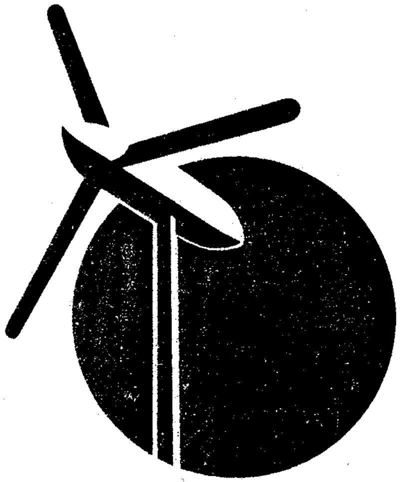
SERI/SP-635-1142

December 1983



Final Draft

Strategies for the Evaluation of Advanced Wind Energy Concepts

Peter South
Richard Mitchell
Eric Jacobs

SERI

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A Division of Midwest Research Institute

1617 Cole Boulevard
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Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

SERI/SP-635-1142
UC Categories: 58, 60

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Prepared under Task No. 1067.10
FTP No. 172

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U.S. Department of Energy
Contract No. DE-AC02-83CH10093

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NOMENCLATURE

A	reference area
A_D	disk area
A_W	wing area (or blade area)
C	chord length of airfoil
c	an empirical constant
C_D	drag coefficient $= \dfrac{\text{drag}}{\frac{\rho}{2} V_R{}^2 A}$
C_{D1}	drag coefficient on element moving downwind
C_{D2}	drag coefficient on element moving upwind
C_L	lift coefficient $= \dfrac{\text{lift}}{\frac{\rho}{2} V_R{}^2 A}$
C_P	power coefficient $= \dfrac{\text{power}}{\frac{\rho}{2} V^3 A}$
C_{P_W}	power coefficient based on wing area $= \dfrac{\text{power}}{\frac{\rho}{2} V^3 A_W}$
D	drag force on element moving downwind
D_1	drag coefficient on element moving downwind
D_2	drag force on element moving upwind
E	energy
H	height
H_r	reference height
I_{xx}	moment of inertia about x axis
I_{yy}	moment of inertia about y axis
k	an empirical value
K	an empirical constant
L	lift force
M	mass flow rate
p	probability that the wind will be within a particular range of speed
P	power
P_S	static pressure in the undisturbed wind
P_{S1}	static pressure far downwind of WECS
P_T	total pressure in the undisturbed wind

NOMENCLATURE (Concluded)

P_{T1}	total pressure far downwind of WECS
P_{T2}	total pressure for downwind of WECS after partial with external flow
r	radius
R_m	maximum rotor radius
R	resultant force
T	streamwise force
t	time
U	velocity of object
v	a selected velocity
V	velocity of wind in undisturbed flow
$\bar{V}$	average wind speed
V_0	wind speed at reference height
V_1	velocity of wind far downwind of WECS
V_2	velocity of wind for downwind of second actuator disk
V_A	axial velocity
VA	volume flow rate
V_D	velocity of wind through actuator disk
V_i	induced velocity
V_R	relative wind velocity
V_r	velocity at reference height
V_T	tangential velocity
α	angle of attack of airfoil
α'	wind shear coefficient
Γ	circulation
ω	angular velocity
ρ	density of air in undisturbed flow
ρ_1	density of air far downwind of WECS
θ	angle

SECTION 1.0

INTRODUCTION

1.1 SUMMARY

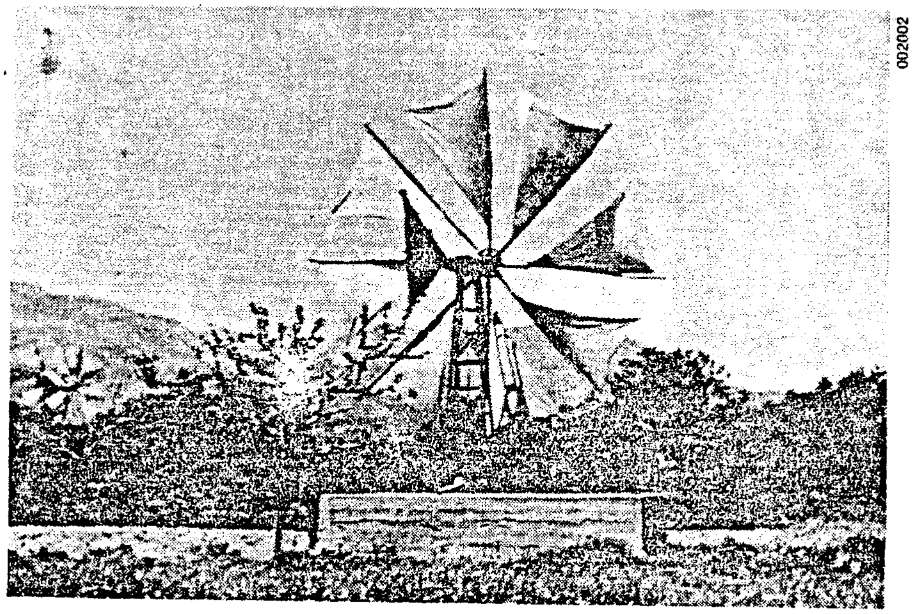
"Wind energy is free" is a popular statement. However, although the wind's energy **is** free, the process of harnessing that energy and converting it to a useful form can be very expensive. Some energy can be extracted with relatively simple devices like those shown in Figure 1-1, but rather sophisticated designs are required to produce large amounts of useable energy at a cost competitive with conventional energy sources.

This report presents the basic principles that govern the derivation of energy from the wind and the limitations of the various devices that are available. A new concept usually consists of relatively conventional components, and it is the particular combination of these components that makes the concept innovative. The evaluation process in this report can be used to determine whether or not the new combination is advantageous. While there are no "magical" solutions to deriving energy from the wind, there are methods that estimate a system's overall performance. This report will show what types of systems have the greatest potential, and should aid the inventor in evaluating the probability and the value of success of his device/system. The report also describes the types of systems that offer little potential for cost-effectiveness; we hope that this will indicate where inventive effort has the least likelihood of success to prevent wasting the effort of inventive researchers.

Wind energy conversion systems (WECS) evolved when alternative forms of energy were relatively expensive and the average power levels required were quite modest. For instance, windmills found on American farms, like the one shown in Figure 1-2, were designed to provide a relatively low power output, but were required to supply the energy year after year. No other source of energy available at that time was as economical and reliable. To meet this need, windmill designs were based on rugged simplicity and low initial cost. The final product was simple, but not crude; the device was actually the result of considerable effort.

As the cost of alternative forms of energy decreased and energy consumption dramatically increased, the wind machines could no longer compete economically with other sources of energy and were relegated to minor roles in the energy market. The recent renewed interest in wind energy is the result of spiralling energy costs. What is needed today is a significant improvement over the rugged but relatively inefficient machine like the farm windmill. While the costs of alternative forms of energy are rising (we may consider them to be high), energy is still a relatively cheap commodity. It is our enormous appetite for energy that makes it so costly, and machines like the farm windmill or the wind machine shown in Figure 1-3 can no longer meet our energy demands.

The size of the required machine depends on the average available wind speed. Note that in a region where the average wind speed is 10 mph, an efficient WECS would have to be 30 ft in diameter to extract an annual average of



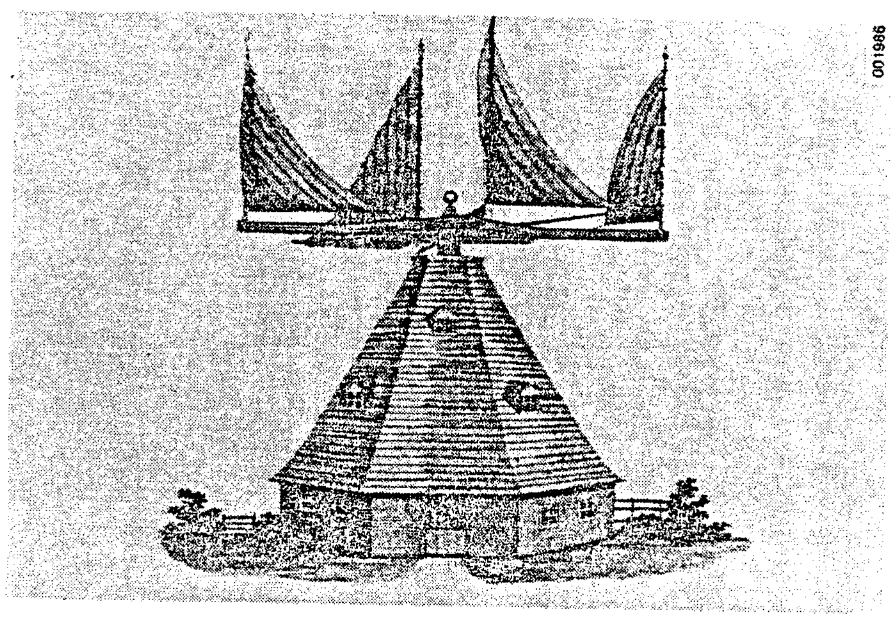


Figure 1-1. Early Wind Energy Devices

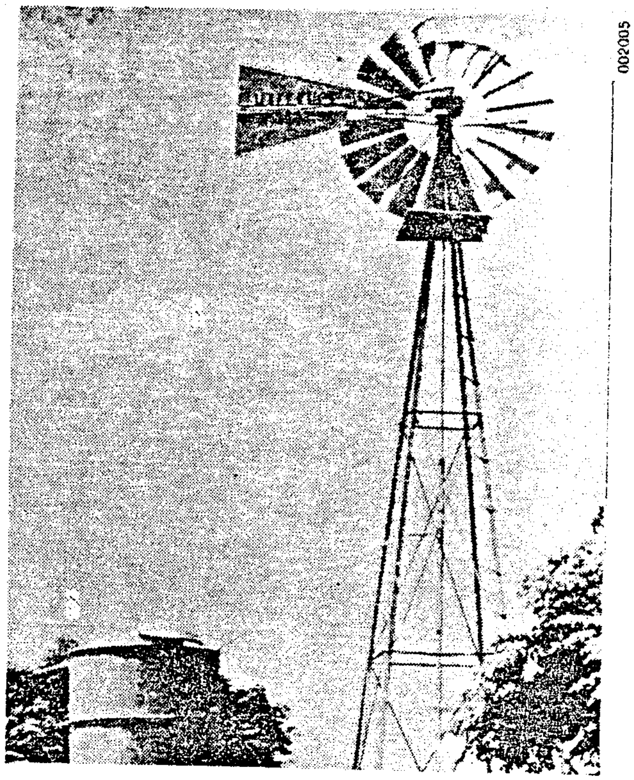


Figure 1-2. Typical American Farm Type Windmill

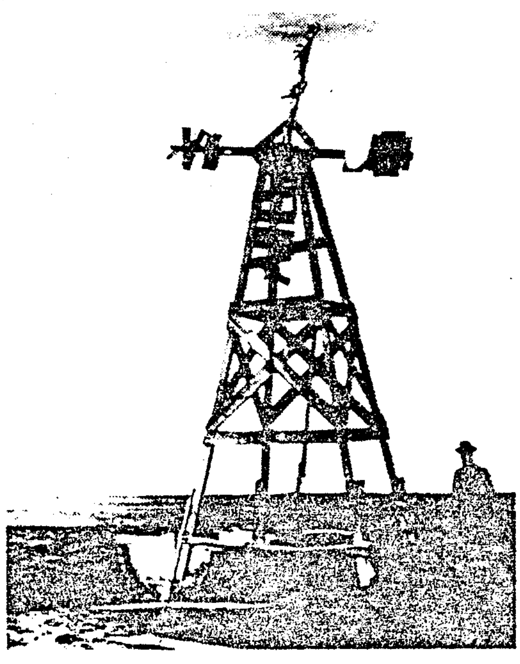


Figure 1-3. A Variant of the American Farm Type Windmill

approximately 50 kWh/day, as indicated by the curve in Figure 1-4. Even at $0.05/kWh, which is a high value for energy that is not available on demand, the annual value of such a WECS would only be about $900. At a site where the wind speed is greater, the annual value would be greater, but there are few sites in the United States with these conditions.

