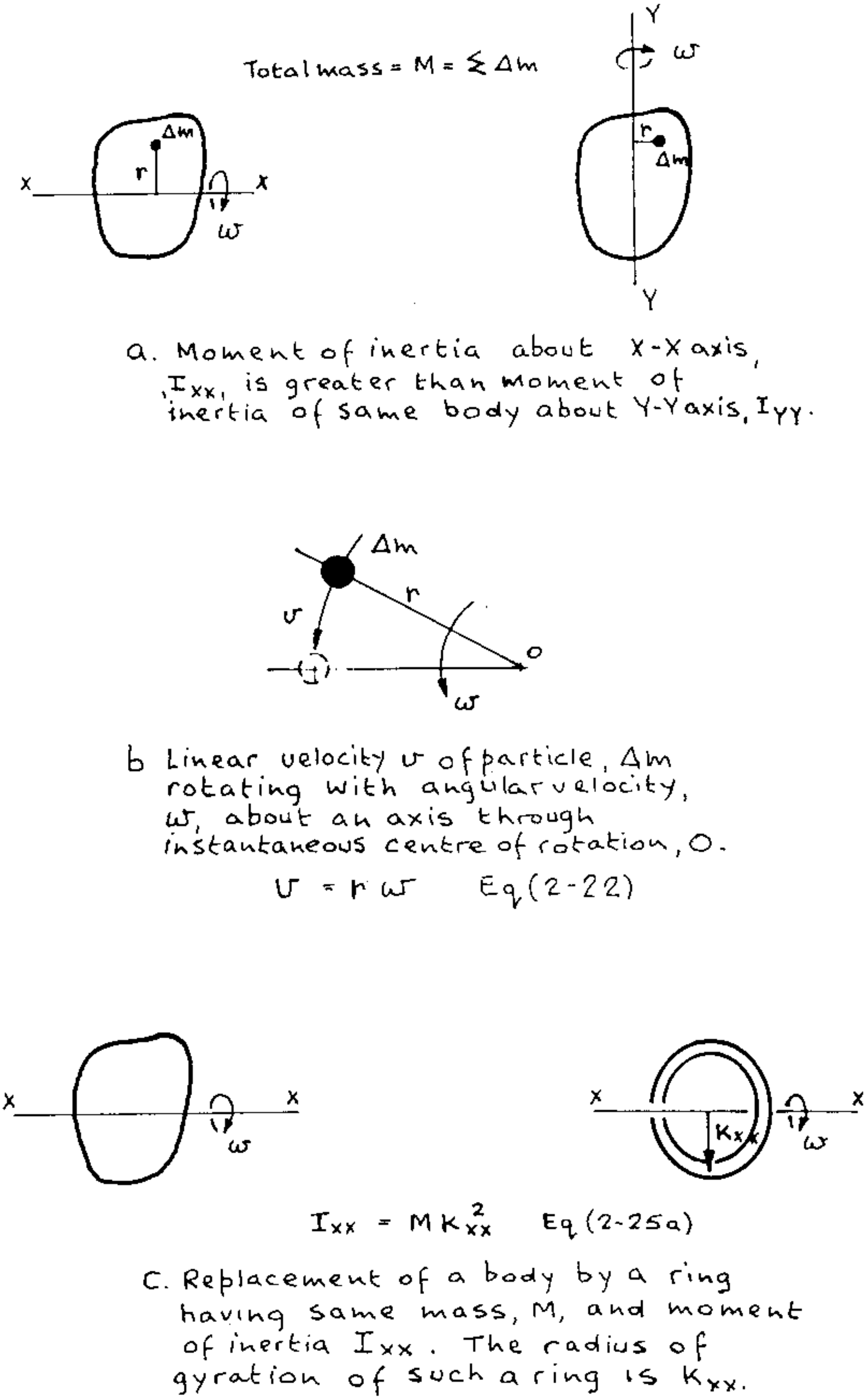


Fig. 2.7 Moment of inertia and radius of gyration.

For a piston engine we can apply eq (2–19) to calculate the *indicated horsepower*, IHP, as long as we know the capacity (total swept volume), the revolutions per minute, rpm, and the *indicated mean effective pressure*, IMEP, within the cylinders:

$$\text{IHP} = \text{IMEP} \times \text{capacity} \times \text{rpm}/33\,000 \qquad (2\text{–}30)$$

Mechanical losses prevent the theoretical IHP being realised. When all such losses are taken into account by using a dynamometer or a *prony brake* to measure the actual power transmitted by the engine drive shaft, we are measuring the *brake horsepower*, BHP (or *shaft brake horsepower*, SHP), where:

$$\text{BHP} = \text{engine mechanical efficiency, } \eta_m \times \text{IHP} \quad (2\text{–}31)$$

For a turbopropeller engine which produces shaft horsepower, plus residual jet thrust, then, in FPSR units:

$$\text{thrust equivalent horsepower} = \text{shaft horsepower} + \text{jet thrust} \times \text{true airspeed}/550 \quad (2\text{–}32a)$$

in which the true airspeed, TAS, is really given in ft/s, so as to keep the units right. Under sea level static conditions 1 TEHP is produced by about 2.6 lbf jet thrust, so that:

$$\text{TEHP} \approx \text{SHP} + \text{jet thrust}/2.6 \quad (2\text{–}32b)$$

However, for practical (non-sales talk) purposes, the engineer counts only SHP. In each of these cases we assume that a propeller is used to produce the ultimate thrust horsepower, THP, and it is necessary to multiply the BHP in eq (2–31), or in eq (2–32b) by propeller efficiency. A wooden propeller has an efficiency around 70 per cent, while a metal propeller is about 80 per cent efficient so that, roughly:

$$\begin{aligned} \text{THP} &= \text{propeller efficiency, } \eta \times \text{BHP} \\ &= 0.7 \text{ to } 0.8 \text{ of the power available from the engine} \end{aligned} \quad (2\text{–}33)$$

under the actual conditions occurring in flight.

Slug (*see* under *Aerodynamics and Aeroplane Geometry*).
Specific heat (*see* under *Thermal*, or *heat energy*).

CONVERSION FACTORS

TEMPERATURE

T deg. F. = $\frac{5}{9}$(T − 32) deg. C.
T deg. C. = (32 + $\frac{9}{5}$T) deg. F.
T deg. C. = (273 + T) deg. K. (Kelvin)

FAHRENHEIT/CELSIUS (CENTIGRADE) CONVERSION TABLE

°C	−40	−30	−20	−10	0	10	20	30	40
°F	−40	−22	−4	14	32	50	68	86	104

In English-speaking countries temperatures at ground level are usually quoted in degrees Fahrenheit while temperatures aloft are reported in degrees Celsius.

DISTANCES

1 inch = 25·4 mm.
1 mm. = 0·03937 inches
(Rainfall is usually measured in inches or millimetres.)
1 ft. = 0·3048 metres
1 metre = 3·2808 ft. = 1·0936 yards
1 statute mile = 5280 ft. = 0·8684 nautical miles = 1·609 km.
1 nautical mile = 6080 ft. = 1·1515 statute miles = 1·8532 km.
1 km. = 1000 metres = 0·5396 nautical miles = 0·6214 statute miles = 3280·8 ft.

SPEEDS

	ft./sec.	100 ft./min.	m./sec.	km./hr.	m.p.h.	knots
1 ft./sec.	1	0·6	0·3048	1·0973	0·6818	0·5921
100 ft./min.	1·667	1	0·508	1·829	1·136	0·9868
1 m./sec.	3·2808	1·968	1	3·6	2·2369	1·9424
1 km./hr.	0·9113	0·5468	0·2778	1	0·6214	0·5396
1 m.p.h.	1·4667	0·88	0·447	1·609	1	0·8684
1 knot	1·6889	1·014	0·5148	1·8532	1·1515	1

2. Fahrenheit-Centigrade Conversion Table

The numbers in the center column, in boldface type, refer to the temperature in either Fahrenheit or Centigrade degrees. If it is desired to convert from Fahrenheit to Centigrade degrees, consider the center column as a table of Fahrenheit temperatures and read the corresponding Centigrade temperature in the column at the left. If it is desired to convert from Centigrade to Fahrenheit degrees, consider the center column as a table of Centigrade values, and read the corresponding Fahrenheit temperature on the right.

SOURCE: Clifford Strock and Richard L. Koral, eds., *Handbook of Air Conditioning, Heating, and Ventilating*, 2d ed. (New York: Industrial Press, 1965).

For conversions not covered in the table, the following formulas are used:

$F = 1.8\,C + 32 \qquad C = (F - 32) \div 1.8$

Deg C		Deg F	Deg C		Deg F
–46	**– 50**	– 58	8.9	**48**	118.4
–40	**– 40**	– 40	9.4	**49**	120.2
–34	**– 30**	– 22	10.0	**50**	122.0
–29	**– 20**	– 4	10.6	**51**	123.8
–23	**– 10**	14	11.1	**52**	125.6
–17.8	**0**	32–	11.7	**53**	127.4
–17.2	**1**	33.8	12.2	**54**	129.2
–16.7	**2**	35.6	12.8	**55**	131.0
–16.1	**3**	37.4	13.3	**56**	132.8
–15.6	**4**	39.2	13.9	**57**	134.6
–15.0	**5**	41.0	14.4	**58**	136.4
–14.4	**6**	42.8	15.0	**59**	138.2
–13.9	**7**	44.6	15.6	**60**	140.0
–13.3	**8**	46.4	16.1	**61**	141.8
–12.8	**9**	48.2	16.7	**62**	143.6
–12.2	**10**	50.0	17.2	**63**	145.4
–11.7	**11**	51.8	17.8	**64**	147.2
–11.1	**12**	53.6	18.3	**65**	149.0
–10.6	**13**	55.4	18.9	**66**	150.8
–10.0	**14**	57.2	19.4	**67**	152.6
– 9.4	**15**	59.0	20.0	**68**	154.4
– 8.9	**16**	60.8	20.6	**69**	156.2
– 8.3	**17**	62.6	21.1	**70**	158.0
– 7.8	**18**	64.4	21.7	**71**	159.8
– 7.2	**19**	66.2	22.2	**72**	161.6
– 6.7	**20**	68.0	22.8	**73**	163.4
– 6.1	**21**	69.8	23.3	**74**	165.2
– 5.6	**22**	71.6	23.9	**75**	167.0
– 5.0	**23**	73.4	24.4	**76**	168.8
– 4.4	**24**	75.2	25.0	**77**	170.6
– 3.9	**25**	77.0	25.6	**78**	172.4
– 3.3	**26**	78.8	26.1	**79**	174.2
– 2.8	**27**	80.6	26.7	**80**	176.0
– 2.2	**28**	82.4	27.2	**81**	177.8
– 1.7	**29**	84.2	27.8	**82**	179.6
– 1.1	**30**	86.0	28.3	**83**	181.4
– 0.6	**31**	87.8	28.9	**84**	183.2
0–	**32**	89.6	29.4	**85**	185.0
0.6	**33**	91.4	30.0	**86**	186.8
1.1	**34**	93.2	30.6	**87**	188.6
1.7	**35**	95.0	31.1	**88**	190.4
2.2	**36**	96.8	31.7	**89**	192.2
2.7	**37**	98.6	32.2	**90**	194.0
3.3	**38**	100.4	32.8	**91**	195.8
3.9	**39**	102.2	33.3	**92**	197.6
4.4	**40**	104.0	33.9	**93**	199.4
5.0	**41**	105.8	34.4	**94**	201.2
5.6	**42**	107.6	35.0	**95**	203.0
6.1	**43**	109.4	35.6	**96**	204.8
6.7	**44**	111.2	36.1	**97**	206.6
7.2	**45**	113.0	36.7	**98**	208.4
7.8	**46**	114.8	37.2	**99**	210.2
8.3	**47**	116.6	37.8	**100**	212.0