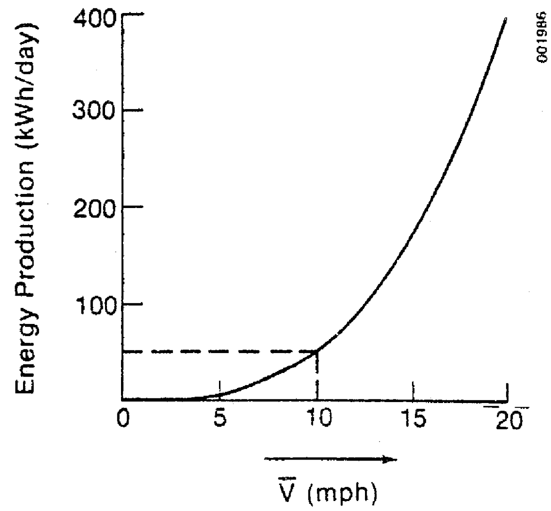


Figure 1-4. Energy Production of a Typical WECS as a Function of Wind Speed

The cost of energy is calculated using a standard cost of energy formula where all the initial costs (such as material, labor, construction, land, permits, etc.) are added together. The sum of the initial costs is then multiplied by a factor that reflects the cost of borrowing money and amortizing the initial costs. There are also recurring costs that reflect the cost of operating, maintaining, and insuring the machine. The amortized initial costs and the recurring costs are then added together to give the total annual cost. The total annual cost is then divided by the annual energy production to give the cost of energy. Initially the cost of energy produced from a WECS will probably be higher than the cost of energy produced from fossil fuels. However the cost of energy produced by a WECS is not likely to inflate to any great extent, whereas the cost of energy produced from fossil fuels may inflate rapidly. Therefore, this method of comparing the cost of energy produced by a WECS to the cost provided by fossil fuels does not account for fossil fuel escalation and the time value of money. One method of making a more valid comparison is to estimate the present value of the life cycle costs of the WECS, and to compare that value with the present value of the energy that the WECS will supply in its lifetime. The comparison does require an accurate prediction of interest and inflation rates over the lifetime of the machine, and these predictions require considerable foresight. (Whitford et al. describes life cycle costing.) Fortunately, to analyze an innovative WECS, it is only necessary to compare the innovative aspects with the conventional aspects, and hence either costing method can be used so long as both are compared on the same basis.

Another aspect that should be considered is the amount of time required to repay the energy invested in constructing the WECS. Some energy will be required to mine, process, and transport the materials, and to construct the machine. If the time required to regenerate this energy investment is significant, it can cause a detrimental increase in the overall energy consumption during the buildup of a high level of WECS-generating capacity. This tradeoff is shown graphically in Figure 1-5.

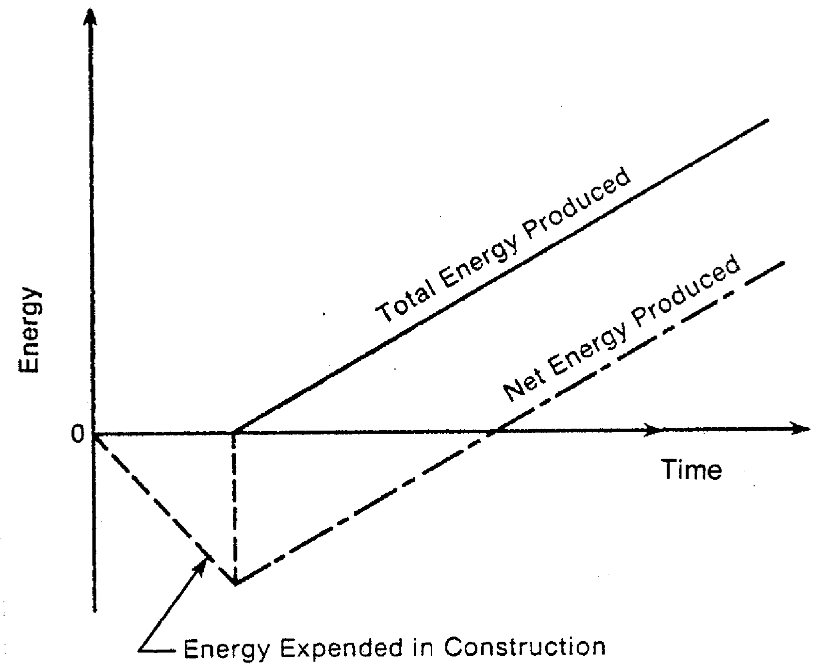


Figure 1-5. Energy Balance for a Wind Energy Device

The WECS problem is therefore to maximize the energy production and minimize the investment in energy, materials, and effort. The machine must operate with little maintenance for long periods and entail few undesirable environmental impacts. Efficiency, power coefficients, and other commonly used parameters are often irrelevant by themselves in evaluating a WECS. Each of these measurements refers only to a particular facet of the performance. Apparent improvements in one measure of system performance can often have a negative impact on another parameter, and result in an overall decrease in the benefit-to-cost ratio. The only individual performance parameter of importance to the benefit-to-cost ratio is the overall system performance (as illustrated conceptually in Figure 1-6).

The transition from an idea to its incorporation in an improved WECS often involves a significant effort. In its raw form the idea is usually not optimized, and the apparent negative impacts can overwhelm the apparent benefits. Therefore, before the real benefits and impacts can be ascertained, some optimization process must be conducted. To evaluate this optimization effort, it is worthwhile to try to estimate the probability of the system's success and the likely impact of the idea on the WECS benefit-to-cost ratio (see Figure 1-7). If the likelihood of success and the potential benefits are small, then obviously time and financial resources should not be expended to pursue the idea. Yet, if the probability of success is high and the potential benefits are great, then time and effort should be spent on evaluating the idea. However, between these two extremes there is a gray area where it is necessary to try to decide whether the potential benefits are worth the effort required to study an idea. One way of evaluating an idea is to consider the evaluation process as a gamble with the developmental effort being the "wager" and "success" the "winning stakes." The value of the wager will be equal to the value of the success multiplied by the probability of success. It is

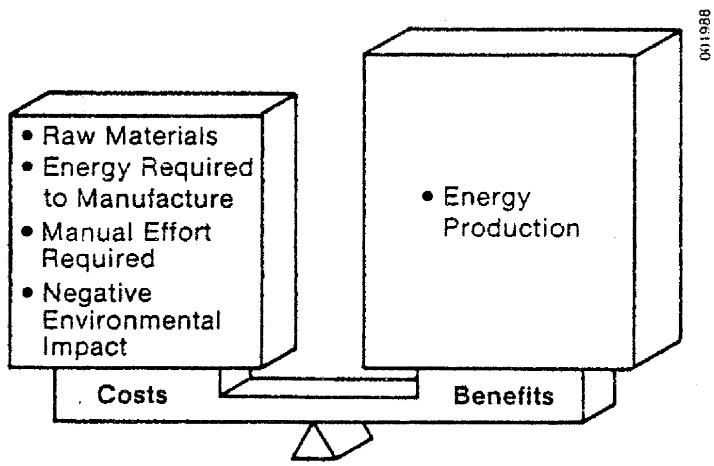


Figure 1-6. Benefits and Costs of a WECS

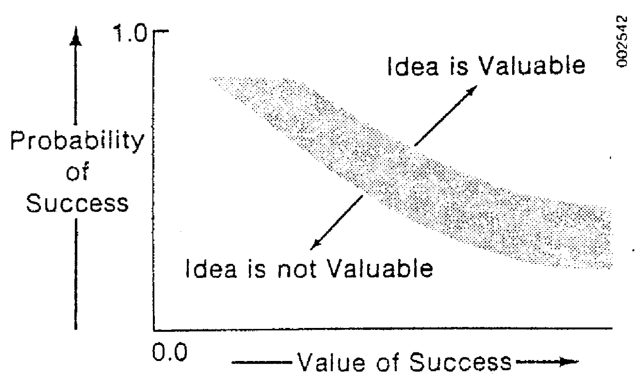


Figure 1-7. Value of an Innovation

difficult to quantify the value of the "wager," but some attempt must be made. It is also important to ensure that the effort required to estimate the value of the wager is not burdensome. No independent investor would risk money on a gamble without having some knowledge of the odds.

There are three stages in any evaluation process. The first stage is to determine whether the idea is really new and whether it is physically possible. If the idea is new it can be assessed to see if it violates any laws of physics; if it does, then the new wind device is worthless.

Second, try to assess the likely performance and cost changes that the new idea will create. These changes can often be roughly estimated by rule-of-thumb methods. If the assessment indicates that the idea will be cost-effective and that there are no significant technological barriers to its implementation, the idea is probably worth pursuing. A negative answer at this stage is not necessarily decisive but does indicate that further analysis should be performed before much effort is devoted to developing the idea.

Finally, try to obtain a first-cut optimization of the configuration suggested by the idea to determine whether or not some simple change might make the idea more cost-effective, and to try to determine whether the technological barriers identified in earlier stages can be overcome.

At any stage there is a certain amount of subjectivity involved in the decision to continue or to drop an idea. Usually the inventor of a concept will have faith and wish to go ahead with less positive evidence than an objective observer would require. If only the inventor's own efforts and capital are involved, then an inventor obviously has the right to follow intuition and continue with the development of a concept. However, when the inventor seeks the support of others, they must be convinced that the idea is worthwhile. In either case, an objective evaluation is necessary to determine if the investment is likely to result in a payoff.

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SECTION 2.0

WIND AND WIND ENERGY

Energy derivation from air requires a reduction in temperature, pressure, or velocity; a change in humidity; or a combination of these factors. However, current successful wind systems operate only on changes in the velocity of the air, as shown schematically in Figure 2-1. Wind energy devices that produce energy by changing the temperature and/or the humidity of the air are heat engines. These devices are discussed in Section 8.8, and are limited by Carnot cycle efficiency.

All wind machines must comply with three fundamental laws of physics--the conservation of mass, momentum, and energy--and the second law of thermodynamics. The law of conservation of mass simply states that "what goes in must come out" (see Figure 2-2). In the steady state, the mass flow through all cross sections of a stream tube must be the same. A stream tube is any real or imaginary boundary surrounding the flow such that no mass crosses the boundary.

The law of conservation of energy states that energy cannot be created or destroyed; as illustrated in Figure 2-3, energy can only be converted into another form. This energy can be divided into higher and lower forms. In an ideal frictionless system, higher energy forms [such as kinetic (velocity) and potential (pressure)] are 100% convertible with each other, and all higher forms are 100% convertible to lower forms. Lower forms of energy (such as heat) are not 100% convertible. In the final analysis, all forms of energy eventually degrade to heat.

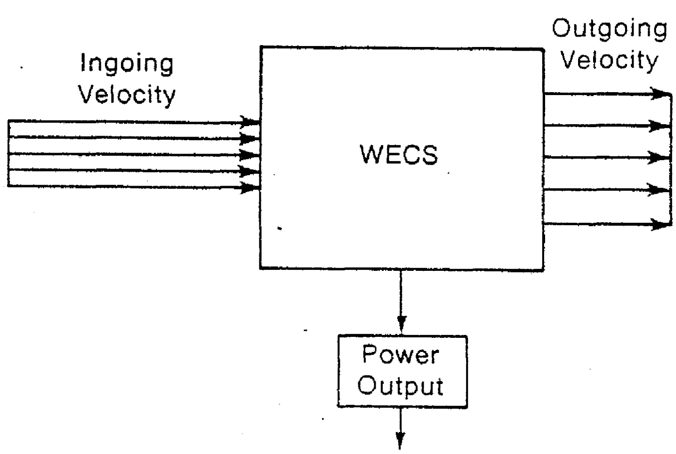


Figure 2-1. Schematic of a WECS

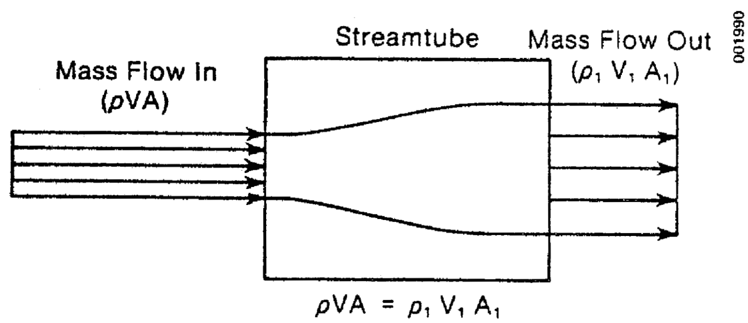


Figure 2-2. Conservation of Mass

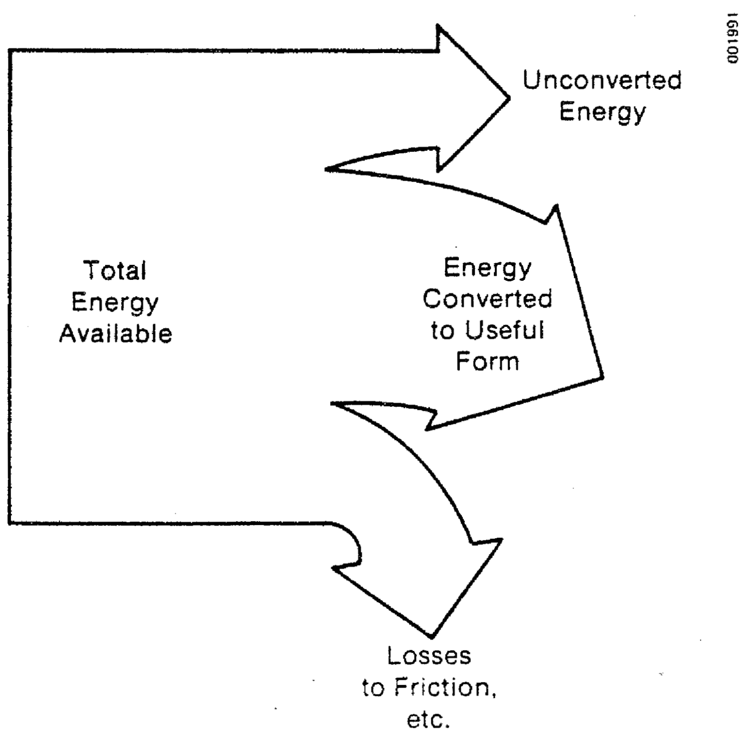


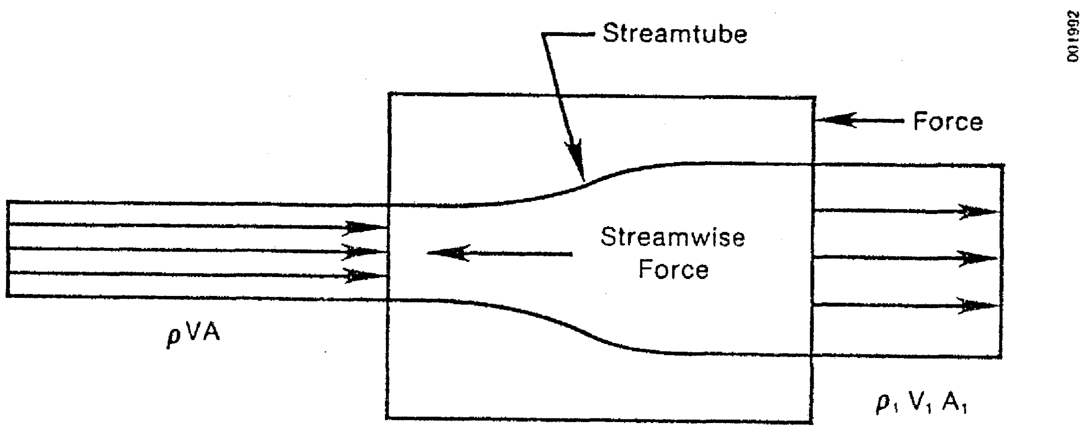
Figure 2-3. Conservation of Energy

Bernoulli showed that in an ideal frictionless streamline flow, kinetic energy could be converted into potential energy in the form of increased static pressure. Thus, if static pressure decreases, the reduced potential energy is converted into an equivalent increase in kinetic energy.

The law of conservation of momentum is shown graphically for a generalized WECS in Figure 2-4. (Newton's law of motion is most useful in the analysis of fluid mechanics.) This law holds that the product of mass and velocity (momentum) will remain constant in a system until a force is applied, and that the change in momentum produced by a force is equal to the product of the force and the time over which it is applied. In a fluid, the application of a force causes a change in flow velocity. Conversely, if there is a change in fluid velocity, then a force has been applied.

The second law of thermodynamics is based upon the observation that energy conversion processes are not completely reversible. In any process there will be some dissipative forces at work, such as friction. These losses lead to a decrease in available energy and an increase in the entropy of the system. Entropy is essentially a measure of disorder, and its increase represents a dissipation of useful energy. It is the second law of thermodynamics that forbids the existence of perpetual motion machines.

The applicability of classical physical laws is sometimes limited. At velocities approaching the speed of light, for example, Einstein showed that Newton's laws of motion must be modified. However, for the conditions experienced by wind machines, the classical laws are completely accurate.



Input Momentum Flux = $(\rho VA)\,V$

Output Momentum Flux = $(\rho_1 V_1 A_1)\,V_1$

Force = Rate of Change of Momentum
= (Mass Flow Rate) × (Change in Velocity)
= $\rho VA\ (V - V_1)$, since $\rho VA = \rho_1 V_1 A_1$

Figure 2-4. Force Changing the Momentum Flux of a Fluid

When power is produced from the wind, the speed of that portion of the wind stream is necessarily reduced. According to the law of conservation of momentum, a force must be present to cause this change in speed, and for a given power output this force will have some minimum value regardless of the details of the extraction mechanism. One mathematical model that can be used to examine wind machines is the actuator disk, shown in Figure 2-5. This model typifies an imaginary ideal device that performs all the required functions perfectly. The actuator disk most accurately represents the conventional horizontal axis wind machine, but it can be adapted for all other types of wind machines. The actuator disk theory for wind machines applies the laws of conservation of momentum and energy to a frictionless streamline flow passing through an actuator disk. The actuator disk represents a device that can convert some of the total pressure in the stream to other forms of energy. Far upstream from the actuator disk, the total pressure in the flow is equal to the sum of the free stream static and dynamic pressures, as illustrated in Figure 2-6.

At some distance far downstream from the disk, the static pressure must return to the free stream value, and hence the change in dynamic pressure from the free stream to downwind of the disk is equal to the change in total pressure through the disk. Because there can be no change in velocity through the disk, the change in static pressure over the short distance is equal to the change in total pressure. Since a force is applied to the fluid in the upstream direction, the presence of the actuator disk reduces velocity and causes the stream tube boundary to diverge far downstream of the disk.

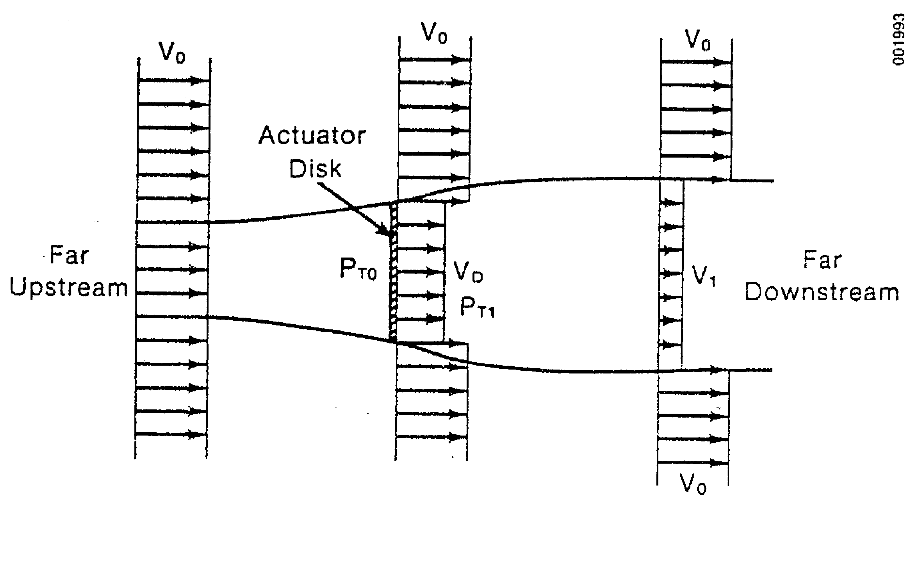
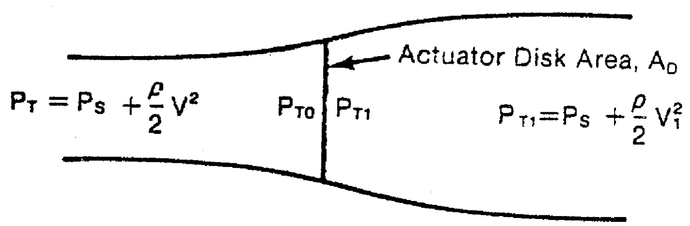


Figure 2-5. Schematic of an Ideal Actuator Disk



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$$\text{Change in Total Pressure} = P_T - P_{T1} = \left(P_S + \frac{\rho}{2} V^2\right) - \left(P_S + \frac{\rho}{2} V_1^2\right)$$

Figure 2-6. Change in Total Pressure Through an Actuator Disk

Power output P of the actuator disk is equal to the product of the change in total pressure across the disk and the volume flowing through the disk, i.e.

$$P = \rho \,\frac{\left(V_0{}^2 - V_1{}^2\right)}{2} \times VA \ ,$$

where $\rho = \rho_0 = \rho_1$, $\rho(V_0{}^2 - V_1{}^2/2)$ is the change in total pressure, and VA is the volume flow rate. For a given volume flow rate the power derived from the wind is a maximum when $V_1 = 0$. P can also be expressed as

$$P = 1/2\left(V_0{}^2 - V_1{}^2\right)\rho V_0 A_0 \ ,$$

where $1/2\ (V_0{}^2 - V_1{}^2)$ is the change in kinetic energy per unit mass and $\rho V_0 A_0$ is the mass flow rate. Since the force on the disk changes the flow rate, a method must be used that relates the flow velocity through the disk to this streamwise force. The power is also equal to the product of the force on the disk and the velocity through the disk. Hence, this force on the disk is equal to the overall change in dynamic pressure in the flow multiplied by the area of the disk. This streamwise force on the disk is

$$T = \frac{\rho}{2}\left(V_0{}^2 - V_1{}^2\right) A_D \ .$$

From conservation of mass, $\rho V_0 A_0 = \rho V_D A_D$. Therefore,

$$T = \frac{\rho}{2}\left(V_0^2 - V_1^2\right)\frac{V_0}{V_D}A$$

$$= \frac{\text{Power}}{V_D}.$$

To satisfy the law of conservation of momentum, the streamwise force on the disk must equal the product of the mass flow through the disk and the overall change in velocity through the disk.

$$T = \rho VA\left(V_0 - V_1\right)$$

$$= \rho VA\frac{\left(V_0^2 - V_1^2\right)}{\left(V_0 + V_1\right)}$$

$$= \frac{\text{Power}}{\frac{V_0 + V_1}{2}}$$

If we equate the two methods for deducing the streamwise force on the disk, the velocity through the disk must be equal to the average of the upwind and downwind velocities:

$$V_D = \frac{V_0 + V_1}{2}.$$

The power output of the ideal actuator disk is then equal to the overall change in dynamic pressure multiplied by the average of the upwind and downwind velocities multiplied by the disk area:

$$P = \frac{\rho}{2}\left(V_0^2 - V_1^2\right)\frac{\left(V_0 + V_1\right)}{2}A_D.$$

The Lanchester-Betz analysis (see Appendix A) shows that the maximum power that can be derived by a given actuator disk occurs when $V_1 = V_0/3$.

A power coefficient is useful when characterizing the performance of a wind machine. The power coefficient is usually defined as the power output of the actuator disk divided by the wind power that would flow through that same disk area if no power were derived i.e. $C_p = P/(1/2\ \rho A_D V_0^3)$. A power coefficient of 0.5 could be obtained if $V_1 = 0$, while the maximum power coefficient that can be obtained is 16/27. Figures 2-7 and 2-8 illustrate the two conditions, respectively.