Conversion Tables for Thermometer Scales

F = Fahrenheit, C = Celsius (centigrade), K = Kelvin

F	C	K	F	C	K	C	F	K	K	F	C
°	°	°	°	°	°	°	°	°	°	°	°
−20	−28.9	244.3	+40	+4.4	277.6	−25	−13.0	248.2	250	−9.7	−23.2
19	28.3	244.8	41	5.0	278.2	24	11.2	249.2	251	7.9	22.2
18	27.8	245.4	42	5.6	278.7	23	9.4	250.2	252	6.1	21.2
17	27.2	245.9	43	6.1	279.3	22	7.6	251.2	253	4.3	20.2
16	26.7	246.5	44	6.7	279.8	21	5.8	252.2	254	2.5	19.2
−15	−26.1	247.0	+45	+7.2	280.4	−20	−4.0	253.2	255	−0.7	−18.2
14	25.6	247.6	46	7.8	280.9	19	2.2	254.2	256	+1.1	17.2
13	25.0	248.2	47	8.3	281.5	18	−0.4	255.2	257	2.9	16.2
12	24.4	248.7	48	8.9	282.0	17	+1.4	256.2	258	4.7	15.2
11	23.9	249.3	49	9.4	282.6	16	3.2	257.2	259	6.5	14.2
−10	−23.3	249.8	+50	+10.0	283.2	−15	+5.0	258.2	260	+8.3	−13.2
9	22.8	250.4	51	10.6	283.7	14	6.8	259.2	261	10.1	12.2
8	22.2	250.9	52	11.1	284.3	13	8.6	260.2	262	11.9	11.2
7	21.7	251.5	53	11.7	284.8	12	10.4	261.2	263	13.7	10.2
6	21.1	252.0	54	12.2	285.4	11	12.2	262.2	264	15.5	9.2
−5	−20.6	252.6	+55	+12.8	285.9	−10	+14.0	263.2	265	+17.3	−8.2
4	20.0	253.2	56	13.3	286.5	9	15.8	264.2	266	19.1	7.2
3	19.4	253.7	57	13.9	287.0	8	17.6	265.2	267	20.9	6.2
2	18.9	254.3	58	14.4	287.6	7	19.4	266.2	268	22.7	5.2
−1	18.3	254.8	59	15.0	288.2	6	21.2	267.2	269	24.5	4.2
0	−17.8	255.4	+60	+15.6	288.7	−5	+23.0	268.2	270	+26.3	−3.2
+1	17.2	255.9	61	16.1	289.3	4	24.8	269.2	271	28.1	2.2
2	16.7	256.5	62	16.7	289.8	3	26.6	270.2	272	29.9	1.2
3	16.1	257.0	63	17.2	290.4	2	28.4	271.2	273	31.7	−0.2
4	15.6	257.6	64	17.8	290.9	−1	30.2	272.2	274	33.5	+0.8
+5	−15.0	258.2	+65	+18.3	291.5	0	+32.0	273.2	275	+35.3	+1.8
6	14.4	258.7	66	18.9	292.0	+1	33.8	274.2	276	37.1	2.8
7	13.9	259.3	67	19.4	292.6	2	35.6	275.2	277	38.9	3.8
8	13.3	259.8	68	20.0	293.2	3	37.4	276.2	278	40.7	4.8
9	12.8	260.4	69	20.6	293.7	4	39.2	277.2	279	42.5	5.8
+10	−12.2	260.9	+70	+21.1	294.3	+5	+41.0	278.2	280	+44.3	+6.8
11	11.7	261.5	71	21.7	294.8	6	42.8	279.2	281	46.1	7.8
12	11.1	262.0	72	22.2	295.4	7	44.6	280.2	282	47.9	8.8
13	10.6	262.6	73	22.8	295.9	8	46.4	281.2	283	49.7	9.8
14	10.0	263.2	74	23.3	296.5	9	48.2	282.2	284	51.5	10.8
+15	−9.4	263.7	+75	+23.9	297.0	+10	+50.0	283.2	285	+53.3	+11.8
16	8.9	264.3	76	24.4	297.6	11	51.8	284.2	286	55.1	12.8
17	8.3	264.8	77	25.0	298.2	12	53.6	285.2	287	56.9	13.8
18	7.8	265.4	78	25.6	298.7	13	55.4	286.2	288	58.7	14.8
19	7.2	265.9	79	26.1	299.3	14	57.2	287.2	289	60.5	15.8
+20	−6.7	266.5	+80	+26.7	299.8	+15	+59.0	288.2	290	+62.3	+16.8
21	6.1	267.0	81	27.2	300.4	16	60.8	289.2	291	64.1	17.8
22	5.6	267.6	82	27.8	300.9	17	62.6	290.2	292	65.9	18.8
23	5.0	268.2	83	28.3	301.5	18	64.4	291.2	293	67.7	19.8
24	4.4	268.7	84	28.9	302.0	19	66.2	292.2	294	69.5	20.8
+25	−3.9	269.3	+85	+29.4	302.6	+20	+68.0	293.2	295	+71.3	+21.8
26	3.3	269.8	86	30.0	303.2	21	69.8	294.2	296	73.1	22.8
27	2.8	270.4	87	30.6	303.7	22	71.6	295.2	297	74.9	23.8
28	2.2	270.9	88	31.1	304.3	23	73.4	296.2	298	76.7	24.8
29	1.7	271.5	89	31.7	304.8	24	75.2	297.2	299	78.5	25.8
+30	−1.1	272.0	+90	+32.2	305.4	+25	+77.0	298.2	300	+80.3	+26.8
31	0.6	272.6	91	32.8	305.9	26	78.8	299.2	301	82.1	27.8
32	0.0	273.2	92	33.3	306.5	27	80.6	300.2	302	83.9	28.8
33	+0.6	273.7	93	33.9	307.0	28	82.4	301.2	303	85.7	29.8
34	1.1	274.3	94	34.4	307.6	29	84.2	302.2	304	87.5	30.8
+35	+1.7	274.8	+95	+35.0	308.2	+30	+86.0	303.2	305	+89.3	+31.8
36	2.2	275.4	96	35.6	308.7	31	87.8	304.2	306	91.1	32.8
37	2.8	275.9	97	36.1	309.3	32	89.6	305.2	307	92.9	33.8
38	3.3	276.5	98	36.7	309.8	33	91.4	306.2	308	94.7	34.8
39	3.9	277.0	99	37.2	310.4	34	93.2	307.2	309	96.5	35.8
+40	+4.4	277.6	+100	+37.8	310.9	+35	+95.0	308.2	310	+98.3	+36.8

Barometer Scales Comparison (°Normal Atmospheric Pressure)

Inches	Millibars	Millimeters
31.00	1050.0	787.0
30.50	1032.9	774.7
30.00	1015.9	762.0
29.92	1013.2	760.0
29.50	999.0	749.3
29.00	982.0	736.6
28.50	965.1	723.9
28.00	948.2	711.2
27.50	931.3	698.5
27.00	914.3	685.8
26.50	897.4	673.1
26.00	880.5	660.4

1 inch = 33.86 millibars = 25.4 millimeters

Correction of Barometer Reading for Height Above Sea Level

All barometers. All values positive.

Height in feet	Outside temperature in degrees Fahrenheit													Height in feet
	−20°	−10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	
5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	5
10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	10
15	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	15
20	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	20
25	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	25
30	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	30
35	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	35
40	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	40
45	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	45
50	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	50
55	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	55
60	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	60
65	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	65
70	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	70
75	0.10	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	75
80	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	80
85	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	85
90	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	90
95	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	95
100	0.13	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	100
105	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.11	105
110	0.14	0.14	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.11	0.11	0.11	110
115	0.15	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	115
120	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12	0.12	0.12	120
125	0.16	0.16	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12	125

THE ICAO STANDARD ATMOSPHERE (DRY AIR)

Pressure	*Temperature*		*Density*	*Altitude*	
mb.	C.	F.	gm./cu.metre	m.	ft.
1013·2	15·0	59·0	1225	0	0
1000	14·3	57·7	1212	111	364
950	11·5	52·7	1163	540	1773
900	8·6	47·4	1113	988	3243
850	5·5	41·9	1063	1457	4781
800	2·3	36·2	1012	1949	6394
750	−1·0	30·1	960	2466	8091
700	−4·6	23·8	908	3012	9882
650	−8·3	17·0	855	3591	11,780
600	−12·3	9·8	802	4206	13,801
550	−16·6	2·1	747	4865	15,962
500	−21·2	−6·2	692	5574	18,289
450	−26·2	−15·2	635	6344	20,812
400	−31·7	−25·1	577	7185	23,574
350	−37·7	−36·0	518	8117	26,631
300	−44·5	−48·2	457	9164	30,065
250	−52·3	−62·2	395	10,363	33,999
200	−56·5	−69·7	322	11,784	38,662
150	−56·5	−69·7	241	13,608	44,647
100	−56·5	−69·7	161	16,180	53,083
90	−56·5	−69·7	145	16,848	55,275
80	−56·5	−69·7	128	17,595	57,726
70	−56·5	−69·7	112	18,442	60,504
60	−56·5	−69·7	96	19,419	63,711
50	−56·5	−69·7	80	20,575	67,503

PRESSURE

Outside of national meteorological services, a number of barometers are calibrated in inches or millimetres of mercury. Such units are not precise measures of pressure; allowance must be made for variations in temperature and in the force of gravity—which increases towards the poles. The relationship between millibars and inches or millimetres of mercury (at 0°C at latitude 45°N) is

1000 mb. = 750·1 mm. = 29·531 inches

the air is a perfectly dry gas;
temperature at sea level 15° Celsius (59° Fahrenheit);
pressure at sea level 29.92 in Hg (1013.25 mb),

$$2\ 116\ \text{lb/ft}^2\ (1.01325 = 10^5\ \text{N/m}^2);$$

density at sea level, ρ_0, 0.00238 slugs/ft^3, 0.0765 lb/ft^3 (1.225 kg/m^3);
temperature lapse rate 1.98°C/1000 ft (6.5°C/km) from sea level to the altitude at

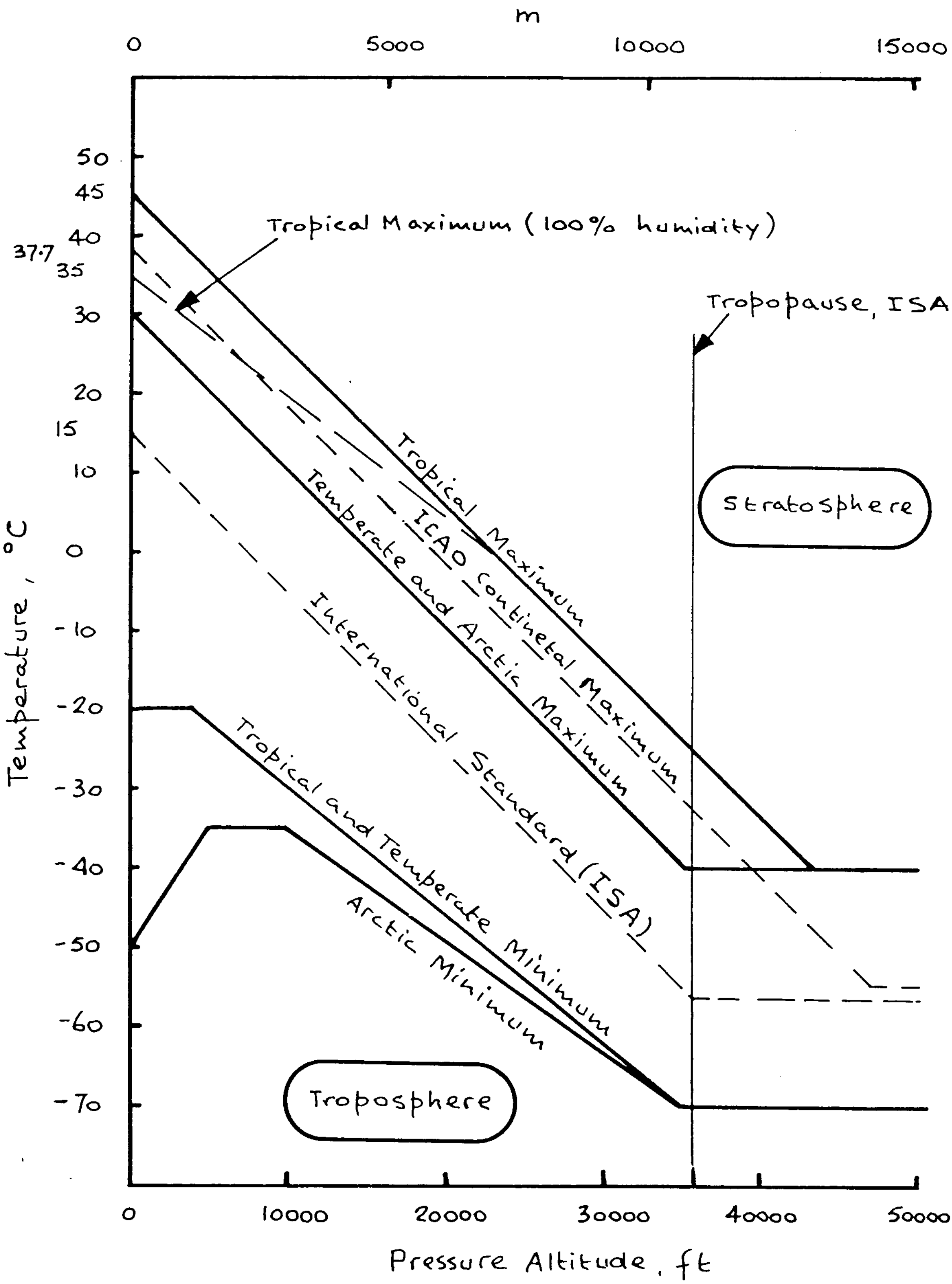


Fig. 2.15 Standard climates shown as envelopes for design purposes (ref. 2.4).

Conversion Factors

Distances and Areas

1 inch = 2.54 cm.
1 cm. = 0.3937 inches
1 ft. = 0.3048 metres
1 metre = 3.281 feet
1 mile = 5280 ft. = 1.609 km.
1 km. = 3281 ft. = 0.622 miles
1 nautical mile = 6080 ft. = 1.151 statute miles
1 sq. in. = 6.451 sq. cm.
1 sq. ft. = 0.0929 sq. m.

Weights and Volumes

1 lb. = 0.4536 kg.
1 kg. = 2.204 lb.
1 gallon = 4.543 litres

Wing loadings

1 lb./sq. ft. = 4.88 kg./sq. m.
1 kg./sq. m. = 0.2048 lb./sq. ft.

Pressure

1 lb./sq. in. = 0.07 kg./sq. cm.
1 kg./sq. cm. = 14.3 lb./sq. in.

Map scales

¼ inch to the mile = 1/253,400
1/500,000 = 0.127 ins. to the mile (approx. ⅛ inch to the mile)

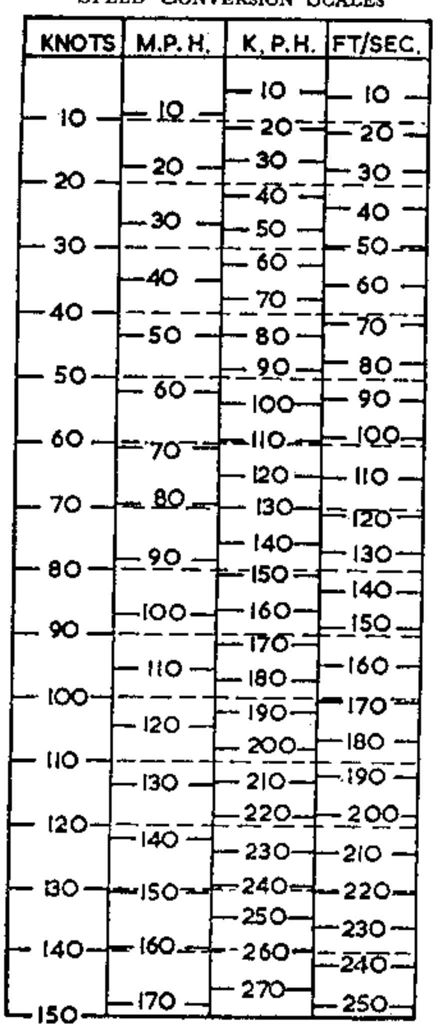
Miscellaneous

1 Radian = 57.29° 'g' (at London) = 32.18 ft./sec^2.
1 cu. ft. of water weighs 62.4 lb.
To convert temperatures in °C to °F., multiply by 9/5 and add 32°

Some Round Figures

$\frac{22}{7} = \pi$. 1 inch = 2½ cm. 1 metre = 3¼ ft.
1 km. = ⅝ mile. 1 sq. m. = 10 sq. ft.
1 kg. = 2¼ lb. 1 lb./sq. ft. = 5 kg./sq. m.

Speed Conversion Scales



Airspeed-Water Gauge Equivalents for A.S.I. Calibration

V_i knots	Inches W.G.	V_i M.P.H.	Inches W.G.
10	0.07	10	0.05
20	0.26	20	0.20
30	0.59	30	0.44
40	1.04	40	0.79
50	1.63	50	1.23
60	2.35	60	1.77
70	3.19	70	2.41
80	4.18	80	3.15
90	5.28	90	3.99
100	6.52	100	4.93
110	7.89	110	5.96
120	9.40	120	7.09
130	11.02	130	8.33
140	12.78	140	9.66
150	14.68	150	11.08
		160	12.61
		170	14.24

The right-hand table gives the dynamic pressures corresponding to equivalent airspeeds in knots and m.p.h., expressed in inches water gauge. The figures are obtained from the following relationships, which do not include the effect of compressibility of the air.

$$(\text{H, inches W.G.}) = 0.0652\,(V_i \text{ knots})^2 = 0.0493\,(V_i \text{ m.p.h.})^2$$

TABLE OF CONVERSION FACTORS

Because different conventions historically have been used to measure various quantities, the following tables have been compiled to sort out the different units. This first table identifies the units typically used for describing a particular quantity. For example, speed might be measured in "miles/hour".