When assuming conditions either upwind or downwind of a machine, it may be adequate to assume isentropic conditions along stream lines upwind of the machine but not necessarily downwind of the machine. There is some evidence that under certain conditions, the external flow can mix with the wake and increase its total pressure, as shown in Figure 2-9. This can result in a pressure drop across the machine greater than the free stream dynamic pressure. Therefore, since the mixing process involves the free stream energy being transferred to the wake, it is not accurate to assume isentropic

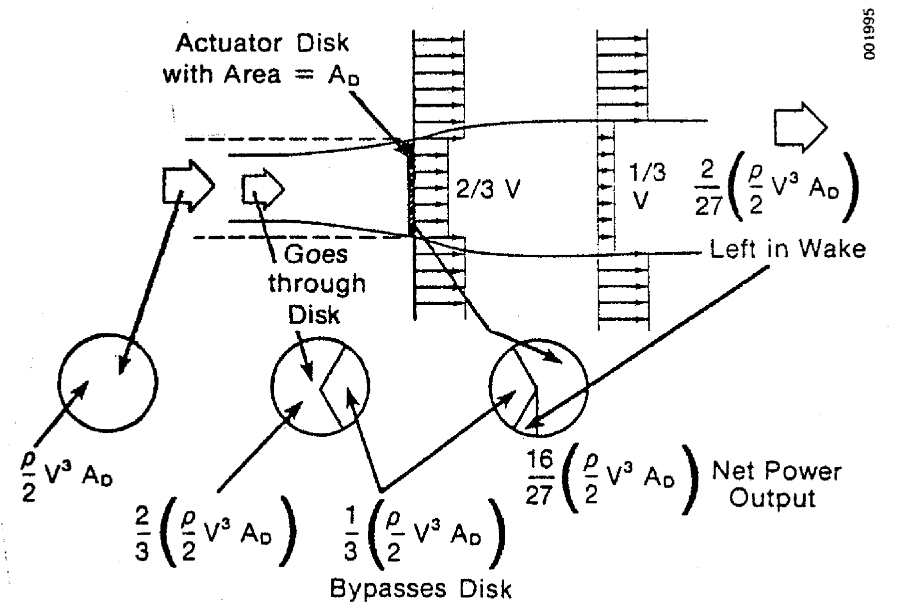


Figure 2-7. Ideal Actuator Disk Operating at the Lanchester-Betz Limit

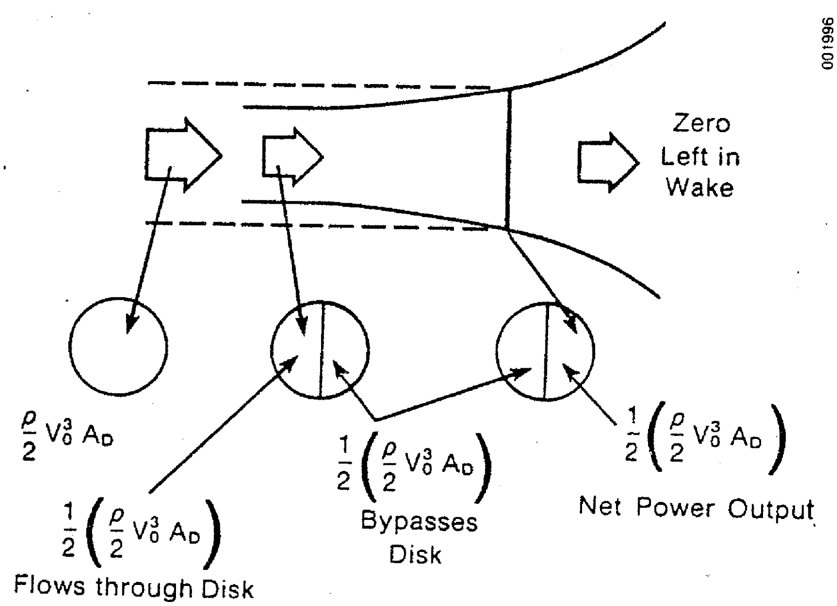


Figure 2-8. Ideal Actuator Disk Operating at Total Pressure Change Equal to Free Stream Dynamic Pressure

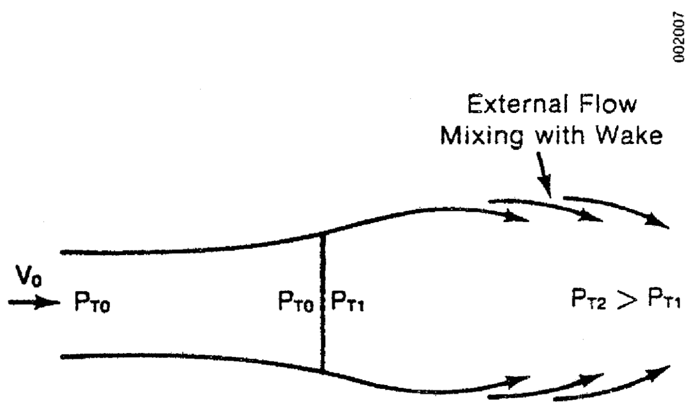


Figure 2-9. External Flow Mixing with Wake to Raise Its Total Pressure

conditions. The increased pressure drop is, however, not likely to be large when compared with the free stream dynamic pressure.

Since the mass flow rate is proportional to the local velocity, the local velocity to the free stream velocity, and the kinetic energy to the square of the free stream velocity, the power in a stream tube is proportional to the cube of the free stream velocity. In some specific systems or applications where wind speed is increased by an object or device that is much larger than the wind machine, such as a hill (see Figure 2-10), the power available can be proportional to the cube of the local velocity, since turbulent mixing of the wake with the main stream can overcome the excessive total pressure deficit that would occur without the mixing.

2.1 WIND CHARACTERISTICS

The free stream velocity of the wind is variable with location, height, and time. Variations due to location are very site-specific and include the description of the local turbulence, which is beyond the scope of this document. The site specific and turbulence concerns are discussed in several reports by Pacific Northwest Laboratories (Cliff and Fichtl 1978, Kerrigan 1978, Doran and Powell 1980, Powell and Connell 1980). The variations with height often are described using a simple power law:

$$V = V_r \left(\frac{H}{H_r}\right)^{\alpha'} ,$$

where

V = wind speed at height H
V_r = wind speed at reference height H_r
α' = wind shear coefficient.

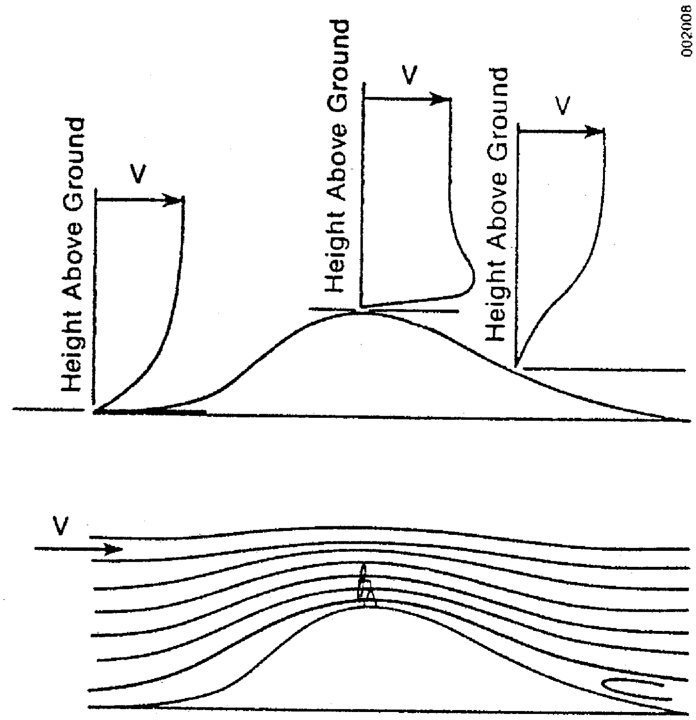


Figure 2-10. WECS Mounted on an Object

The wind gradient is produced by large-scale atmospheric conditions, so it is not usually affected by the terrain. Hence, if the particular site has a large α value, as illustrated in Figure 2-11, it implies that the winds at the site are weaker than they would be in smooth terrain and hence that there may be a much better site nearby.

The varying nature of the wind with time can be described in terms of the probability of the occurrence of any wind speed. Probability describes the fraction of the time that the wind speed is within a particular range in a given period of time. The mathematical tool usually used to describe this wind speed distribution is the Weibull distribution (see Figure 2-12):

$$P(v<V) = \left\{1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]\right\} .$$

The probability that the wind will be between $\left(v - \frac{\Delta v}{2}\right)$ and $\left(v + \frac{\Delta v}{2}\right)$ is

$$P\left\{\left(v - \frac{\Delta v}{2}\right) \leq v \leq \left(v + \frac{\Delta v}{2}\right)\right\} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]\Delta v ,$$

where c and k are site-specific empirical constants, and Δv is an increment in velocity.

The distribution of wind speed varies with geographic locality, as stated previously. To partially account for these variations, the parameter k can be modified. In the trade wind regions, a value of 4 for k is appropriate; in the temperate, maritime, and continental regions, a value of 2 is more accurate. This special case of k = 2 is called the Rayleigh distribution (see Figure 2-13).