Most quantities can also be described in terms of the following three basic dimensions:

length	L
mass	M
time	T

For example, speed is given in terms of length divided by time, which can be written as "L/T". This description, called "dimensional analysis", is useful in determining whether an equation is correct. The product of the dimensions on each side of the equal sign must match. For example:

$$\text{Distance} = \text{Speed} \times \text{Time}$$
$$L = L/T \times T$$

The dimension on the left side of the equal sign is length, L. On the right side of the equal sign, the product of L/T times T is L, which matches the left side of the equation.

The second table is a Conversion Table, showing how to convert from one set of units to another. It might be necessary to take the reciprocal of the conversion factor or to make more than one conversion to get the desired results.

Measured Quantities and Their Common Units

Length(L)	Area(L^2)	Volume(L^3)
mile(mi.)	sq. mile(mi^2)	gallon(gal.)
yard(yd.)	sq. yard(yd^2)	quart(qt.)
foot(ft.)	sq. foot(ft^2)	pint(pt.)
inch(in.)	sq. inch(in^2)	ounce(oz.)
fathom(fath.)	acre	cu. foot(ft^3)
kilometer(km.)	sq. kilometer(km^2)	cu. yard(yd^3)
meter(m.)	sq. meter(m^2)	cu. inch(in^3)
centimeter(cm.)	sq. centimeter(cm^2)	liter(l)
micron(μ)		cu. centimeter(cm^3)
angstrom(Å)		acre-foot
		cord(cd)
		cord-foot
		barrel(bbl.)

Mass(M)	Speed(L/T)	Flow Rate(L^3/T)
pound(lb.)	feet/minute (ft./min.)	cu. feet/min.
ton(short)	feet/sec.	cu. meter/min.
ton(long)	mile/hour	liters/sec.
ton(metric)	mile/min.	gallons/min.
gram(g.)	kilometer/hr.	gallons/sec.
kilogram(kg.)	kilometer/min.	
	kilometer/sec.	

Pressure(M/L/T^2)	Energy(ML^2/T^2)	Power(ML^2/T^3)
atmosphere(atm.)	British thermal unit(Btu.)	Btu./min.
pounds/sq. inch(psi)	calories(cal.)	Btu./hour
inches of mercury	foot-pound	watt
cm. of mercury	joule	joule/sec.
feet of water	kilowatt-hour (kw-hr.)	cal./min.
	horsepower-hour (hp.-hr.)	horsepower(hp.)

Time(T)	Energy Density(M/T^2)	Power Density(M/T^3)
year(yr)	calories/sq. cm.	cal./sq. cm./min.
month	Btu./sq. foot	Btu./sq. foot/hr
day	langley	langley/min.
hour(hr.)	watthr./sq. foot	watt/sq. cm.
minute(min.)		
second(sec.)		

Table of Conversion Factors

MULTIPLY	BY	TO OBTAIN:
Acres	43560	Sq. feet
"	0.004047	Sq. kilometers
"	4047	Sq. meters
"	0.0015625	Sq. miles
"	4840	Sq. yards
Acre-feet	43560	Cu. feet
"	1233.5	Cu. meters
"	1613.3	Cu. yards
Angstroms(Å)	1×10^{-8}	Centimeters
"	3.937×10^{-9}	Inches
"	0.0001	Microns
Atmospheres(atm.)	76	Cm. of Hg(0°C)
"	1033.3	Cm. of H_2O(4°C)
"	33.8995	Ft. of H_2O(39.2°F)
"	29.92	In. of Hg(32°F)
"	14.696	Pounds/sq. inch(psi)
Barrels(petroleum, U.S.)(bbl.)	5.6146	Cu. feet
"	35	Gallons(Imperial)
"	42	Gallons(U.S.)
"	158.98	Liters
British Thermal Unit(Btu)	251.99	Calories, gm
"	777.649	Foot-pounds
"	0.00039275	Horsepower-hours
"	1054.35	Joules
"	0.000292875	Kilowatt-hours
"	1054.35	Watt-seconds
Btu/hr.	4.2	Calories/min.
"	777.65	Foot-pounds/hr.
"	0.0003927	Horsepower
"	0.000292875	Kilowatts
"	0.292875	Watts(or joule/sec.)
Btu/lb.	7.25×10^{-4}	Cal/gram
Btu/sq. ft.	0.271246	Calories/sq. cm. (or langleys)
"	0.292875	Watt-hour/sq. foot
Btu/sq. ft./hour	3.15×10^{-7}	Kilowatts/sq. meter
"	4.51×10^{-3}	Cal./sq. cm./min(or langleys/min)
"	3.15×10^{-8}	Watts/sq. cm.
Calories(cal.)	0.003968	Btu.
"	3.08596	Foot-pounds

"	1.55857×10^{-6}	Horsepower-hours
"	4.184	Joules (or watt-secs)
"	1.1622×10^{-6}	Kilowatt-hours
Calories, food unit (Cal.)	1000	Calories
Calories/min.	0.003968	Btu/min.
"	0.06973	Watts
Calories/sq. cm.	3.68669	Btu/sq. ft.
"	1.0797	Watt-hr/sq. foot
Cal./sq. cm./min.	796320.	Btu/sq. foot/hr.
"	251.04	Watts/sq. cm.
Candle power (spherical)	12.566	Lumens
Centimeters(cm.)	0.032808	Feet
"	0.3937	Inches
"	0.01	Meters
"	10.000	Microns
Cm. of Hg(0°C)	0.0131579	Atmospheres
"	0.44605	Ft. of H_2O(4°C)
"	0.19337	Pounds/sq. inch
Cm. of H_2O(4°C)	0.0009678	Atmospheres
"	0.01422	Pounds/sq. inch
Cm./sec.	0.032808	Feet/sec.
"	0.022369	Miles/hr.
Cords	8	Cord-feet
"	128(or 4×4×8)	Cu. feet
Cu. centimeters	3.5314667	Cu. feet
"	0.06102	Cu. inches
"	1×10^{-6}	Cu. meters
"	0.001	Liters
"	0.0338	Ounces(U.S. fluid)
Cu. feet(ft.^{3})	0.02831685	Cu. meters
"	7.4805	Gallons(U.S., liq.)
"	28.31685	Liters
"	29.922	Quarts(U.S., liq.)
Cu. ft. of H_2O (60°F)	62.366	Pounds of H_2O
Cu. feet/min.	471.947	Cu. cm./sec.
Cu. inches(in.^{3})	16.387	Cu. cm.
"	0.0005787	Cu. feet
"	0.004329	Gallons(U.S., liq.)
"	0.5541	Ounces(U.S., fluid)
Cu. meters	1×10^6	Cu. centimeters
"	35.314667	Cu. feet
"	264.172	Gallons(U.S., liq.)
"	1000	Liters
Cu. yard	27	Cu. feet
"	0.76455	Cu. meters
"	201.97	Gallons(U.S., liq.)
Cubits	18	Inches
Fathoms	6	Feet
"	1.8288	Meters
Feet(ft.)	30.48	Centimeters
"	12	Inches
"	0.00018939	Miles(statute)
Feet of H_2O(4°C)	0.029499	Atmospheres
"	2.2419	Cm. of Hg(0°C)
"	0.433515	Pounds/sq. inch
Feet/min.	0.508	Centimeters/second
"	0.018288	Kilometers/hr.
"	0.0113636	Miles/hr.
Foot-candles	1	Lumens/sq. foot
Foot-pounds	0.001285	Btu.
"	0.324048	Calories
"	5.0505×10^{-7}	Horsepower-hours
"	3.76616×10^{-7}	Kilowatt-hours
Furlong	220	Yards
Gallons(U.S., dry)	1.163647	Gallons(U.S., liq.)
Gallons(U.S., liq.)	3785.4	Cu. centimeters
"	0.13368	Cu. feet
"	231	Cu. inches
"	0.0037854	Cu. meters
"	3.7854	Liters
"	8	Pints(U.S., liq.)
"	4	Quarts(U.S., liq.)
Gallons/min.	2.228×10^{-3}	Cu. feet/sec.
"	0.06308	Liters/sec.
Grams	0.035274	Ounces(avdp.)
"	0.002205	Pounds(avdp.)
Grams-cm.	9.3011×10^{-8}	Btu.
Grams/meter^2	3.98	Short ton/acre
"	8.92	lbs./acre
Horsepower	42.4356	Btu./min.
"	550	Foot-pounds/sec.
"	745.7	Watts
Horsepower-hrs.	2546.14	Btu.
"	641616	Calories
"	1.98×10^6	Foot-pounds
"	0.7457	Kilowatt-hours
Inches	2.54	Centimeters
"	0.83333	Feet
In. of Hg(32°F)	0.03342	Atmospheres
"	1.133	Feet of H_2O
"	0.4912	Pounds/sq. inch
In. of Water(4°C)	0.002458	Atmospheres
"	0.07355	In. of Mercury(32°F)
"	0.03613	Pounds/sq. inch
Joules	0.0009485	Btu.
"	0.73756	Foot-pounds
"	0.0002778	Watt-hours
"	1	Watt-sec.
Kilo calories/gram	1378.54	Btu/lb
Kilograms	2.2046	Pounds(avdp.)
Kilograms/hectare	.893	lbs/acre
Kilograms/hectare	.0004465	Short ton/acre
Kilometers	1000	Meters
"	0.62137	Miles(statute)
Kilometer/hr.	54.68	Feet/min.
Kilowatts	3414.43	Btu./hr.
"	737.56	Foot-pounds/sec.
"	1.34102	Horsepower
Kilowatt-hours	3414.43	Btu.
"	1.34102	Horsepower-hours
Knots	51.44	Centimeter/sec.
"	1	Mile(nautical)/hr.
"	1.15078	Miles(Statute)/hr.
Langleys	1	Calories/sq. cm.
Liters	1000	Cu. centimeters
"	0.0353	Cu. feet
"	0.2642	Gallons(U.S., liq.)
"	1.0567	Quarts(U.S., liq.)
Lbs./acre	.0005	Short ton/acre
Liters/min.	0.0353	Cu. feet/min.
"	0.2642	Gallons(U.S., liq.)/min.
Lumens	0.079577	Candle power(spherical)
Lumens(at 5550Å)	0.0014706	Watts
Meters	3.2808	Feet
"	39.37	Inches
"	1.0936	Yards
Meters/sec.	2.24	Miles/hr.
Micron	10000	Angstroms
"	0.0001	Centimeters
Miles(statute)	5280	Feet

Conversion Factors—Continued

"	1.6093	Kilometers
"	1760	Yards
Miles/hour	44.704	Centimeter/sec.
"	88	Feet/min.
"	1.6093	Kilometer/hr.
"	0.447	Meters/second
Milliliter	1	Cu. centimeter
Millimeter	0.1	Centimeter
Ounces(avdp.)	0.0625	Pounds(avdp.)
Ounces(U.S., liq.)	29.57	Cu. centimeters
"	1.8047	Cu. inches
"	0.0625(or 1/16)	Pint(U.S., liq.)
Pints(U.S., liq.)	473.18	Cu. centimeters
"	28.875	Cu. inches
"	0.5	Quarts(U.S., liq.)
Pounds(avdp.)	0.45359	Kilograms
"	16	Ounces(avdp.)
Pounds of water	0.01602	Cu. feet of water
"	0.1198	Gallons(U.S., liq.)
Pounds/acre	0.0005	Short ton/acre
Pounds/sq. inch	0.06805	Atmospheres
"	5.1715	Cm. of mercury(0°C)
"	27.6807	In. of water(39.2°F)
Quarts(U.S., liq.)	0.25	Gallons(U.S., liq.)
"	0.9463	Liters
"	32	Ounces(U.S., liq.)
"	2	Pints(U.S., liq.)
Radians	57.30	Degrees
Sq. centimeters	0.0010764	Sq. feet
"	0.1550	Sq. inches
Sq. feet	2.2957×10^{-5}	Acres
"	0.09290	Sq. meters
Sq. inches	6.4516	Sq. centimeters
"	0.006944	Sq. feet
Sq. kilometers	247.1	Acres
"	1.0764×10^{7}	Sq. feet
"	0.3861	Sq. miles
Sq. meters	10.7639	Sq. feet
"	1.196	Sq. yards
Sq. miles	640	Acres
"	2.788×10^{7}	Sq. feet
"	2.590	Sq. kilometers
Sq. yards	9(or 3×3)	Sq. feet
"	0.83613	Sq. meters
Tons, long	1016	Kilograms
"	2240	Pounds(avdp.)
Tons(metric)	1000	Kilograms
"	2204.6	Pounds(avdp.)
Tons, metric/hectare	0.446	Short ton/acre
Tons(short)	907.2	Kilograms
"	2000	Pounds(avdp.)
Watts	3.4144	Btu./hr.
"	0.05691	Btu./min.
"	14.34	Calories/min.
"	0.001341	Horsepower
"	1	Joule/sec.
Watts/sq. cm.	3172	Btu./sq. foot/hr.
Watt-hours	3.4144	Btu.
"	860.4	Calories
"	0.001341	Horsepower-hours
Yards	3	Feet
"	0.9144	Meters

Gravitational or Engineer's System of Units

The other system of units is called the "gravitational" or "engineer's system." The unit of force is taken as the lb., and the unit of mass is called the slug. (You see, all masses have a tendency "to stay put"; they are all reluctant to move; they are very sluggish.)

A mass of 1 slug is that which when acted upon by a force of 1 lb. will move with an acceleration of 1 ft. per sec.².

But we have already seen that a force of 1 lb. will cause a mass of g lb. to move with an acceleration of 1 ft. per sec.².

Therefore, *a mass of 1 slug is equivalent to a mass of g lb.*

The mass of a body in slugs is equal to $\dfrac{\textit{its weight in lb.}}{g}$

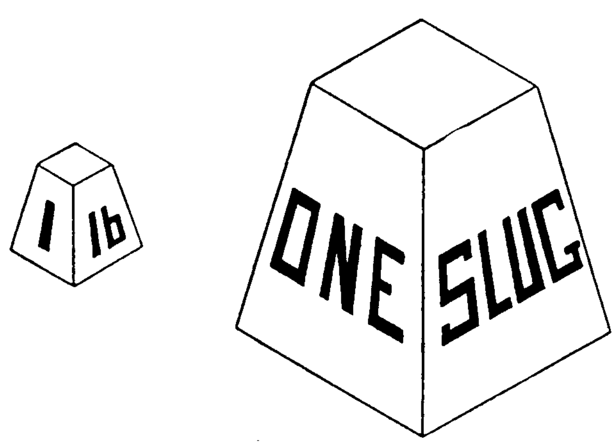


FIG. 29—THE TWO UNITS OF MASS

If a force of 1 lb. were applied to the mass of 1 lb., it would move with an acceleration of 32·2 ft. per sec.². If a force of 1 lb. were applied to the mass of 1 slug, it would move with an acceleration of 1 ft. per sec.². The slug is approximately 32·2 times as big as the pound.