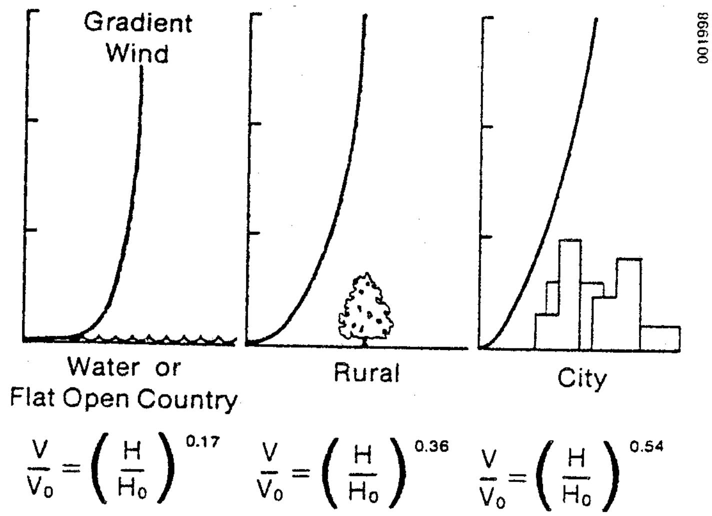


Figure 2-11. Typical Wind Profiles

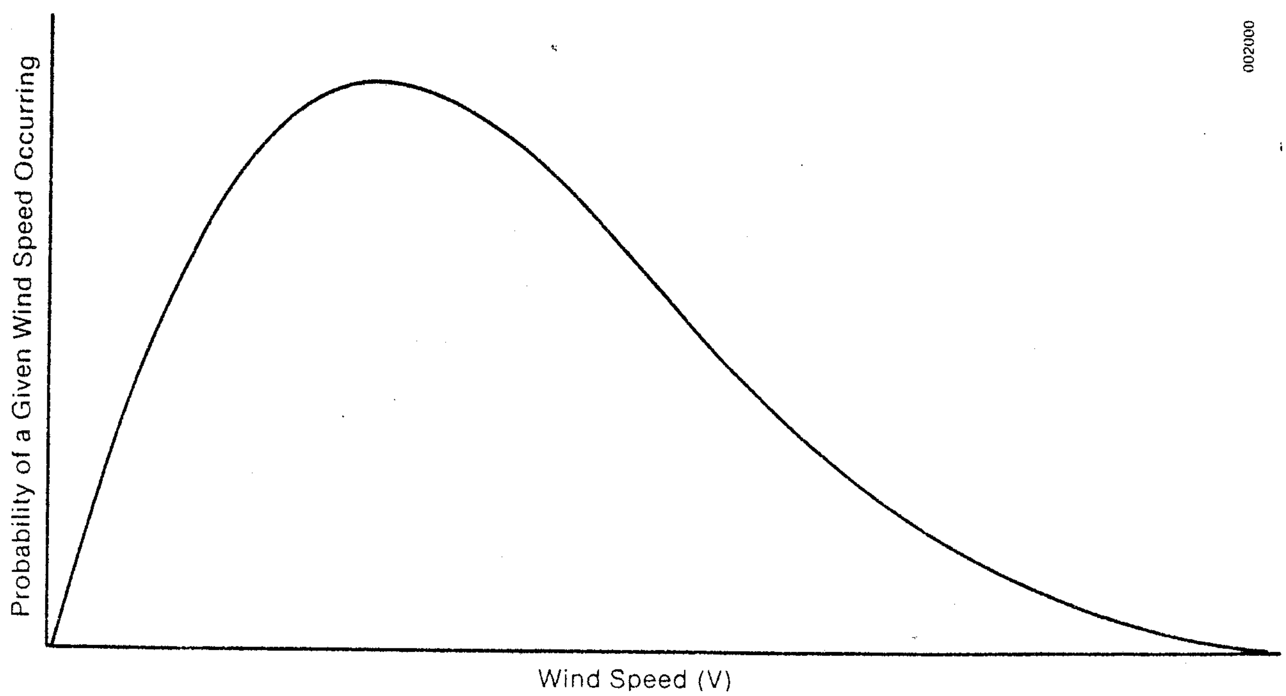


Figure 2-12. Rayleigh Wind Speed Distribution

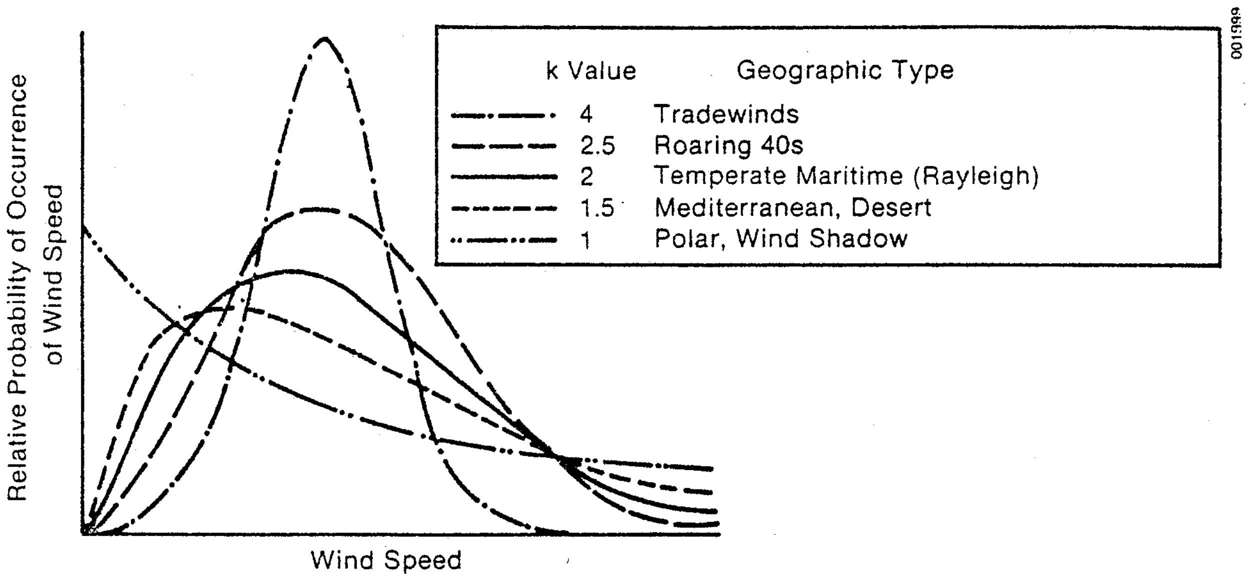
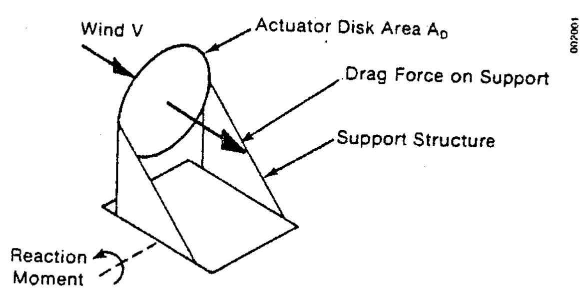


Figure 2-13. Various Weibull Distributions



$$\text{Ideal Power} = \frac{16}{27}\left(\frac{\rho}{2} V_0^3 A_D\right)$$

$$\text{Ideal Drag} = \frac{\text{Power}}{V_D}$$

$$= \frac{3}{2}\frac{\text{Power}}{V}$$

$$= \frac{8}{9}\left(\frac{\rho}{2} V^2 A_D\right)$$

Actuator disk must have sufficient strength to transmit distributed drag force to support.
Support must transmit drag force to ground.
Actuator disk must be equipped with device to convert power to useable form.

Figure 2-14. Minimum Possible WECS

The Weibull and Rayleigh distributions only give the probability that a particular wind speed will occur and do not indicate how rapidly changes will occur. Generally wind speeds are measured with devices that respond more rapidly to changes and are affected by smaller eddies than WECS. Therefore, the apparent distribution of wind speeds recorded by the measuring device and a full-scale machine used for power generation may well be different. Nevertheless, the fact that the data available on distribution of wind speed are not complete or in the most desirable form should not prevent us from using them. It simply indicates that these data must be used with caution.

2.2 WECS PERFORMANCE

When evaluating the potential of a new WECS concept, it is important to make a reasonably accurate assessment of the performance. It is important to know the maximum performance and how this performance will vary with wind speed. If the new WECS is significantly different from any other, accurate predictions of its performance will be difficult. However, with a really novel configuration, any predictions of the characteristics will be relatively inaccurate, so that only an optimistic and a pessimistic prediction are needed. On the other hand, if the configuration includes only minor modifications of well understood designs, then the effects of the changes can be accurately predicted. In such cases, the prediction must be accurate so that there can be reliable information on whether the modifications are cost-effective.

Usually, we can estimate the maximum performance of a WECS by using some rule-of-thumb approximations. If it has a device like an unaugmented actuator disk, the maximum power coefficient will be somewhat less than 0.6. If the device is augmented with a diffuser, the maximum power coefficient is likely to be less than 0.6 when based upon the diffuser exit area. For other devices there is often some simple way of making an estimate of the maximum power coefficient.

It is difficult to design a WECS to operate at maximum power coefficient over a wide range of wind speeds; hence the WECS is likely to operate at less than maximum power coefficient for part of the time. The maximum power output will also be limited to prevent overloading of the power conversion system. The WECS will usually have some fixed losses that are proportional to the installed power. For instance, a generator might require some power for excitation. These fixed losses must be supplied before any useful power output is obtained.

To calculate the energy production of a WECS, one must know how long it will operate at any particular power level in a given wind regime. This information is provided by the wind speed distribution. Energy output can thus be calculated by integrating the product of the wind speed distribution curve and the power output curve and multiplying the result by time:

$$E = T \int_0^\infty [P(V)]\ [1/2\ \rho A C_p V^3] dV \ .$$

Generally P(V) is represented by the Rayleigh distribution when calculating WECS performance on a non-site specific basis. The Weibull distribution can be used for more site specific estimates. Because of the cubic relationship between the power available in the wind and the wind speed, analysis shows that the average available power is greater than the power output at the average wind speed. Thus for a Rayleigh distribution the available energy is 1.91 times the energy output based on the average wind speed; i.e., $E_{Rayleigh} = 1.91\ E(\overline{V})$.

For Weibull distributions with values of k greater than 2, the ratio is somewhat less; and for k less than 2, the ratio is greater than 1.91. These ratios should be applied to practical design problems with caution and should definitely not be used as multipliers to predict the average annual energy output. In practice, much of this energy is not available because a greater fraction of the energy is carried by infrequent high winds that are not economical to harness.

2.3 SUMMARY

All wind energy conversion devices obey the laws of conservation of mass, momentum, and energy. They are also restricted by the second law of thermodynamics. The maximum power output of a WECS is limited to the volume flow rate through the device multiplied by the change in free stream dynamic pressure. The drag loading on the WECS, necessary to derive energy, reduces the flow through it. Hence, for a given size the maximum power is produced when the product of flow rate and energy derived per unit of volume is a maximum. It is possible to specify the properties of the minimum possible wind machine. The minimum WECS must act upon a stream tube of sufficient cross sectional area, and it must apply an axial force to this stream that exceeds a certain value. Figure 2-14 shows the requirements for the minimum WECS.

In addition to conversion efficiency or power coefficient, wind characteristics also significantly affect WECS performance. Wind speed varies with height and time, requiring accurate modeling of these characteristics to estimate WECS performance. Changes in wind direction must also be considered when calculating WECS performance.

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SECTION 3.0

ROTOR CONFIGURATIONS

The actuator disk model assumes that there is some mechanism to produce a force on the wind and convert the wind energy to mechanical energy. There are only two fundamental mechanisms for deriving energy from the wind: aerodynamic lift and drag (illustrated in Figure 3-1). Since lift is defined as the force normal to the relative flow and drag is defined as the force aligned with the relative flow, any other force can be considered as being composed of lift and drag components.

Aerodynamic drag is the force component experienced by an object that tends to make it move downwind. This force is proportional to the square of the relative velocity. If the object is allowed to move downwind at some speed less than the speed of the wind in the direction of the force, then it can be defined as a drag device WECS and will have a power output limited to the

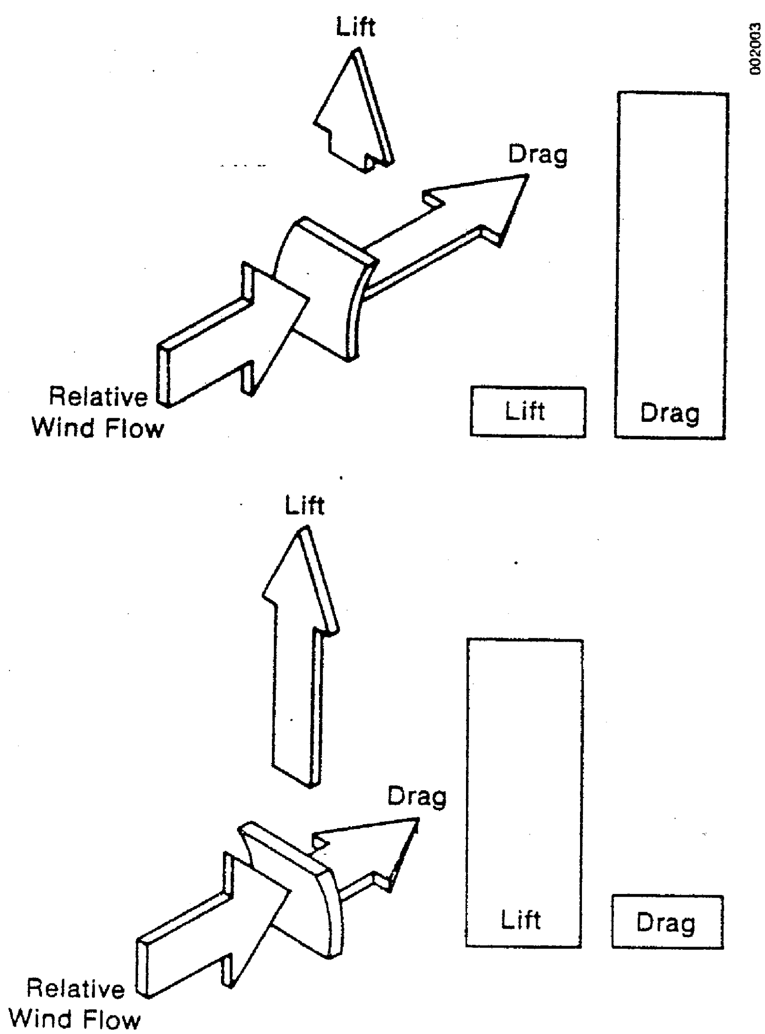

Figure 3-1. Generalized Lift and Drag Devices

force multiplied by its velocity in the direction of the force. The relative wind seen by an object is composed of the vector difference of the object velocity and the wind velocity. Since the force is proportional to the square of the relative wind speed, the drag force will decrease as the downwind speed of the object increases and falls to zero when the object moves downwind at the speed of the wind. There will hence be some optimum speed for the object to move downwind to produce maximum power, and this occurs when the object is moving downwind at one third of the wind speed. The analysis in Appendix C shows that the optimum average power output of the drag object is

$$P < \frac{4}{27}\left(\frac{\rho}{2} V^3 A\right) ,$$

where A is the active element area projected normal to the stream tube. Since only one third of the power extracted from the wind is actually converted to useful power when the drag device is operating at maximum power, the actuator disk analysis does not apply to a device that uses drag elements as a fundamental power extraction mechanism.

Aerodynamic lift is defined as the component of force that is normal to the relative wind and is produced by a device called an airfoil. Any device that produces circulation is considered an airfoil. (For a detailed study of airfoils, see Abbott and Von Doenhoff 1959.) Most airfoils are passive devices that produce lift by means of their shape and orientation to the relative wind. Good passive airfoils have a rounded leading edge and a sharp trailing edge, as illustrated in Figure 3-2. The leading edge radius and the surface contours can be designed to give a range of aerodynamic characteristics. The distance between leading edge and trailing edge is called the chord length, and the line connecting these points is called the chord line. The angle between the chord line and the relative wind is called the angle of attack.

The aerodynamic lift generated by an airfoil for unit of span is

$$L = \frac{\rho}{2} V_R^2 \, C \, C_L ,$$

where the quantity C_L is the section lift coefficient. The lift coefficient is related to the airfoil angle of attack, as shown in Figure 3-3. The lift coefficient at zero angle of attack is a function of the shape of the airfoil and increases at the rate of approximately 0.1 per degree until stall is approached. At stall the flow no longer adheres to the upper surface of the airfoil, and the aerodynamic lift can decrease rapidly with increasing angle of attack.

Ideal airfoils do not produce a drag force, but all real airfoils do produce a drag. The aerodynamic drag on a good airfoil is usually quite small until the stall is approached. It then rises rapidly with increasing angle of attack.

If the wind velocity has some component normal to the velocity of the object, the lift vector will be tilted to produce a component in the direction of motion, as shown in the vector diagram in Figure 3-4. Since power is the product of the speed and the force in the direction of motion, the lifting object can produce a power output when there is a component of the wind speed normal to its direction of motion and the device using aerodynamic lift can be defined as a lifting device WECS.

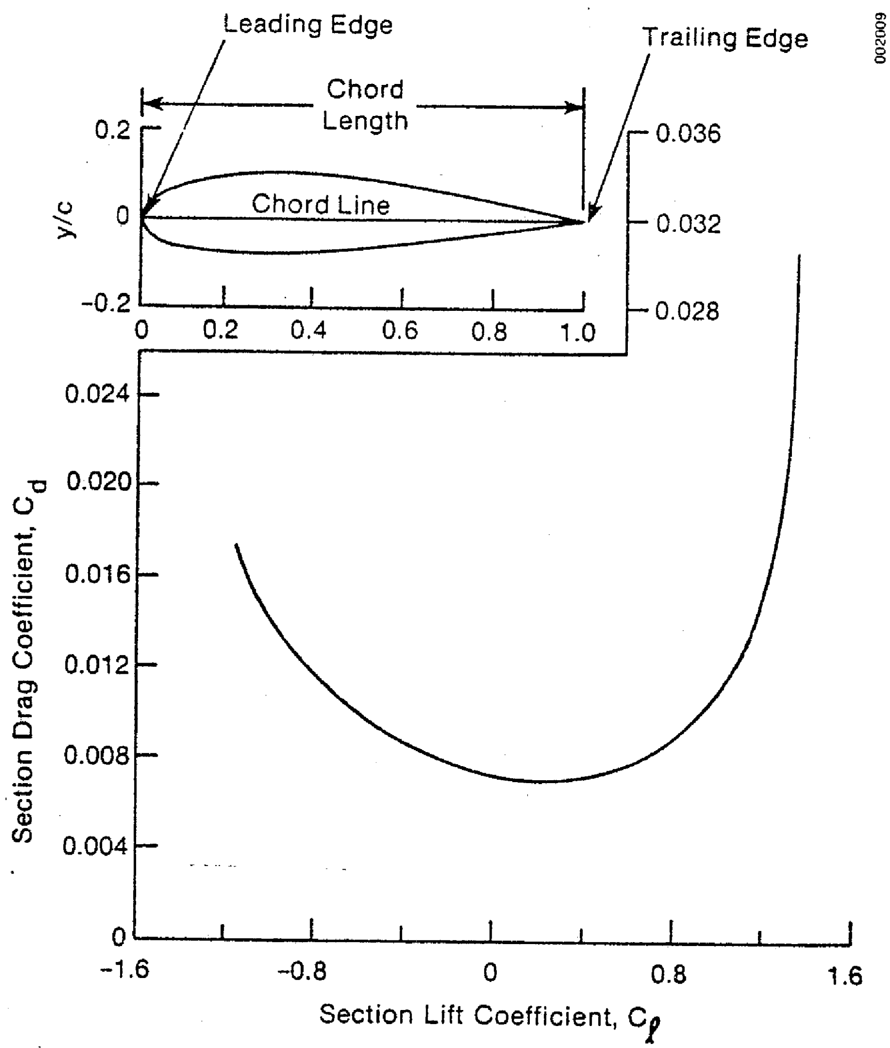

Figure 3-2. Typical Passive Airfoil and Its Lift-to-Drag Relationship

The analysis given in Appendix C shows that elements using aerodynamic lift and moving at relatively high speeds across the wind can very effectively derive power from the wind. The lifting object--which we can call a wing--can be many times as effective at producing power from the wind as a drag object (see Figure 3-4). In the ideal case of an isolated high-aspect-ratio wing using airfoils that have low drag coefficients, the lifting elements will approach the requirements for the actuator disk analysis. According to the isolated lifting wing analysis in Appendix C, an airfoil must have a maximum ratio C_L^3/C_D^2 to produce the maximum power from a given wing area. High lift coefficients in themselves are not necessarily desirable unless accompanied by low drag coefficients. It can also be shown that the condition required to extract the most power from a given disk area is that C_L/C_D be a maximum.

Aerodynamic lift can also be produced by active devices. There are many different types of active airfoils, but all use power to produce the lift. One

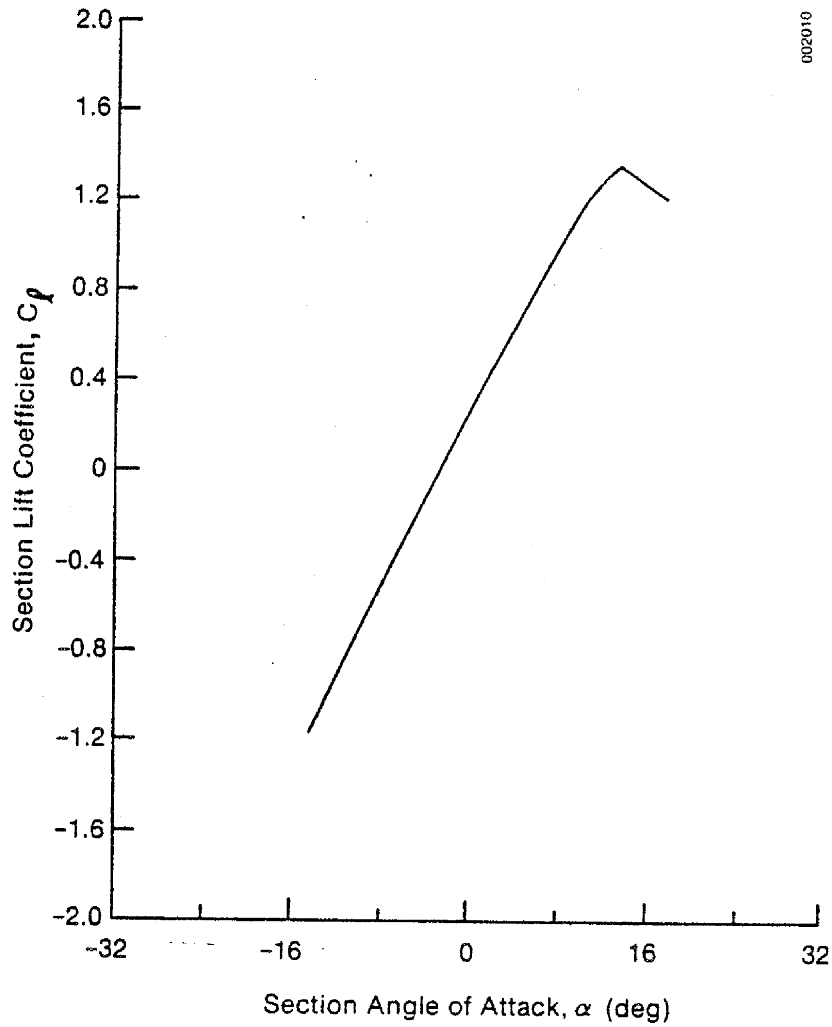

Figure 3-3. Typical Lift Coefficient to Angle of Attack Relationship for a Cambered Passive Airfoil

example of a powered airfoil is the spinning cylinder shown in Figure 3-5, which produces lift referred to as the magnus effect. If a cylinder has its axis aligned normal to the relative wind direction and is spun at a high rate of speed about its axis, it can produce a high lift coefficient. Another type of active airfoil uses a jet of air to cause circulation about the airfoil and hence produce a high lift coefficient. A further type uses suction to attach the boundary layer to the airfoil to delay flow separation and to produce a high lift coefficient. With all powered airfoils, the power required to produce the lift is considered an effective drag force as it detracts from performance; when this effective drag is added to the aerodynamic drag, the ratio of C_L^3/C_D^2 is usually not as high as that obtained with passive airfoils. Therefore the powered airfoil is usually less effective at producing power from the wind than a passive airfoil. The powered airfoil lift coefficient is also only weakly dependent upon angle of attack, and this can be a disadvantage.

Another factor apparent from the isolated lifting wing analysis in Appendix C is that the wing is most effective when it is moving at a high speed, as shown in Figure 3-6. At high speeds, the wing is moving in a direction that is almost normal to the lift vector. Intuitively one might expect that the maximum power would be produced when moving in the direction of the

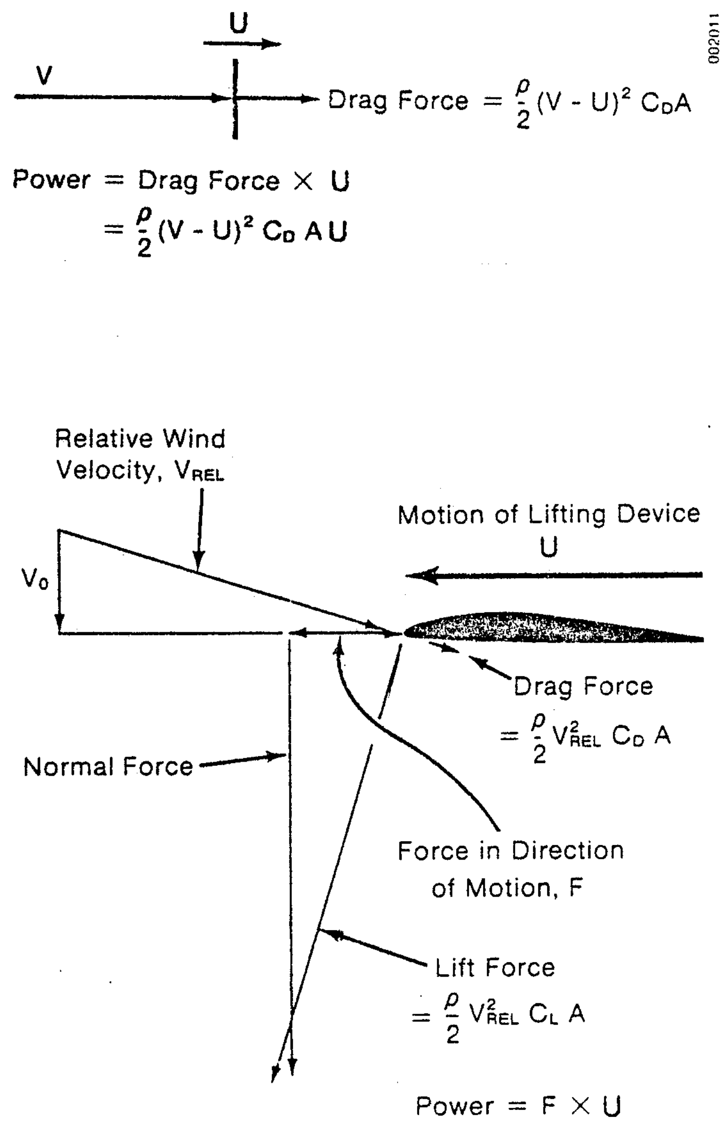

Figure 3-4. Definition of Forces on Lift and Drag Devices

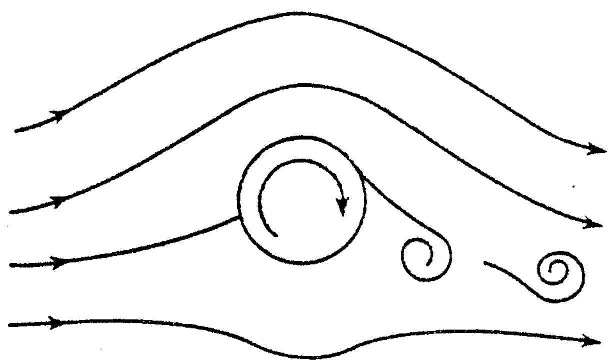

Figure 3-5. **Spinning Cylinder Used as an Active Airfoil to Produce a High Lift Coefficient (Magnus Effect)**