Useful equations and Conversion Factors

1. Areas of a rectangle = Length x width
   Areas of a circle $= \pi \times (\text{radius})^2$

   Surface area of a cylinder
   $= 2\pi \times \text{radius} \times \text{height} + 2\pi \times (\text{radius})^2$
   Surface area of a sphere $= 4\pi\ (\text{radius})^2$

2. Volumes of a rectangular tank
   = Length x Width x Height
   Volumes of a cylinder $= \pi \times (\text{radius})^2 \times \text{Height}$
   Volumes of a sphere $= \frac{4}{3}\pi \times (\text{radius})^3$

3. $$\text{Retention time} = \frac{\text{Volume of Tank}}{\text{Rate of flow of liquid or gas}}$$

4. 1 inch = 2.54 cms. 1 m. = 3.28 feet
   1 foot = 0.305 m. 1 sq. ft. = 0.093 sq. m.
   1 sq. m. = 10.76 sq. ft. 1 cu. ft. = 28 litres = 0.028 m^3.

5. 1 gallon = 4.55 litres 1 litre = 0.22 gallons
   1 m^3 = 220 gallons

6. 1 gallon occupies 0.161 cu. ft. 1,000 litres in 1 cu. m.
   1 cu. ft. = 6.23 gallons

7. 1 gallon of water weighs 10 lbs.
   1 litre of water weighs 1 kg.

8. 1 lb. = 0.454 kg. 1 kg. = 0.221 lb.
   2240 lb. = 1 ton = 1.02 tonnes 1000 kg. = 1 tonne = 0.984 tonne

9. 1 part per million = 1 milligram/litre = 1 gm/m^3
   1% = 10,000 ppm = 10,000 mgm/litre = 10 gm/litre

10. 1 cu. ft./lb. = 0.062 m^3/kg. 1 m^3/kg. = 16.1 cu. ft./lb.

11. 1 lb./cu. ft. = 16.2 kg./m^3. 1 kg./m^3. = 0.062lb./cu. ft.

12. 1 acre = 4,840 sq. yards = 0.405 hectares
    1 hectare = 10,000 sq. metres = 2.47 acres

13. $T\,°F = \frac{5}{9}\,(T - 32)\,°C$ $T\,°C = \frac{9}{5}\,T + 32\,°F$

14. Pressure: 1 in. of water = 0.25 m. bar
    1 lb/sq. in. (psi) = 68.95 m.bar
    1 atmosphere = 1.013 m.bar

15. 1 British Thermal Unit = 0.252 Kcals.
    1 BTU = 1,055 Joules 1 Kcal = 3.97 BTU
    1 Joule = 9.5×10^{-4} BTU 1 Kcal = 4.19 kJ.

16. 100,000 BTU = 1 Therm = 29.3 kilowatt hours

17. 1 BTU/cu. ft. = 0.038 J/cm^3 (or Mega Joules/m^3)
    1 J/cm^3 = 27.0 BTU/cu. ft.

18. 1 BTU/lb. = 2320 J/kg. 1J/kg. = 4.29×10^{-3} BTU/lb.

19. 1 BTU/hr. = 0.0011 mJ/hr.

20. Heat transfer coefficient:
    1 BTU/ft.^{2}/°F/hr. = 20.44 kJ/m^2/°C/hr.

APPENDIX: Conversion Factors

To convert from:	To:	Multiply by:
Length		
centimeters (cm)	inches	0.394
feet (ft)	centimeters	30.5
inches (in)	centimeters	2.54
kilometers (km)	miles	0.621
meters (m)	feet	3.28
meters (m)	yards	1.094
miles (mi)	kilometers	1.609
millimeters (mm)	inches	0.0394
yards (yd)	meters	0.914
Area		
acres	hectares	0.405
acres	sq. meters	4047
hectares (ha)	acres	2.47
hectares (ha)	sq. meters	10,000
sq. centimeters (cm^2)	sq. inches	0.155
sq. feet (ft^2)	sq. meters	0.0929
sq. inches (in^2)	sq. centimeters	6.45
sq. kilometers (km^2)	sq. miles	0.386
sq. kilometers (km^2)	hectares	100
sq. meters (m^2)	sq. feet	10.76
sq. yards (yd^2)	sq. meters	0.836
Volume		
barrels (petroleum, bbl)	liters	159
cubic centimeters (cm^3)	cubic inches	0.0610
cubic feet (ft^3)	cubic meters	0.0283
cubic inches (in^3)	cubic centimeters	16.39
cubic meters (m^3)	cubic feet	35.3
cubic meters (m^3)	cubic yards	1.308
cubic yards (yd^3)	cubic meters	0.765
gallons (gal) US	liters	3.79
gallons (gal) Imp.	liters	4.545
gallons (gal) Imp.	gallons, US	1.20
Weight		
grams (g)	ounces, avdp.	0.0353
kilograms (kg)	pounds	2.205
ounces avdp. (oz)	grams	28.3
pounds (lb)	kilograms	0.454
tons (long)	pounds	2240
tons (long)	kilograms	1016
tons (metric)	pounds	2205
tons (metric)	kilograms	1000
tons (short)	pounds	2000
tons (short)	kilograms	907

To convert from:	To:	Multiply by:
Pressure		
atmosphere	grams/sq.cm	1033
atmosphere	pounds/sq.in	14.7
pounds/sq.in (psi)	grams/sq.cm	70.3
Energy		
British thermal units (Btu)	kilojoules	1.054
calories (cal)	joules	4.19
ergs	joules	1×10^{-7}
kilojoules (kJ)	Btu	0.948
joules (J)	calories	0.239
kilowatt-hours (kWh)	megajoules	3.6
megajoules (MJ)	kilojoules	1000
gigajoules (GJ)	megajoules	1000
terajoules (TJ)	gigajoules	1000
Energy Density		
Btu/gal	joules/cm^3	0.27
Btu/ft^3	kJ/m^3	36.5
Power		
horsepower (hp)	Btu/min	42.4
horsepower (hp)	horsepower (metric)	1.014
horsepower (hp)	kilowatts	0.746
kilowatts (kW)	horsepower	1.341
watts (W)	Btu/hour	3.41
watts (W)	joules/sec	1
Miscellaneous		
liter petrol	megajoules	35
kilogram oil	megajoules	43.2
barrel oil equivalent	gigajoules	6.1
ton coal equivalent	gigajoules	29.3
ton coal equivalent	barrels oil equivalent	4.8
pounds/acre	kilograms/hectare	1.1

A. Conversions

Speed

1 m/s	=	2.24 mph
1 mph	=	0.446 m/s
1 knot	=	1.15 mph
1 mph	=	0.870 knots

Length

1 meter	=	3.28 feet
1 foot	=	0.305 meters
1 kilometer	=	0.620 miles
1 mile	=	1.61 kilometers

Area

1 square kilometer	=	0.386 square miles
1 square kilometer	=	1,000,000 square meters
1 square kilometer	=	100 hectares
1 square mile	=	2.59 square kilometers
1 square foot	=	0.093 square meters
1 square meter	=	10.76 square feet
1 hectare	=	10,000 square meters
1 hectare	=	2.47 acres
1 acre	=	0.405 hectares
1 acre	=	4049 square meters

Volume

1 cubic meter	=	35.3 cubic feet
1 cubic feet	=	0.028 cubic meters
1 liter	=	0.264 gallons
1 gallon	=	3.78 liters
1 cubic meter	=	1000 liters
1 cubic meter	=	264 gallons
1 gallon	=	0.0038 cubic meters

Flow Rate

1 liter/second	=	0.0044 gallons/minute
1 gallon/minute	=	227 liters/second
1 cubic meter/minute	=	264 gallons/minute
1 gallon/minute	=	0.0038 cubic meters/minute

Weight

1 metric ton	=	1.10 tons
1 kilogram	=	2.20 pounds
1 pound	=	0.454 kilograms

Energy Equivalency of Common Fuels

1 kWh = 3413 BTU
= 3.41 ft^3 of natural gas
= 0.034 gallon of oil
= 0.00017 cord of wood

1 Therm = 10^5 BTU
= 100 ft^3 of natural gas
= 1 gallon of oil
= 29.3 kWh of electricity
= 0.005 cord of wood

1 gallon of oil = 1×10^5 BTU

1 cord of wood = 2×10^7 BTU

1000 ft^3 (Mcf) natural gas = 1×10^6 BTU

USEFUL ENERGY CONVERSION FACTORS

For example: 1 BTU has the energy of .00029 Kilo-watt-hours

One of these ↓ / Has the energy of: →	BTU	K-watt hour	Kilo-Calorie	Horse-power hour	Gallon of gasoline
BTU (British Thermal Unit)	1	.00029	.252	.00039	7.4x10^{-6}
Kilo-watt-hour	3412	1	859	1.34	.025
Kilo-calorie	3.97	.0016	1	.00156	2.5x10^{-5}
Horse-power hour	2544	.745	640	1	.0188
Gallon of gasoline	135,000	39.5	34,000	53.0	1
One pound raised one foot (one foot-pound)	.000128	3.7x10^{-7}	.00032	5.0x10^{-7}	9.5x10^{-9}
Joule (a metric unit)	.000948	2.8x10^{-7}	.00024	9.3x10^{-8}	7.0x10^{-9}
Energy collected by 40 sq. ft. S-rotor in 15 mph wind for one hour (see prob. 1.1 on page 12)	282	.0828	71.0	.110	.0021
Energy converted to electricity in line above (see prob. 1.2 on page 12)	127	.0374	32.0	.050	.00094
One gallon of water lifted 100 feet	1.06	.00031	.267	.00041	7.8x10^{-6}
Solar energy hitting one sq. ft. for one hour*	442	.129	111	.173	.0033
One gallon of water heated from 70 F to 212 F	1184	.347	298	.465	.0088
One gallon of water at 212 F boiled away	8078	2.36	2034	3.17	.060
One cu. ft. natural gas	1000	.29	252	.39	.0074
One gallon ethyl alcohol	84,000	24.6	21,100	33.0	.622
One cord of wood (average)	12,000,000	3,660	3,150,000	4,910	92.5
One ton of coal	25,000,000	7,327	6,300,000	9,830	185
One ton vehicle moving at 55 mph	257	.075	64.7	.101	.00257

WARNING: These conversion factors refer to the total energy available and not to useful work. There will always be losses in converting one form of energy into work. That is part of the Second Law of Thermodynamics. That is also why you can't expect one gallon of boiling water to move a car at over 55 mph!

*This is the solar energy available above the earth's atmosphere. There is considerable loss in going through the air.

Note on scientific notation: The superscript above the 10 refers to where the decimal point goes. For example, 7.4x10^{-6} = 0.0000074 and 2.5x10^{-5} = 0.000025

Conversion Tables

1. Conversion Factors

To Convert From	To	Multiply By
Btu	Gram calories	251.9958
Btu	Kilogram calories	.00397
Btu	Cubic centimeters atmospheres	10405.6
Btu	Cubic foot atmospheres	.36747
Btu	Foot pounds	777.649
Btu	Horsepower hours	.0003927
Btu	Kilowatt hours	.00029287
Btu/square foot	Langleys	.271
Btu/hour/square foot/°F	Watts/CM²/°C	5.6820×10^{4}
Cubic foot atmospheres	Btu	2.721
Cubic feet of water	Gallons	7.4805
Cubic feet of water	Pounds	62.366
Foot pounds	Btu	.001285
Gallons of water	Cubic feet	0.13368
Gallons of water	Pounds	8.3453
Gram calories	Btu	.00397
Horsepower	Foot pounds/hour	1,980,000.
Horsepower	Foot pounds/minute	33,000.
Horsepower	Foot pounds/second	550.
Horsepower	Kilowatts	.7457
Horsepower	Watts	745.7
Horsepower hours	Btu	2546.14

To Convert From	To	Multiply By
Horsepower years	Btu	22,304,186.4
Kilogram calories	Btu	3.97
Kilowatts	Horsepower	1.34102
Kilowatt hours	Btu	3414.43
Langleys	Btu/square foot	3.69
Lumens (at 5,550 Å)	Watts	0.0014706
Months (mean calendar)	Hours	730.1
Pints (U.S., liq)	Cubic centimeters	473.18
Pints	Cubic inches	28.875
Pounds of water	Cubic feet of water	0.01602
Pounds of water	Gallons (U.S., liq)	0.1198
Watts	Btu/hour	3.4144
Watts	Btu/minute	0.05691
Watts	Calories/minute	14.34
Watts	Horsepower	0.001341
Watts/square centimeter	Btu/square feet/hour	3,172.
Watt-hours	Btu	3.4144
Watt-hours	Calories	860.4
Watt-hours	Horsepower hours	0.001341

APPENDIX C

CONVERSION FACTORS

To Change	Into	Multiply by
BTU	cal	252
BTU	joules	1,055
BTU	kcal	0.252
BTU	kWh	2.93×10^{-4}
BTU ft^{-2}	langleys ($cal\ cm^{-2}$)	0.271
cal	BTU	3.97×10^{-5}
cal	ft-lb	3.09
cal	joules	4.184
cal	kcal	0.001
cal min^{-1}	watts	0.0698
cm	inches	0.394
cc or cm^3	$in.^3$	0.0610
ft^3	liters	28.3
$in.^3$	cc or cm^3	16.4
ft	m	0.305
ft-lb	cal	0.324
ft-lb	joules	1.36
ft-lb	kg-m	0.138
ft-lb	kWh	3.77×10^{-7}
gal	liters	3.79
hp	kW	0.745
inches	cm	2.54
joules	BTU	9.48×10^{-4}
joules	cal	0.239
joules	ft-lb	0.738
kcal	BTU	3.97
kcal	cal	1,000
kcal min^{-1}	kW	0.0698
kg-m	ft-lb	7.23
kg	lb	2.20
kW	hp	1.34
kWh	BTU	3,413

kWh	ft-lb	2.66×10^6
kW	kcal min^{-1}	14.3
langleys ($cal\ cm^2$)	BTU ft^{-2}	3.69
langleys min^{-1} ($cal\ cm^{-2}\ min^{-1}$)	watts cm^{-2}	0.0698
liters	gal	0.264
liters	qt	1.06
m	ft	3.28
lb	kg	0.454
qt	liters	0.946
cm^2	ft^2	0.00108
cm^2	$in.^2$	0.155
ft^2	m^2	0.0929
m^2	ft^2	10.8
watts cm^{-2}	langleys min^{-1} ($cal\ cm^2$)	14.3

TRIANGULATION.

Triangulation is an application of the principles of trigonometry to the calculation of inaccessible lines and angles. A common occasion for its use is illustrated in Fig. 1, where the line of survey crosses a stream too wide and deep for actual measurement. Set two points A and B on line, one on each side of the stream. Estimate roughly the distance $A\,B$. Suppose the estimate is 425 ft. Set another point C, making the distance $A\,C$ equal to the estimated distance $A\,B = 425$ ft. Set the transit at A and measure the angle $B\,A\,C =$ say, 79° 00′. Next set up at the point C and measure the angle $A\,C\,B =$ say, 56° 20′. The angle $A\,B\,C$ is then determined by subtracting the sum of the angles A and C from 180°; thus, 79° 00′ + 56° 20′ = 135° 20′; 180° 00′ − 135° 20′ = 44° 40′ = the angle $A\,B\,C$. We now have a side and three angles of a triangle given, to find the other two sides $A\,B$ and $C\,B$. In trigonometry, it is demonstrated that, *in any triangle the sines of the angles are proportional to the lengths of the sides opposite to them.* In other words, $\sin A : \sin B = B\,C : A\,C$; or, $\sin A : \sin C = B\,C : A\,B$, and $\sin B : \sin C = A\,C : A\,B$.

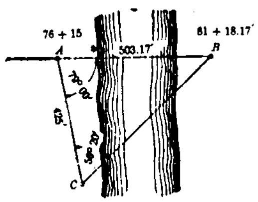


FIG. 1.

Hence, we have sin 44° 40′ : sin 56° 20′ = 425 : side $A\,B$;

sin 56° 20′ = .83228;

.83228 × 425 = 353.719;

sin 44° 40′ = .70298;

353.719 ÷ .70298 = 503.17 ft. = side $A\,B$.

Adding this distance to 76 + 15, the station of the point A, we have 81 + 18.17, the station at B.

Another case is the following: Two tangents, $A\,B$ and $C\,D$ (see Fig. 2), which are to be united by a curve, meet at some inaccessible point E. Tangents are the straight portions of a line of railroad. The angle $C\,E\,F$, which the tangents make with each other, and the distances $B\,E$ and $C\,E$ are required. Two points A and B of the tangent $A\,B$, and two points C and D of the tangent $C\,D$, being carefully located, set the transit at B, and backsighting to A, measure the angle $E\,B\,C = 21° 45′$; set up at C, and, backsighting to D, measure the angle $E\,C\,B = 21° 25′$. Measure the side $B\,C = 304.2$ ft.

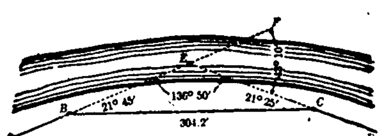


FIG. 2.

Angle $C\,E\,F$ being an exterior angle of triangle $E\,B\,C$ equals sum of $E\,B\,C$ and $E\,C\,B$ = 21° 45′ + 21° 25′ = 43° 10′; angle $B\,E\,C$ = 180° − $C\,E\,F$ = 136° 50′. From trigonometry, we have:

sin 136° 50′ : sin 21° 45′ = 304.2 ft. : $C\,E$;

sin 21° 45′ = .37056;

.37056 × 304.2 = 112.724352;

sin 136° 50′ = .68412;

side $C\,E$ = 112.724352 ÷ .68412 = 164.77 ft.

Again, we find $B\,E$ by the following proportion:

sin 136° 50′ : sin 21° 25′ = 304.2 : side $B\,E$;

sin 21° 25′ = .36515;

.36515 × 304.2 = 111.07863;

sin 136° 50′ = .68412;

side $B\,E$ = 111.07863 ÷ .68412 = 162.36 ft.

A building H, Fig. 3, lies directly in the path of the line $A\,B$, which must be produced beyond H. Set a plug at B, and then turn an angle $D\,B\,C$ = 60°. Set a plug at C in the line $B\,C$, at a suitable distance from B, say, 150 ft. Set up at C, and turn an angle $B\,C\,D$ = 60°, and set a plug at D, 150 ft. from C. The point D will be in the prolongation of $A\,B$. Then, set up at D, and backsighting to C, turn the angle $C\,D\,D'$ = 120°. $D\,D'$ will be the line required, and the distance $B\,D$ will be 150 ft., since $B\,C\,D$ is an equilateral triangle.

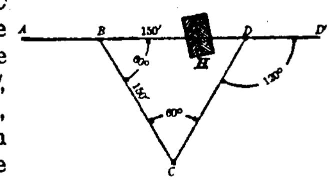


FIG. 3.

$A\,B$ and $C\,D$, Fig. 4, are tangents intersecting at some inaccessible point H. The line $A\,B$ crosses a dock $O\,P$, too wide for direct measurement, and the wharf $L\,M$. F is a point on the line $A\,B$ at the wharf crossing. It is required to find the distance $B\,H$ and the angle $F\,H\,G$. At B, an angle of 103° 30′ is turned to the left and the point E set 217′ from B = to the estimated distance $B\,F$. Setting up at E, the angle $B\,E\,F$ is found to be 39° 00′.

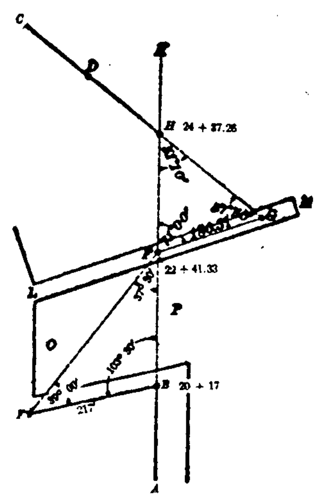


FIG. 4.

Whence, we find the angle $B\,F\,E$ = 180° − (103° 30′ + 39°) = 37° 30′.

From trigonometry, we have

sin 37° 30′ : sin 39° 00′ = 217 ft. : side $B\,F$;

sin 39° 00′ = .62932;

.62932 × 217 = 136.56244;

sin 37° 30′ = .60876;

side $B\,F$ = 136.56244 ÷ .60876 = 224.33 ft.

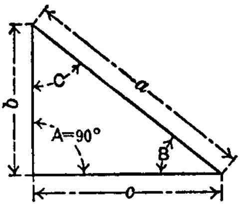
Whence, we find station F to be 20 + 17 + 224.33 = 22 + 41.33. Set up at F and turn an angle $H\,F\,G$ = 71° 00′ and set up at a point G where the line $C\,D$ prolonged intersects $F\,G$. Measure the angle $F\,G\,H$ = 57° 50′, and the side $F\,G$ = 180.3. The angle $F\,H\,G$ = 180° − (71° + 57° 50′) = 51° 10′. From trigonometry we have

sin 51° 10′ : sin 57° 50′ = 180.3 : side $F\,H$.

Sin 57° 50′ = .84650; .84650 × 180.3 = 152.62395; sin 51° 10′ = .77897; side $F\,H$ = 152.62395 ÷ .77897 = 195.93 ft.; whence we find station H to be 24 + 37.26.

Solving Right-angled Triangles

Formulas

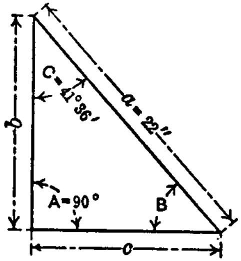


As shown in the illustration, the sides of the right-angled triangle are designated a, b, and c. The angles opposite each of these sides are designated A, B, and C, respectively.

Angle A, opposite the hypotenuse a, is the right angle, and is, therefore, always one of the known quantities.

Sides and Angles Known	Formulas for Sides and Angles to be Found		
Sides a and b....................	$c = \sqrt{a^2 - b^2}$	$\sin B = \frac{b}{a}$	$C = 90° - B$
Sides a and c....................	$b = \sqrt{a^2 - c^2}$	$\sin C = \frac{c}{a}$	$B = 90° - C$
Sides b and c....................	$a = \sqrt{b^2 + c^2}$	$\tan B = \frac{b}{c}$	$C = 90° - B$
Side a; angle B..................	$b = a \times \sin B$	$c = a \times \cos B$	$C = 90° - B$
Side a; angle C..................	$b = a \times \cos C$	$c = a \times \sin C$	$B = 90° - C$
Side b; angle B..................	$a = \frac{b}{\sin B}$	$c = b \times \cot B$	$C = 90° - B$
Side b; angle C..................	$a = \frac{b}{\cos C}$	$c = b \times \tan C$	$B = 90° - C$
Side c; angle B..................	$a = \frac{c}{\cos B}$	$b = c \times \tan B$	$C = 90° - B$
Side c; angle C..................	$a = \frac{c}{\sin C}$	$b = c \times \cot C$	$B = 90° - C$

Examples

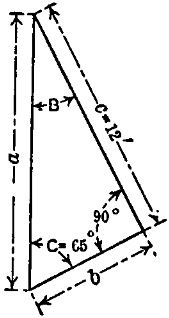


Sides and angles known:

$$a = 22 \text{ inches}; \quad C = 41 \text{ degrees } 36 \text{ minutes.}$$

Then, by the formulas given herewith:

$$b = a \times \cos C = 22 \times \cos 41^\circ\, 36' = 22 \times 0.74780$$
$$= 16.4516 \text{ inches.}$$
$$c = a \times \sin C = 22 \times \sin 41^\circ\, 36' = 22 \times 0.66393$$
$$= 14.6065 \text{ inches.}$$
$$B = 90^\circ - 41^\circ\, 36' = 48^\circ\, 24'.$$

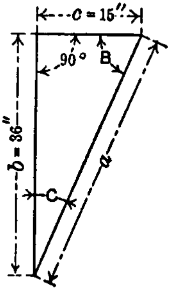


Sides and angles known:

$$c = 12 \text{ feet}; \quad C = 65 \text{ degrees.}$$

Then, by the formulas:

$$a = \frac{c}{\sin C} = \frac{12}{\sin 65^\circ} = \frac{12}{0.90631} = 13.2405 \text{ feet.}$$
$$b = c \times \cot C = 12 \times \cot 65^\circ = 12 \times 0.46631$$
$$= 5.5957 \text{ feet.}$$
$$B = 90^\circ - 65^\circ = 25^\circ.$$



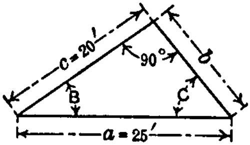
Sides known:

$$b = 36 \text{ inches}; \quad c = 15 \text{ inches.}$$

Then, by the formulas:

$$a = \sqrt{b^2 + c^2} = \sqrt{36^2 + 15^2} = \sqrt{1296 + 225}$$
$$= \sqrt{1521} = 39 \text{ inches.}$$
$$\tan B = \frac{b}{c} = \frac{36}{15} = 2.4.$$

Hence,
$$B = 67^\circ\, 23'.$$
$$C = 90^\circ - 67^\circ\, 23' = 22^\circ\, 37'.$$



Sides known:

$$a = 25 \text{ feet}; \quad c = 20 \text{ feet.}$$

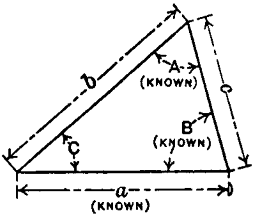
From the formulas:

$$b = \sqrt{a^2 - c^2} = \sqrt{25^2 - 20^2} = \sqrt{625 - 400}$$
$$= \sqrt{225} = 15 \text{ feet.}$$
$$\sin C = \frac{c}{a} = \frac{20}{25} = 0.8.$$

Hence,
$$C = 53^\circ\, 8'.$$
$$B = 90^\circ - 53^\circ\, 8' = 36^\circ\, 52'.$$

Solving Oblique-angled Triangles

Formulas



One side and two angles known.

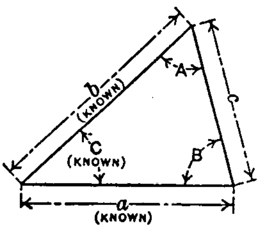
Call the known side a, the angle opposite it A, and the other known angle B. Then:

$$C = 180° - (A + B).$$

$$b = \frac{a \times \sin B}{\sin A}. \qquad c = \frac{a \times \sin C}{\sin A}.$$

$$\text{Area} = \frac{a \times b \times \sin C}{2}.$$

If angles B and C are given, but not A, then $A = 180° - (B + C)$, the other formulas being the same.



Two sides and the angle between them known.

Call the known sides a and b and the known angle between them C. Then:

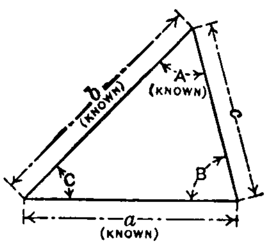
$$\tan A = \frac{a \times \sin C}{b - a \times \cos C}.$$

$$B = 180° - (A + C). \qquad c = \frac{a \times \sin C}{\sin A}.$$

Side c may also be found directly as below:

$$c = \sqrt{a^2 + b^2 - 2\,ab \times \cos C}.$$

$$\text{Area} = \frac{a \times b \times \sin C}{2}.$$



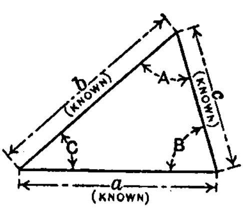
Two sides and the angle opposite one of the sides known.

Call the known angle A, the side opposite it a, and the other known side b. Then:

$$\sin B = \frac{b \times \sin A}{a}. \qquad C = 180° - (A + B).$$

$$c = \frac{a \times \sin C}{\sin A}.$$

$$\text{Area} = \frac{a \times b \times \sin C}{2}.$$



All three sides known.