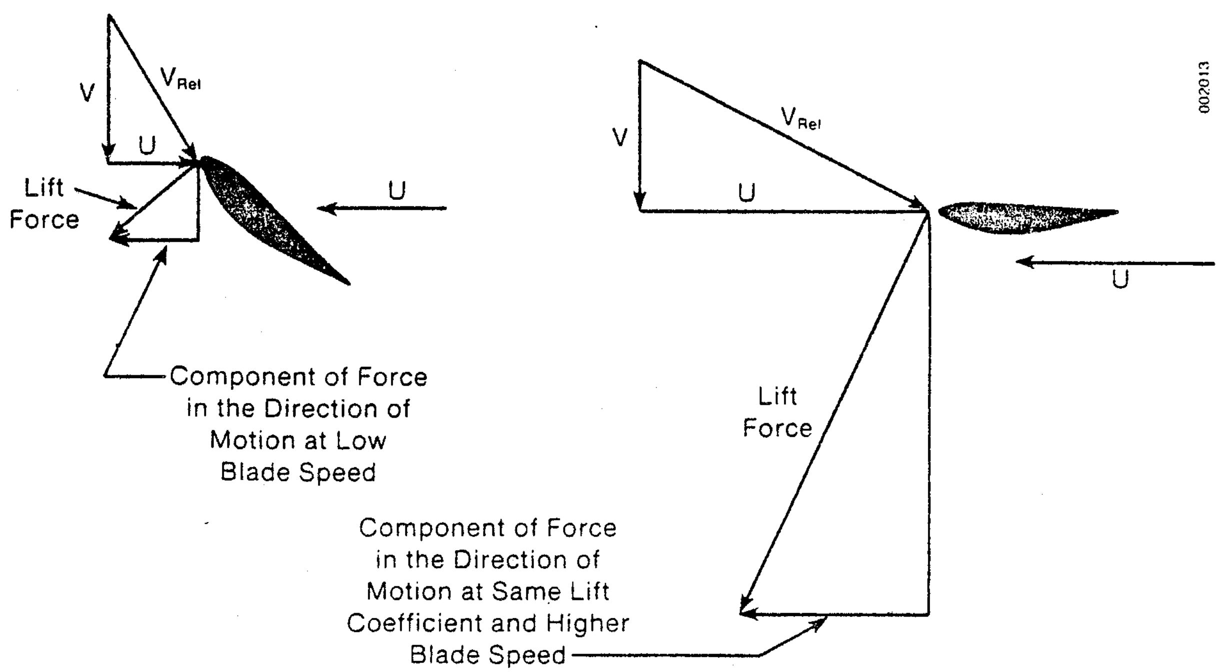

Figure 3-6. **Comparison of Force in the Direction of Motion Produced by an Isolated Blade Operating at the Same Lift Coefficient at Low and High Speeds**

lift vector. This apparent anomaly is explained by the fact that at a constant lift coefficient, the lifting force on the wing is proportional to the square of the relative velocity, and while the component of this force in the direction of motion relative to the lifting force is approximately inversely proportional to the ratio of relative wind speed to wing speed. Thus the magnitude of the force in the direction of motion actually increases with wing speed.

The actuator disk analysis shows that in order to derive power, a force must be produced to act upon the wind and reduce its speed. The wing shown in Figure 3-7 is moving at high speed across the wind and produces a lift force that is essentially aligned with the wind velocity. Hence, the lift on the wing is the drag force that the disk applies to the wind.

The concept of induced velocity V_i is used to describe the effect of a force on the wind (see Figure 3-7). It is a necessary result of the force. The induced velocity is proportional to the force and inversely proportional to the mass flow rate of the air affected by the force. The induced velocity cannot be eliminated, but its magnitude can be decreased by increasing the mass of air affected by the force. One mathematical model used for calculating the induced velocity is the shed vortex illustrated in Figure 3-8. The induced velocity that is applicable to the actuator disk can be calculated using the actuator disk analysis.

The concept of induced effects describes what a three dimensional lifting wing does to the wind, and how this reacts both upon the wing and upon any other devices that are adjacent to it. For an isolated lifting wing, the induced angle of attack is directly proportional to the lift coefficient and inversely proportional to the aspect ratio. The induced drag is equal to the

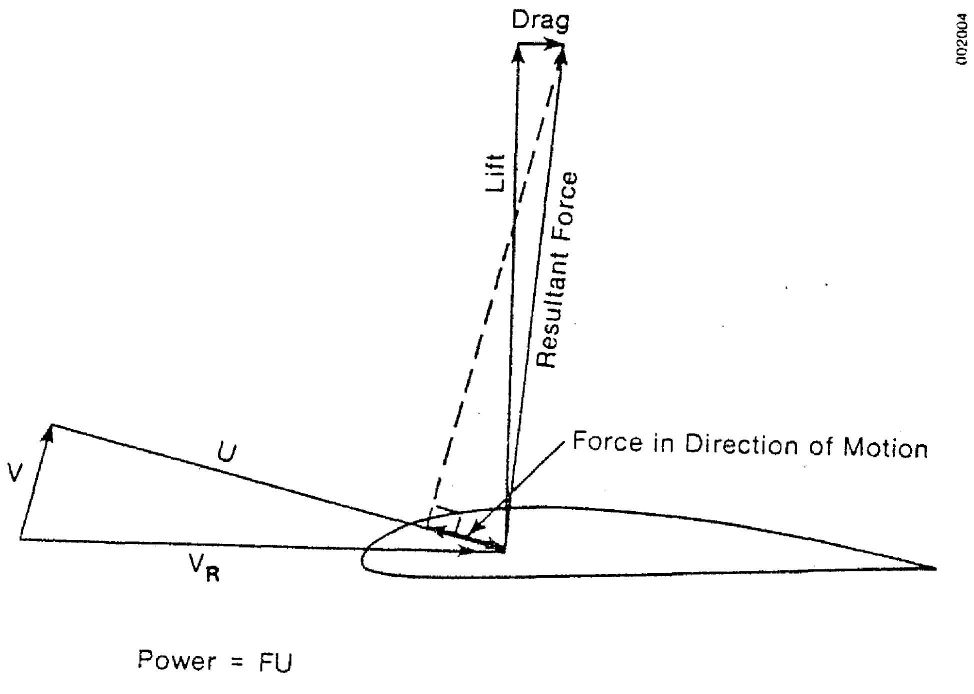

Figure 3-7. Forces Acting on an Airfoil Moving in Wind

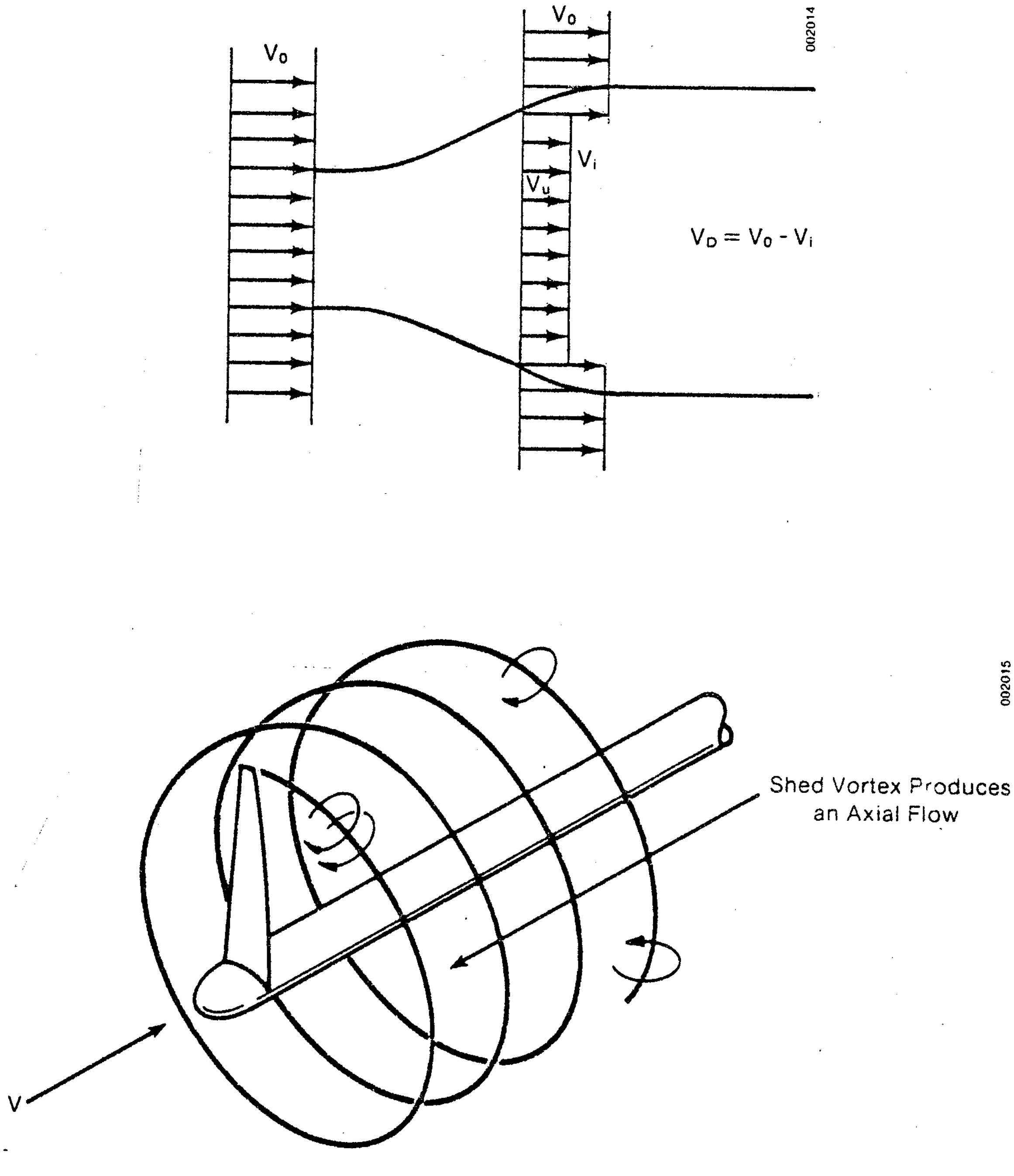

Figure 3-8. Velocity Induced by Loading

lift on the wing multiplied by the induced angle of attack. The induced angle of attack always tends to reduce the lift on the wing. If the wing is followed by a second similar wing carrying an equal lift, the induced effects on this second wing will be three times as large as the first wing.

If the lifting wings travel in other than a straight-line path, the induced effects will be similar in character although different in magnitude from those experienced by the translating wing. It is the induced effects that limit the power output of a wind machine, and these effects must be accurately accounted for if a reasonable prediction of the performance is to be obtained.

3.1 SUMMARY

A comparison of the effectiveness of the lift and drag elements, illustrated in Figure 3-9, shows that the lifting element is far superior to the drag element for each unit of area. However, the power output per unit of area is not the only consideration. The amount of energy produced per unit of cost for the complete system is important. Therefore it is necessary to evaluate the impact of each element on the entire system. Thus, any type of device that appears inappropriate early in an evaluation stage should not be discarded because this evaluation stage might later turn out to be largely irrelevant.