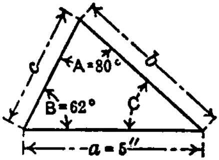
Call the sides a, b, and c, and the angles opposite them A, B, and C. Then:

$$\cos A = \frac{b^2 + c^2 - a^2}{2\,bc}.$$

$$\sin B = \frac{b \times \sin A}{a}. \qquad C = 180° - (A + B).$$

$$\text{Area} = \frac{a \times b \times \sin C}{2}.$$

Examples



Sides and angles known:

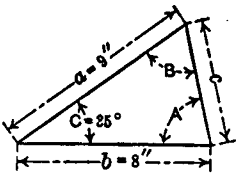
$$a = 5 \text{ inches}; \ A = 80 \text{ degrees}; \ B = 62 \text{ degrees}.$$

Then, by the formulas opposite:

$$C = 180° - (80° + 62°) = 180° - 142° = 38°.$$

$$b = \frac{a \times \sin B}{\sin A} = \frac{5 \times \sin 62°}{\sin 80°} = \frac{5 \times 0.88295}{0.98481} = 4.483 \text{ inches}.$$

$$c = \frac{a \times \sin C}{\sin A} = \frac{5 \times \sin 38°}{\sin 80°} = \frac{5 \times 0.61566}{0.98481} = 3.126 \text{ inches}.$$



Sides and angles known:

$$a = 9 \text{ inches}; \ b = 8 \text{ inches}; \ C = 35 \text{ degrees}.$$

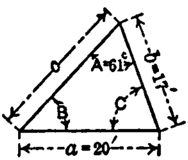
$$\tan A = \frac{a \times \sin C}{b - a \times \cos C} = \frac{9 \times \sin 35°}{8 - 9 \times \cos 35°}$$

$$= \frac{9 \times 0.57358}{8 - 9 \times 0.81915} = \frac{5.16222}{0.62765} = 8.22468.$$

Hence, $A = 83° \ 4'$.

$$B = 180° - (A + C) = 180° - 118° \ 4' = 61° \ 56'.$$

$$c = \frac{a \times \sin C}{\sin A} = \frac{9 \times 0.57358}{0.99269} = 5.2 \text{ inches}.$$



Sides and angles known:

$$a = 20 \text{ feet}; \ b = 17 \text{ feet}; \ A = 61 \text{ degrees}.$$

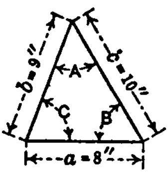
$$\sin B = \frac{b \times \sin A}{a} = \frac{17 \times \sin 61°}{20}$$

$$= \frac{17 \times 0.87462}{20} = 0.74343.$$

Hence, $B = 48° \ 1'$.

$$C = 180° - (A + B) = 180° - 109° \ 1' = 70° \ 59'.$$

$$c = \frac{a \times \sin C}{\sin A} = \frac{20 \times \sin 70° \ 59'}{\sin 61°} = \frac{20 \times 0.94542}{0.87462} = 21.62 \text{ feet}.$$



Sides known:

$$a = 8 \text{ inches}; \ b = 9 \text{ inches}; \ c = 10 \text{ inches}.$$

$$\cos A = \frac{b^2 + c^2 - a^2}{2\,bc} = \frac{9^2 + 10^2 - 8^2}{2 \times 9 \times 10}$$

$$= \frac{81 + 100 - 64}{180} = \frac{117}{180} = 0.65000.$$

Hence, $A = 49° \ 27'$.

$$\sin B = \frac{b \times \sin A}{a} = \frac{9 \times 0.75984}{8} = 0.85482.$$

Hence, $B = 58° \ 44'$.

$$C = 180° - (A + B) = 180° - 108° \ 11' = 71° \ 49'.$$

x	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Δ	ADD				
	0°·0	0°·1	0°·2	0°·3	0°·4	0°·5	0°·6	0°·7	0°·8	0°·9		1′	2′	3′	4′	5′
0°	0·0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	18	3	6	9	12	15
1	·0175	0192	0209	0227	0244	0262	0279	0297	0314	0332		3	6	9	12	15
2	·0349	0366	0384	0401	0419	0436	0454	0471	0488	0506		3	6	9	12	15
3	·0523	0541	0558	0576	0593	0610	0628	0645	0663	0680		3	6	9	12	15
4	·0698	0715	0732	0750	0767	0785	0802	0819	0837	0854		3	6	9	12	14
5	0·0872	0889	0906	0924	0941	0958	0976	0993	1011	1028		3	6	9	12	14
6	·1045	1063	1080	1097	1115	1132	1149	1167	1184	1201		3	6	9	12	14
7	·1219	1236	1253	1271	1288	1305	1323	1340	1357	1374		3	6	9	12	14
8	·1392	1409	1426	1444	1461	1478	1495	1513	1530	1547		3	6	9	11	14
9	·1564	1582	1599	1616	1633	1650	1668	1685	1702	1719		3	6	9	11	14
10	0·1736	1754	1771	1788	1805	1822	1840	1857	1874	1891		3	6	9	11	14
11	·1908	1925	1942	1959	1977	1994	2011	2028	2045	2062		3	6	9	11	14
12	·2079	2096	2113	2130	2147	2164	2181	2198	2215	2233	17	3	6	9	11	14
13	·2250	2267	2284	2300	2317	2334	2351	2368	2385	2402		3	6	8	11	14
14	·2419	2436	2453	2470	2487	2504	2521	2538	2554	2571		3	6	8	11	14
15	0·2588	2605	2622	2639	2656	2672	2689	2706	2723	2740		3	6	8	11	14
16	·2756	2773	2790	2807	2823	2840	2857	2874	2890	2907		3	6	8	11	14
17	·2924	2940	2957	2974	2990	3007	3024	3040	3057	3074		3	6	8	11	14
18	·3090	3107	3123	3140	3156	3173	3190	3206	3223	3239		3	6	8	11	14
19	·3256	3272	3289	3305	3322	3338	3355	3371	3387	3404		3	5	8	11	14
20	0·3420	3437	3453	3469	3486	3502	3518	3535	3551	3567		3	5	8	11	14
21	·3584	3600	3616	3633	3649	3665	3681	3697	3714	3730		3	5	8	11	14
22	·3746	3762	3778	3795	3811	3827	3843	3859	3875	3891		3	5	8	11	13
23	·3907	3923	3939	3955	3971	3987	4003	4019	4035	4051	16	3	5	8	11	13
24	·4067	4083	4099	4115	4131	4147	4163	4179	4195	4210		3	5	8	11	13
25	0·4226	4242	4258	4274	4289	4305	4321	4337	4352	4368		3	5	8	11	13
26	·4384	4399	4415	4431	4446	4462	4478	4493	4509	4524		3	5	8	10	13
27	·4540	4555	4571	4586	4602	4617	4633	4648	4664	4679		3	5	8	10	13
28	·4695	4710	4726	4741	4756	4772	4787	4802	4818	4833		3	5	8	10	13
29	·4848	4863	4879	4894	4909	4924	4939	4955	4970	4985		3	5	8	10	13
30	0·5000	5015	5030	5045	5060	5075	5090	5105	5120	5135	15	3	5	8	10	13
31	·5150	5165	5180	5195	5210	5225	5240	5255	5270	5284		2	5	7	10	12
32	·5299	5314	5329	5344	5358	5373	5388	5402	5417	5432		2	5	7	10	12
33	·5446	5461	5476	5490	5505	5519	5534	5548	5563	5577		2	5	7	10	12
34	·5592	5606	5621	5635	5650	5664	5678	5693	5707	5721		2	5	7	10	12
35	0·5736	5750	5764	5779	5793	5807	5821	5835	5850	5864		2	5	7	9	12
36	·5878	5892	5906	5920	5934	5948	5962	5976	5990	6004	14	2	5	7	9	12
37	·6018	6032	6046	6060	6074	6088	6101	6115	6129	6143		2	5	7	9	12
38	·6157	6170	6184	6198	6211	6225	6239	6252	6266	6280		2	5	7	9	11
39	·6293	6307	6320	6334	6347	6361	6374	6388	6401	6414		2	4	7	9	11
40	0·6428	6441	6455	6468	6481	6494	6508	6521	6534	6547		2	4	7	9	11
41	·6561	6574	6587	6600	6613	6626	6639	6652	6665	6678	13	2	4	7	9	11
42	·6691	6704	6717	6730	6743	6756	6769	6782	6794	6807		2	4	6	9	11
43	·6820	6833	6845	6858	6871	6884	6896	6909	6921	6934		2	4	6	8	11
44	·6947	6959	6972	6984	6997	7009	7022	7034	7046	7059		2	4	6	8	10
45	0·7071	7083	7096	7108	7120	7133	7145	7157	7169	7181		2	4	6	8	10
46	·7193	7206	7218	7230	7242	7254	7266	7278	7290	7302	12	2	4	6	8	10
47	·7314	7325	7337	7349	7361	7373	7385	7396	7408	7420		2	4	6	8	10
48	·7431	7443	7455	7466	7478	7490	7501	7513	7524	7536		2	4	6	8	10
49	0·7547	7559	7570	7581	7593	7604	7615	7627	7638	7649		2	4	6	8	9

$\frac{O}{H}$

x	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Δ	ADD				
	0°·0	0°·1	0°·2	0°·3	0°·4	0°·5	0°·6	0°·7	0°·8	0°·9		1′	2′	3′	4′	5′
50°	0·7660	7672	7683	7694	7705	7716	7727	7738	7749	7760		2	4	6	7	9
51	·7771	7782	7793	7804	7815	7826	7837	7848	7859	7869	11	2	4	5	7	9
52	·7880	7891	7902	7912	7923	7934	7944	7955	7965	7976		2	4	5	7	9
53	·7986	7997	8007	8018	8028	8039	8049	8059	8070	8080		2	3	5	7	9
54	·8090	8100	8111	8121	8131	8141	8151	8161	8171	8181	10	2	3	5	7	8
55	0·8192	8202	8211	8221	8231	8241	8251	8261	8271	8281		2	3	5	7	8
56	·8290	8300	8310	8320	8329	8339	8348	8358	8368	8377		2	3	5	6	8
57	·8387	8396	8406	8415	8425	8434	8443	8453	8462	8471		2	3	5	6	8
58	·8480	8490	8499	8508	8517	8526	8536	8545	8554	8563	9	2	3	5	6	8
59	·8572	8581	8590	8599	8607	8616	8625	8634	8643	8652		1	3	4	6	7
60	0·8660	8669	8678	8686	8695	8704	8712	8721	8729	8738		1	3	4	6	7
61	·8746	8755	8763	8771	8780	8788	8796	8805	8813	8821		1	3	4	6	7
62	·8829	8838	8846	8854	8862	8870	8878	8886	8894	8902	8	1	3	4	5	7
63	·8910	8918	8926	8934	8942	8949	8957	8965	8973	8980		1	3	4	5	6
64	·8988	8996	9003	9011	9018	9026	9033	9041	9048	9056		1	3	4	5	6
65	0·9063	9070	9078	9085	9092	9100	9107	9114	9121	9128		1	2	4	5	6
66	·9135	9143	9150	9157	9164	9171	9178	9184	9191	9198	7	1	2	4	5	6
67	·9205	9212	9219	9225	9232	9239	9245	9252	9259	9265		1	2	3	4	6
68	·9272	9278	9285	9291	9298	9304	9311	9317	9323	9330		1	2	3	4	5
69	·9336	9342	9348	9354	9361	9367	9373	9379	9385	9391	6	1	2	3	4	5
70	0·9397	9403	9409	9415	9421	9426	9432	9438	9444	9449		1	2	3	4	5
71	·9455	9461	9466	9472	9478	9483	9489	9494	9500	9505		1	2	3	4	5
72	·9511	9516	9521	9527	9532	9537	9542	9548	9553	9558		1	2	3	3	4
73	·9563	9568	9573	9578	9583	9588	9593	9598	9603	9608	5	1	2	2	3	4
74	·9613	9617	9622	9627	9632	9636	9641	9646	9650	9655		1	2	2	3	4
75	0·9659	9664	9668	9673	9677	9681	9686	9690	9694	9699		1	1	2	3	4
76	·9703	9707	9711	9715	9720	9724	9728	9732	9736	9740	4	1	1	2	3	3
77	·9744	9748	9751	9755	9759	9763	9767	9770	9774	9778		1	1	2	2	3
78	·9781	9785	9789	9792	9796	9799	9803	9806	9810	9813		1	1	2	2	3
79	·9816	9820	9823	9826	9829	9833	9836	9839	9842	9845		1	1	2	2	3
80	0·9848	9851	9854	9857	9860	9863	9866	9869	9871	9874	3	0	1	1	2	2
81	·9877	9880	9882	9885	9888	9890	9893	9895	9898	9900		0	1	1	2	2
82	·9903	9905	9907	9910	9912	9914	9917	9919	9921	9923		0	1	1	1	2
83	·9925	9928	9930	9932	9934	9936	9938	9940	9942	9943	2	0	1	1	1	2
84	·9945	9947	9949	9951	9952	9954	9956	9957	9959	9960		0	1	1	1	1
85	0·9962	9963	9965	9966	9968	9969	9971	9972	9973	9974		0	0	1	1	1
86	·9976	9977	9978	9979	9980	9981	9982	9983	9984	9985	1	0	0	1	1	1
87	·9986	9987	9988	9989	9990	9990	9991	9992	9993	9993						
88	·9994	9995	9995	9996	9996	9997	9997	9997	9998	9998		See Table below.				
89	0·9998	9999	9999	9999	9999	1·000	1·000	1·000	1·000	1·000						
90	1·0000															

Sines of Angles near 90°

° ′	sine	°
86 48		86·80
	0·9985	
86 54		86·91
	0·9986	
87 01		87·02
	0·9987	
87 08		87·13
	0·9988	
87 15		87·25
	0·9989	
87 22		87·37
	0·9990	
87 30		87·50
	0·9991	
87 38		87·63
	0·9992	
87 46		87·78

° ′	sine	°
87 46		87·7
	0·9993	
87 56		87·9
	0·9994	
88 05		88·0
	0·9995	
88 16		88·2
	0·9996	
88 29		88·4
	0·9997	
88 43		88·7
	0·9998	
89 00		89·0
	0·9999	
89 25		89·4
	1·0000	
90 00		90·0

The values in the centre columns represent the sines for all angles lying between the successive ranges shown in the outer columns. Thus sin 87° 20′ is 0·9989. For inverse use, the best angle for a given sine is the one lying midway between the adjacent ranges; if the difference is odd, choose the angle nearer 90°. Thus if sin x = 0·9988, x = 87° 12′.

For tabulated angles read the sine value in the half-line above; e.g., sin 87° 38′ = 0·9991.

x	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Δ	SUBTRACT				
	0°·0	0°·1	0°·2	0°·3	0°·4	0°·5	0°·6	0°·7	0°·8	0°·9		1′	2′	3′	4′	5′
0°	1·000	1·000	1·000	1·000	1·000	1·000	0·9999	0·9999	0·9999	0·9999	·	See table at foot of page.				
1	0·9998	9998	9998	9997	9997	9997	9996	9996	9995	9995						
2	·9994	9993	9993	9992	9991	9990	9990	9989	9988	9987						
3	·9986	9985	9984	9983	9982	9981	9980	9979	9978	9977	1	0	0	1	1	1
4	·9976	9974	9973	9972	9971	9969	9968	9966	9965	9963		0	0	1	1	1
5	0·9962	9960	9959	9957	9956	9954	9952	9951	9949	9947		0	1	1	1	1
6	·9945	9943	9942	9940	9938	9936	9934	9932	9930	9928	2	0	1	1	1	2
7	·9925	9923	9921	9919	9917	9914	9912	9910	9907	9905		0	1	1	1	2
8	·9903	9900	9898	9895	9893	9890	9888	9885	9882	9880		0	1	1	2	2
9	·9877	9874	9871	9869	9866	9863	9860	9857	9854	9851	3	0	1	1	2	2
10	0·9848	9845	9842	9839	9836	9833	9829	9826	9823	9820		1	1	2	2	3
11	·9816	9813	9810	9806	9803	9799	9796	9792	9789	9785		1	1	2	2	3
12	·9781	9778	9774	9770	9767	9763	9759	9755	9751	9748		1	1	2	2	3
13	·9744	9740	9736	9732	9728	9724	9720	9715	9711	9707	4	1	1	2	3	3
14	·9703	9699	9694	9690	9686	9681	9677	9673	9668	9664		1	1	2	3	4
15	0·9659	9655	9650	9646	9641	9636	9632	9627	9622	9617		1	2	2	3	4
16	·9613	9608	9603	9598	9593	9588	9583	9578	9573	9568	5	1	2	2	3	4
17	·9563	9558	9553	9548	9542	9537	9532	9527	9521	9516		1	2	3	3	4
18	·9511	9505	9500	9494	9489	9483	9478	9472	9466	9461		1	2	3	4	5
19	·9455	9449	9444	9438	9432	9426	9421	9415	9409	9403		1	2	3	4	5
20	0·9397	9391	9385	9379	9373	9367	9361	9354	9348	9342	6	1	2	3	4	5
21	·9336	9330	9323	9317	9311	9304	9298	9291	9285	9278		1	2	3	4	5
22	·9272	9265	9259	9252	9245	9239	9232	9225	9219	9212		1	2	3	4	6
23	·9205	9198	9191	9184	9178	9171	9164	9157	9150	9143	7	1	2	4	5	6
24	·9135	9128	9121	9114	9107	9100	9092	9085	9078	9070		1	2	4	5	6
25	0·9063	9056	9048	9041	9033	9026	9018	9011	9003	8996		1	3	4	5	6
26	·8988	8980	8973	8965	8957	8949	8942	8934	8926	8918		1	3	4	5	6
27	·8910	8902	8894	8886	8878	8870	8862	8854	8846	8838	8	1	3	4	5	7
28	·8829	8821	8813	8805	8796	8788	8780	8771	8763	8755		1	3	4	6	7
29	·8746	8738	8729	8721	8712	8704	8695	8686	8678	8669		1	3	4	6	7
30	0·8660	8652	8643	8634	8625	8616	8607	8599	8590	8581		1	3	4	6	7
31	·8572	8563	8554	8545	8536	8526	8517	8508	8499	8490	9	2	3	5	6	8
32	·8480	8471	8462	8453	8443	8434	8425	8415	8406	8396		2	3	5	6	8
33	·8387	8377	8368	8358	8348	8339	8329	8320	8310	8300		2	3	5	6	8
34	·8290	8281	8271	8261	8251	8241	8231	8221	8211	8202		2	3	5	7	8
35	0·8192	8181	8171	8161	8151	8141	8131	8121	8111	8100	10	2	3	5	7	8
36	·8090	8080	8070	8059	8049	8039	8028	8018	8007	7997		2	3	5	7	9
37	·7986	7976	7965	7955	7944	7934	7923	7912	7902	7891		2	4	5	7	9
38	·7880	7869	7859	7848	7837	7826	7815	7804	7793	7782	11	2	4	5	7	9
39	0·7771	7760	7749	7738	7727	7716	7705	7694	7683	7672		2	4	6	7	9

Cosines of Small Angles

° ′	cosine	°	° ′	cosine	°
0 00		0·0	2 13		2·21
	1·0000			0·9992	
0 34		0·5	2 21		2·36
	0·9999			0·9991	
0 59		0·9	2 29		2·49
	0·9998			0·9990	
1 16		1·2	2 37		2·62
	0·9997			0·9989	
1 30		1·5	2 44		2·74
	0·9996			0·9988	
1 43		1·7	2 51		2·86
	0·9995			0·9987	
1 54		1·9	2 58		2·97
	0·9994			0·9986	
2 03		2·0	3 05		3·08
	0·9993			0·9985	
2 13		2·2	3 11		3·19

This table is similar to that given for sines on page 15; thus

cos 2° 40′ = 0·9989

0·9986 = cos 3° 2′

A

H.

x	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Δ	SUBTRACT 1′	2′	3′	4′	5′
40°	0·7660	7649	7638	7627	7615	7604	7593	7581	7570	7559		2	4	6	8	9
41	·7547	7536	7524	7513	7501	7490	7478	7466	7455	7443		2	4	6	8	10
42	·7431	7420	7408	7396	7385	7373	7361	7349	7337	7325		2	4	6	8	10
43	·7314	7302	7290	7278	7266	7254	7242	7230	7218	7206	12	2	4	6	8	10
44	·7193	7181	7169	7157	7145	7133	7120	7108	7096	7083		2	4	6	8	10
45	0·7071	7059	7046	7034	7022	7009	6997	6984	6972	6959		2	4	6	8	10
46	·6947	6934	6921	6909	6896	6884	6871	6858	6845	6833		2	4	6	8	11
47	·6820	6807	6794	6782	6769	6756	6743	6730	6717	6704		2	4	6	9	11
48	·6691	6678	6665	6652	6639	6626	6613	6600	6587	6574	13	2	4	7	9	11
49	·6561	6547	6534	6521	6508	6494	6481	6468	6455	6441		2	4	7	9	11
50	0·6428	6414	6401	6388	6374	6361	6347	6334	6320	6307		2	4	7	9	11
51	·6293	6280	6266	6252	6239	6225	6211	6198	6184	6170		2	5	7	9	11
52	·6157	6143	6129	6115	6101	6088	6074	6060	6046	6032		2	5	7	9	12
53	·6018	6004	5990	5976	5962	5948	5934	5920	5906	5892	14	2	5	7	9	12
54	·5878	5864	5850	5835	5821	5807	5793	5779	5764	5750		2	5	7	9	12
55	0·5736	5721	5707	5693	5678	5664	5650	5635	5621	5606		2	5	7	10	12
56	·5592	5577	5563	5548	5534	5519	5505	5490	5476	5461		2	5	7	10	12
57	·5446	5432	5417	5402	5388	5373	5358	5344	5329	5314		2	5	7	10	12
58	·5299	5284	5270	5255	5240	5225	5210	5195	5180	5165		2	5	7	10	12
59	·5150	5135	5120	5105	5090	5075	5060	5045	5030	5015	15	3	5	8	10	13
60	0·5000	4985	4970	4955	4939	4924	4909	4894	4879	4863		3	5	8	10	13
61	·4848	4833	4818	4802	4787	4772	4756	4741	4726	4710		3	5	8	10	13
62	·4695	4679	4664	4648	4633	4617	4602	4586	4571	4555		3	5	8	10	13
63	·4540	4524	4509	4493	4478	4462	4446	4431	4415	4399		3	5	8	10	13
64	·4384	4368	4352	4337	4321	4305	4289	4274	4258	4242		3	5	8	11	13
65	0·4226	4210	4195	4179	4163	4147	4131	4115	4099	4083		3	5	8	11	13
66	·4067	4051	4035	4019	4003	3987	3971	3955	3939	3923	16	3	5	8	11	13
67	·3907	3891	3875	3859	3843	3827	3811	3795	3778	3762		3	5	8	11	13
68	·3746	3730	3714	3697	3681	3665	3649	3633	3616	3600		3	5	8	11	14
69	·3584	3567	3551	3535	3518	3502	3486	3469	3453	3437		3	5	8	11	14
70	0·3420	3404	3387	3371	3355	3338	3322	3305	3289	3272		3	5	8	11	14
71	·3256	3239	3223	3206	3190	3173	3156	3140	3123	3107		3	6	8	11	14
72	·3090	3074	3057	3040	3024	3007	2990	2974	2957	2940		3	6	8	11	14
73	·2924	2907	2890	2874	2857	2840	2823	2807	2790	2773		3	6	8	11	14
74	·2756	2740	2723	2706	2689	2672	2656	2639	2622	2605		3	6	8	11	14
75	0·2588	2571	2554	2538	2521	2504	2487	2470	2453	2436		3	6	8	11	14
76	·2419	2402	2385	2368	2351	2334	2317	2300	2284	2267		3	6	8	11	14
77	·2250	2233	2215	2198	2181	2164	2147	2130	2113	2096	17	3	6	9	11	14
78	·2079	2062	2045	2028	2011	1994	1977	1959	1942	1925		3	6	9	11	14
79	·1908	1891	1874	1857	1840	1822	1805	1788	1771	1754		3	6	9	11	14
80	0·1736	1719	1702	1685	1668	1650	1633	1616	1599	1582		3	6	9	11	14
81	·1564	1547	1530	1513	1495	1478	1461	1444	1426	1409		3	6	9	11	14
82	·1392	1374	1357	1340	1323	1305	1288	1271	1253	1236		3	6	9	12	14
83	·1219	1201	1184	1167	1149	1132	1115	1097	1080	1063		3	6	9	12	14
84	·1045	1028	1011	0993	0976	0958	0941	0924	0906	0889		3	6	9	12	14
85	0·0872	0854	0837	0819	0802	0785	0767	0750	0732	0715		3	6	9	12	14
86	·0698	0680	0663	0645	0628	0610	0593	0576	0558	0541		3	6	9	12	15
87	·0523	0506	0488	0471	0454	0436	0419	0401	0384	0366		3	6	9	12	15
88	·0349	0332	0314	0297	0279	0262	0244	0227	0209	0192		3	6	9	12	15
89	0·0175	0157	0140	0122	0105	0087	0070	0052	0035	0017	18	3	6	9	12	15
90	0·0000															

x	0′ 0°·0	6′ 0°·1	12′ 0°·2	18′ 0°·3	24′ 0°·4	30′ 0°·5	36′ 0°·6	42′ 0°·7	48′ 0°·8	54′ 0°·9	Δ	ADD				
												1′	2′	3′	4′	5′
0°	0·0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	18	3	6	9	12	15
1	·0175	0192	0209	0227	0244	0262	0279	0297	0314	0332		3	6	9	12	15
2	·0349	0367	0384	0402	0419	0437	0454	0472	0489	0507		3	6	9	12	15
3	·0524	0542	0559	0577	0594	0612	0629	0647	0664	0682		3	6	9	12	15
4	·0699	0717	0734	0752	0769	0787	0805	0822	0840	0857		3	6	9	12	15
5	0·0875	0892	0910	0928	0945	0963	0981	0998	1016	1033		3	6	9	12	15
6	·1051	1069	1086	1104	1122	1139	1157	1175	1192	1210		3	6	9	12	15
7	·1228	1246	1263	1281	1299	1317	1334	1352	1370	1388		3	6	9	12	15
8	·1405	1423	1441	1459	1477	1495	1512	1530	1548	1566		3	6	9	12	15
9	·1584	1602	1620	1638	1655	1673	1691	1709	1727	1745		3	6	9	12	15
10	0·1763	1781	1799	1817	1835	1853	1871	1890	1908	1926		3	6	9	12	15
11	·1944	1962	1980	1998	2016	2035	2053	2071	2089	2107		3	6	9	12	15
12	·2126	2144	2162	2180	2199	2217	2235	2254	2272	2290		3	6	9	12	15
13	·2309	2327	2345	2364	2382	2401	2419	2438	2456	2475		3	6	9	12	15
14	·2493	2512	2530	2549	2568	2586	2605	2623	2642	2661		3	6	9	12	15
15	0·2679	2698	2717	2736	2754	2773	2792	2811	2830	2849		3	6	9	13	16
16	·2867	2886	2905	2924	2943	2962	2981	3000	3019	3038	19	3	6	10	13	16
17	·3057	3076	3096	3115	3134	3153	3172	3191	3211	3230		3	6	10	13	16
18	·3249	3269	3288	3307	3327	3346	3365	3385	3404	3424		3	6	10	13	16
19	·3443	3463	3482	3502	3522	3541	3561	3581	3600	3620		3	7	10	13	16
20	0·3640	3659	3679	3699	3719	3739	3759	3779	3799	3819	20	3	7	10	13	17
21	·3839	3859	3879	3899	3919	3939	3959	3979	4000	4020		3	7	10	13	17
22	·4040	4061	4081	4101	4122	4142	4163	4183	4204	4224		3	7	10	14	17
23	·4245	4265	4286	4307	4327	4348	4369	4390	4411	4431		3	7	10	14	17
24	·4452	4473	4494	4515	4536	4557	4578	4599	4621	4642	21	4	7	11	14	18
25	0·4663	4684	4706	4727	4748	4770	4791	4813	4834	4856		4	7	11	14	18
26	·4877	4899	4921	4942	4964	4986	5008	5029	5051	5073	22	4	7	11	15	18
27	·5095	5117	5139	5161	5184	5206	5228	5250	5272	5295		4	7	11	15	18
28	·5317	5340	5362	5384	5407	5430	5452	5475	5498	5520		4	8	11	15	19
29	·5543	5566	5589	5612	5635	5658	5681	5704	5727	5750	23	4	8	12	15	19
30	0·5774	5797	5820	5844	5867	5890	5914	5938	5961	5985		4	8	12	16	20
31	·6009	6032	6056	6080	6104	6128	6152	6176	6200	6224	24	4	8	12	16	20
32	·6249	6273	6297	6322	6346	6371	6395	6420	6445	6469		4	8	12	16	20
33	·6494	6519	6544	6569	6594	6619	6644	6669	6694	6720	25	4	8	13	17	21
34	·6745	6771	6796	6822	6847	6873	6899	6924	6950	6976		4	9	13	17	21
35	0·7002	7028	7054	7080	7107	7133	7159	7186	7212	7239	26	4	9	13	17	22
36	·7265	7292	7319	7346	7373	7400	7427	7454	7481	7508	27	5	9	14	18	23
37	·7536	7563	7590	7618	7646	7673	7701	7729	7757	7785	28	5	9	14	19	23
38	·7813	7841	7869	7898	7926	7954	7983	8012	8040	8069		5	10	14	19	24
39	·8098	8127	8156	8185	8214	8243	8273	8302	8332	8361	29	5	10	15	19	24
40	0·8391	8421	8451	8481	8511	8541	8571	8601	8632	8662	30	5	10	15	20	25
41	·8693	8724	8754	8785	8816	8847	8878	8910	8941	8972	31	5	10	16	21	26
42	·9004	9036	9067	9099	9131	9163	9195	9228	9260	9293	32	5	11	16	21	27
43	·9325	9358	9391	9424	9457	9490	9523	9556	9590	9623	33	6	11	17	22	28
44	·9657	9691	9725	9759	9793	9827	9861	9896	9930	9965	34	6	11	17	23	28
45	1·0000	0035	0070	0105	0141	0176	0212	0247	0283	0319	36	6	12	18	24	30
46	·0355	0392	0428	0464	0501	0538	0575	0612	0649	0686	37	6	12	18	25	31
47	·0724	0761	0799	0837	0875	0913	0951	0990	1028	1067	38	6	13	19	25	32
48	·1106	1145	1184	1224	1263	1303	1343	1383	1423	1463	40	7	13	20	27	33
49	1·1504	1544	1585	1626	1667	1708					41	7	14	20	27	34
						1708	1750	1792	1833	1875	42	7	14	21	28	35

$\frac{O}{A}$.

x	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Δ	ADD				
	0°·0	0°·1	0°·2	0°·3	0°·4	0°·5	0°·6	0°·7	0°·8	0°·9		1′	2′	3′	4′	5′
50°	1·192	196	200	205	209	213	217	222	226	230		1	1	2	3	4
51	·235	239	244	248	253	257	262	266	271	275		1	2	2	3	4
52	·280	285	289	294	299	303	308	313	317	322		1	2	2	3	4
53	·327	332	337	342	347	351	356	361	366	371		1	2	2	3	4
54	·376	381	387	392	397	402	407	412	418	423	5	1	2	3	3	4
55	1·428	433	439	444	450	455	460	466	471	477		1	2	3	4	5
56	·483	488	494	499	505	511	517	522	528	534		1	2	3	4	5
57	·540	546	552	558	564	570	576	582	588	594	6	1	2	3	4	5
58	·600	607	613	619	625	632	638	645	651	658		1	2	3	4	5
59	·664	671	678	684	691	698	704	711	718	725		1	2	3	5	6
60	1·732	739	746	753	760	767	775	782	789	797	7	1	2	4	5	6
61	·804	811	819	827	834	842	849	857	865	873		1	3	4	5	6
62	·881	889	897	905	913	921	929	937	946	954	8	1	3	4	5	7
63	1·963	971	980	988	1·997	2·006	2·014	2·023	2·032	2·041		1	3	4	6	7
64	2·050	059	069	078	087	097	106	116	125	135	9	2	3	5	6	8
65	2·145	154	164	174	184	194	204	215	225	236	10	2	3	5	7	8
66	·246	257	267	278	289	300	311	322	333	344	11	2	4	6	7	9
67	·356	367	379	391	402	414	426	438	450	463	12	2	4	6	8	10
68	·475	488	500	513	526	539	552	565	578	592	13	2	4	6	9	11
69	·605	619	633	646	660	675	689	703	718	733	14	2	5	7	9	12
70	2·747	762	778	793	808	824	840	856	872	888	16	3	5	8	11	13
71	2·904	921	937	954	971	2·989	3·006	3·024	3·042	3·060	17	3	6	9	11	14
72	3·078	096	115	133	152	3·172					19	3	6	9	13	16
						172	191	211	230	251	20	3	7	10	13	17
73	·271	291	312	333	354	376					21	4	7	10	14	18
						376	398	420	442	465	22	4	7	11	15	18
74	·487	511	534	558	582	606					24	4	8	12	16	20
						606	630	655	681	706	25	4	8	13	17	21
75	3·732	758	785	812	839	867					27	4	9	14	18	22
						867	895	923	952	981	29	5	10	14	19	24
76	4·011	041	071	102	134	4·165					31	5	10	15	21	26
						165	198	230	264	297	33	6	11	17	22	28
77	4·331	366	402	437	474	511					36	6	12	18	24	30
						511	548	586	625	665	39	6	13	19	26	32
78	4·705	745	787	829	872	4·915					42	7	14	21	28	35
						4·915	4·959	5·005	5·050	5·097	46	8	15	23	31	38
79	5·145	193	242	292	343	5·396					50	8	17	25	33	42
						396	449	503	558	614	55	9	18	28	37	46
80	5·671	5·730	5·789	5·850	5·912	5·976						10	20	30	41	51
						5·976	6·041	6·107	6·174	6·243		11	23	34	45	56
81	6·314	6·386	6·460	6·535	6·612	6·691						13	25	38	50	63
						6·691	6·772	6·855	6·940	7·026		14	28	42	57	71
82	7·115	7·207	7·300	7·396	7·495	7·596	7·700	7·806	7·916	8·028						
83	8·144	8·264	8·386	8·513	8·643	8·777	8·915	9·058	9·205	9·357						
84	9·514	9·677	9·845	10·02	10·20	10·39	10·58	10·78	10·99	11·20						
85	11·43	11·66	11·91	12·16	12·43	12·71	13·00	13·30	13·62	13·95						
86	14·30	14·67	15·06	15·46	15·89	16·35	16·83	17·34	17·89	18·46						
87	19·08	19·74	20·45	21·20	22·02	22·90	23·86	24·90	26·03	27·27						
88	28·64	30·14	31·82	33·69	35·80	38·19	40·92	44·07	47·74	52·08						
89	57·29	63·66	71·62	81·85	95·49	114·6	143·2	191·0	286·5	573·0						
90	∞															

Differences vary too rapidly for interpolation by P.P.s. See table on page 22.

P.P.s for differences exceeding 14, if not shown on this page, should be taken from the inside end cover of the book. For angles between 72° and 82° P.P.s based on actual differences should be used.

The *capital recovery factor* is determined from bankers' tables or formulas. It is defined as the value of capital to the individual. It may be the interest rate that your money would earn if you invested it, or the annual cost of a loan made to finance the extra cost of the passive system. For example, the capital recovery factor of a 10% 30-year loan is 0.106.

To illustrate the use of the formula, if we assume, for example, that

—the passive solar heating system costs $5,000 above installed conventional construction costs,

—the capital recovery factor is 0.106 for a 30-year loan at 10% interest,

—the operating and maintenance cost for the system is $25 a year, and

—the annual solar heating contribution is 100 million Btu's,

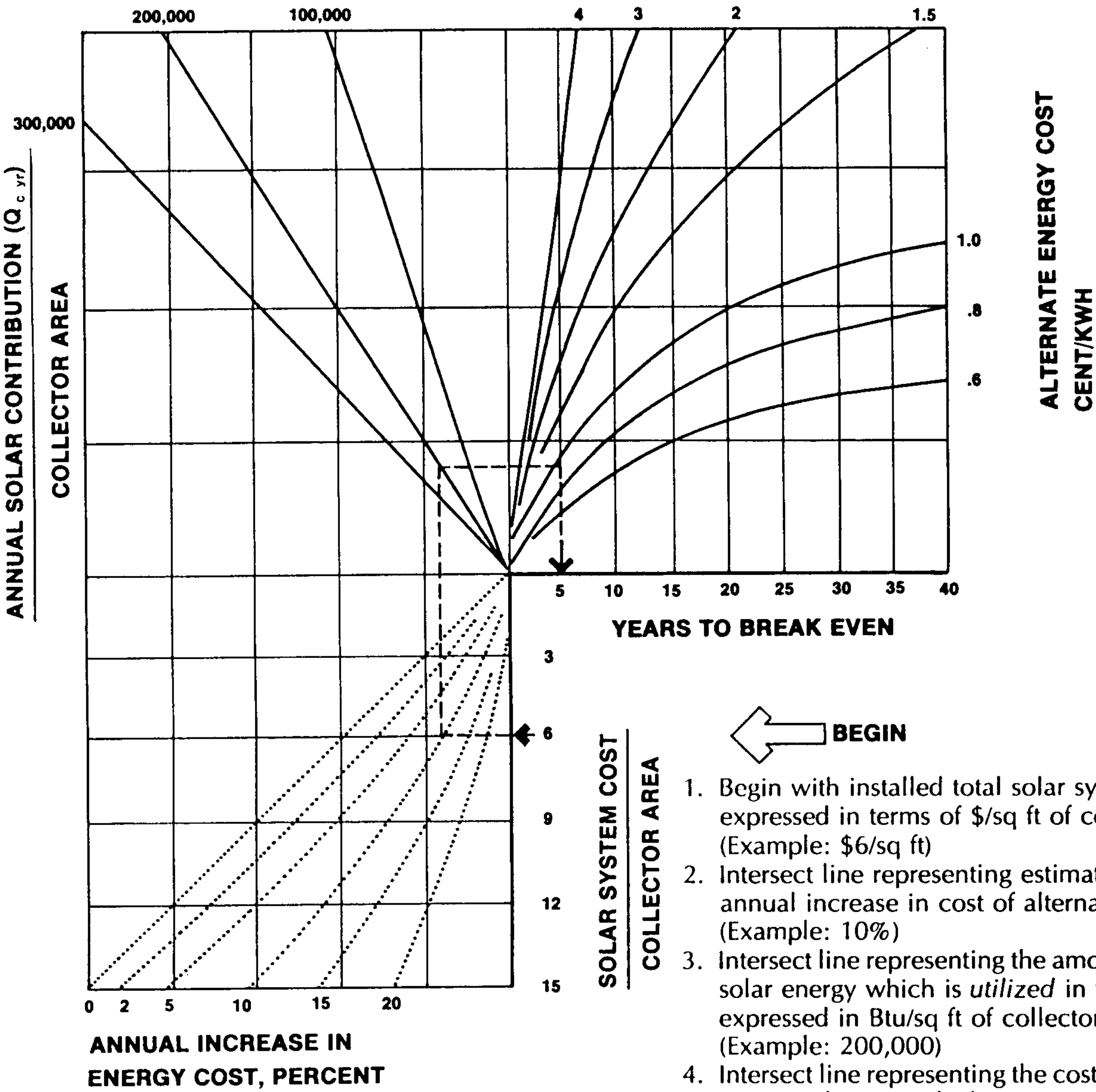
from the formula, the cost of solar heat is then:

$$\text{cost of solar heat} = \frac{(\$5{,}000 \times 0.106) + \$25}{100 \text{ million Btu's}}$$

$$= \$5.55 \text{ per million Btu's.}$$

This figure does not take into account considerations that would make the cost less expensive, such as tax incentives, deduction of interest payments and business depreciation, or considerations that can make it more expensive, such as property tax evaluation increases and fuel cost deductions (business expense).

Another method for calculating the cost effectiveness of a system is the nomograph in figure 1-9. This method allows for the increase in future annual fuel costs to be included in the procedure. By plotting the cost of the system, the annual projected increase in energy costs, the annual solar heating contribution and the cost of conventional fuel, the nomograph computes the break-even time on the system's initial cost.



1. Begin with installed total solar system cost, expressed in terms of \$/sq ft of collector. (Example: \$6/sq ft)
2. Intersect line representing estimated average annual increase in cost of alternate fuels. (Example: 10%)
3. Intersect line representing the amount of collected solar energy which is *utilized* in the building, expressed in Btu/sq ft of collector/year. (Example: 200,000)
4. Intersect line representing the cost of alternate fuels expressed in cents/kwh. (Example: Gas at 1.0 cent/kwh)
5. Read the number of years to break even on the initial investment. (Example: 5 years)

Based on 8% interest, 1% maintenance/year.

Fig. 1-9: Solar system cost nomograph.

Source: Adapted from GSA, "Energy Conservation Design Guidelines for New Office Buildings," as quoted by P.D. Maycock in "Solar Energy: The Outlook for Widespread Commercialization of Solar Heating and Cooling," ERDA.

Table 1-4 Capital Recovery Factors

Years	Interest Rate						
	5½%	6%	7%	8%	10%	12%	15%
1	1.055 00	1.060 00	1.070 00	1.080 00	1.100 00	1.120 00	1.150 00
2	0.541 62	0.545 44	0.553 09	0.560 77	0.576 19	0.591 70	0.615 12
3	0.370 65	0.374 11	0.381 05	0.388 03	0.402 11	0.416 35	0.437 98
4	0.285 29	0.288 59	0.295 23	0.301 92	0.315 47	0.329 23	0.350 27
5	0.234 18	0.237 40	0.243 89	0.250 46	0.263 80	0.277 41	0.298 32
6	0.200 18	0.203 36	0.209 80	0.216 32	0.229 61	0.243 23	0.264 24
7	0.175 96	0.179 14	0.185 55	0.192 07	0.205 41	0.219 12	0.240 36
8	0.157 86	0.161 04	0.167 47	0.174 01	0.187 44	0.201 30	0.222 85
9	0.143 84	0.147 02	0.153 49	0.160 08	0.173 64	0.187 68	0.209 57
10	0.132 67	0.135 87	0.142 38	0.149 03	0.162 75	0.176 98	0.199 25
11	0.123 57	0.126 79	0.133 36	0.140 08	0.153 96	0.168 42	0.191 07
12	0.116 03	0.119 28	0.125 90	0.132 70	0.146 76	0.161 44	0.184 48
13	0.109 68	0.112 96	0.119 65	0.126 52	0.140 78	0.155 68	0.179 11
14	0.104 28	0.107 58	0.114 34	0.121 30	0.135 75	0.150 87	0.174 69
15	0.099 63	0.102 96	0.109 79	0.116 83	0.131 47	0.146 82	0.171 02
16	0.095 58	0.098 95	0.105 86	0.112 98	0.127 82	0.143 39	0.167 95
17	0.092 04	0.095 44	0.102 43	0.109 63	0.124 66	0.140 46	0.165 37
18	0.088 92	0.092 36	0.099 41	0.106 70	0.121 93	0.137 94	0.163 19
19	0.086 15	0.089 62	0.096 75	0.104 13	0.119 55	0.135 76	0.161 34
20	0.083 68	0.087 18	0.094 39	0.101 85	0.117 46	0.133 88	0.159 76
21	0.081 46	0.085 00	0.092 29	0.099 83	0.115 62	0.132 24	0.158 42
22	0.079 47	0.083 05	0.090 41	0.098 03	0.114 01	0.130 81	0.157 27
23	0.077 67	0.081 28	0.088 71	0.096 42	0.112 57	0.129 56	0.156 28
24	0.076 04	0.079 68	0.087 19	0.094 98	0.111 30	0.128 46	0.155 43
25	0.074 55	0.078 23	0.085 81	0.093 68	0.110 17	0.127 50	0.154 70
26	0.073 19	0.076 90	0.084 56	0.092 51	0.109 16	0.126 65	0.154 07
27	0.071 95	0.075 70	0.083 43	0.091 45	0.108 26	0.125 90	0.153 53
28	0.070 81	0.074 59	0.082 39	0.090 49	0.107 45	0.125 24	0.153 06
29	0.069 77	0.073 58	0.081 45	0.089 62	0.106 73	0.124 66	0.152 65
30	0.068 81	0.072 65	0.080 59	0.088 83	0.106 08	0.124 14	0.152 30
31	0.067 92	0.071 79	0.079 80	0.088 11	0.105 50	1.123 69	0.152 00
32	0.067 10	0.071 00	0.079 07	0.087 45	0.104 97	0.123 28	0.151 73
33	0.066 33	0.070 27	0.078 41	0.086 85	0.104 50	0.122 92	0.151 50
34	0.065 63	0.069 60	0.077 80	0.086 30	0.104 07	0.122 60	0.151 31
35	0.064 97	0.068 97	0.077 23	0.085 80	0.103 69	0.122 32	0.151 13

NB:

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