In a real system, the lift or drag elements cannot usually be treated as isolated elements, and their effectiveness will therefore be reduced over that of the ideal case. For drag elements, the effects are usually small unless

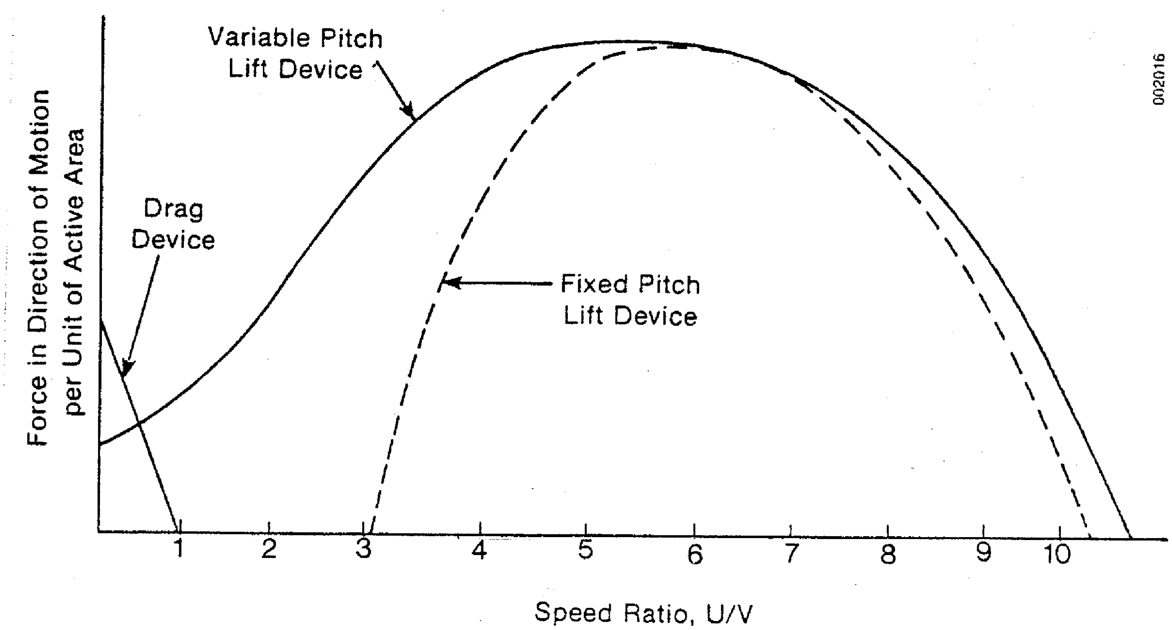

Figure 3-9. Force in the Direction of Motion Versus Speed Ratio for Typical Isolated Lift and Drag Devices of Equal Active Area

one element is either partly or wholly downwind of another. For lift elements, the concept of induced velocity is used.

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SECTION 4.0

SYSTEM CONFIGURATIONS

4.1 SUMMARY

Whether the primary elements work on lift or drag principles, they are likely to be constrained to move in some orbital path, like the examples shown in Figure 4-1. When selecting a configuration for a wind energy converter the orbital path must be considered. We are free to choose the shape, the orientation, and the method of maintaining the orbital path. The shape of the orbital path can vary from circular, through elliptic or race track, to linear, as shown in Figure 4-2. With the circular or elliptic configuration, the primary element speed is usually a constant; but with the linear path, the element usually is in simple harmonic motion.

The orientation of the path is partly determined by the type of primary element. The drag device can only produce power when traveling downwind, so the orbital path should be oriented accordingly to be most effective. As an example, an orbit in a vertical plane normal to the wind direction cannot be used for the drag device because the elements don't move downwind (see Figure 4-3). Another example is that in general, an orbit in the vertical plane requires orientation, and hence it needs a yawing mechanism. If the orbital path is in a horizontal plane, then a yawing mechanism may not be necessary (see Figure 4-4).

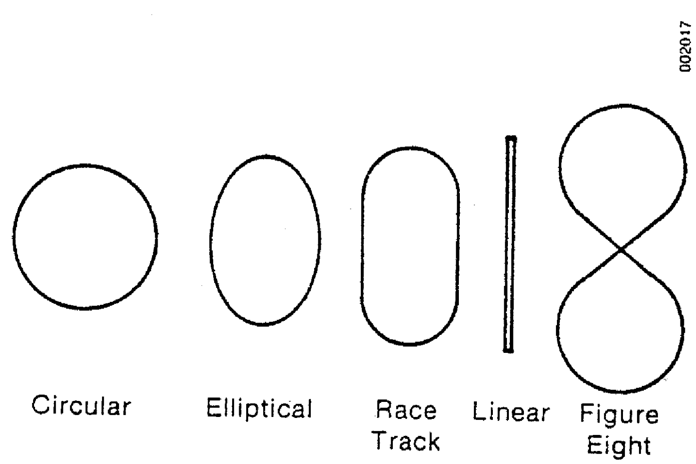


Figure 4-1. Typical Orbital Paths

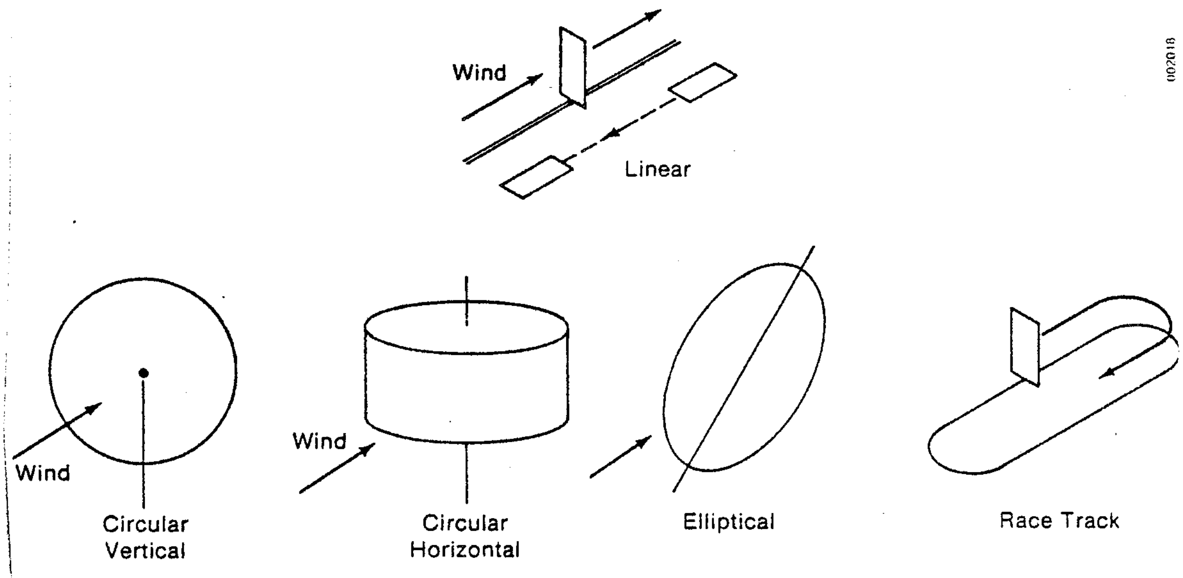


Figure 4-2. Some Examples of the Uses of Orbital Paths

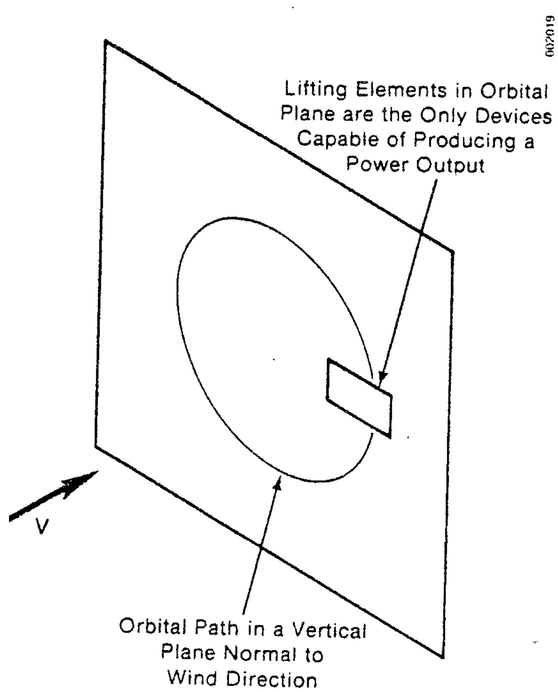


Figure 4-3. Vertical Orbital Path Normal to the Wind

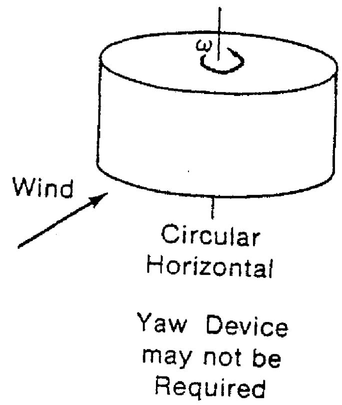


Figure 4-4. Horizontal Orbital Path

There are two distinct choices when selecting the orbital path of a lifting device. The orientation of the path as well as the orientation of the lifting elements to the orbital plane can be chosen. The lifting elements can be within the orbital plane or essentially normal to it. If the elements are within the orbital plane, then they will only extract power from winds normal to the plane (Figure 4-3). Hence, they will require that the orbital path be in a vertical plane normal to the wind direction and will require a yawing mechanism. When the lifting elements are normal to the orbital plane, they cannot extract power from any wind that is in the orbital plane. The orbital plane could then be either in a vertical plane aligned with the wind and require a yawing mechanism or in a horizontal plane requiring no yawing mechanism as shown in Figure 4-5.

One example of a device with lifting elements in the plane of the orbital path and the orbital plane normal to the relative wind is the conventional horizontal axis machine. Generally, the aerodynamic loads of these machines are essentially constant throughout the orbital path while gravitational loads are cyclical. The consequence of the constant aerodynamic loads is that the angle of attack is essentially constant throughout the orbital path and hence, power control can be achieved by simple collective blade pitch control. The effect of the cyclic gravitational loads becomes more apparent as size increases, and it can cause fatigue problems on large machines.

One variant of the orbital path in the horizontal plane with lifting elements normal to the plane is the conventional Vertical Axis Wind Turbine (VAWT). With this type of machine, the aerodynamic loads are cyclical while the gravitational loads are constant. A consequence of the cyclic aerodynamic loads is that the lifting elements will usually be subject to load reversal during the cycle; this factor limits the choice of airfoil sections and introduces

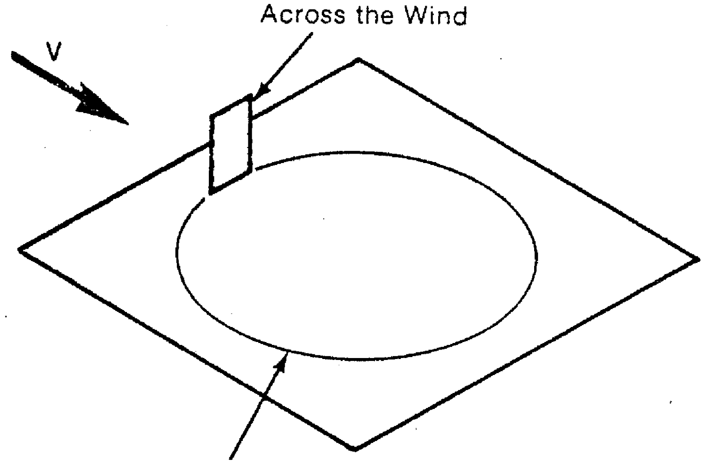


Figure 4-5. Orbital Path in a Horizontal Plane with Lifting Elements Extending Normal to the Plane

fatigue. Passive airfoils will most likely have some degree of symmetry while powered airfoils will most likely be made to accommodate the change in power flow required to produce the lift change. The cyclic aerodynamic loading also means that power control usually requires cyclic blade pitch control or controlled blade stall. The constant gravity load eliminates fatigue problems due to gravity. Stresses resulting from structural size are therefore not so severe, and it is likely that economic limits to size will occur before the structural limit is reached.

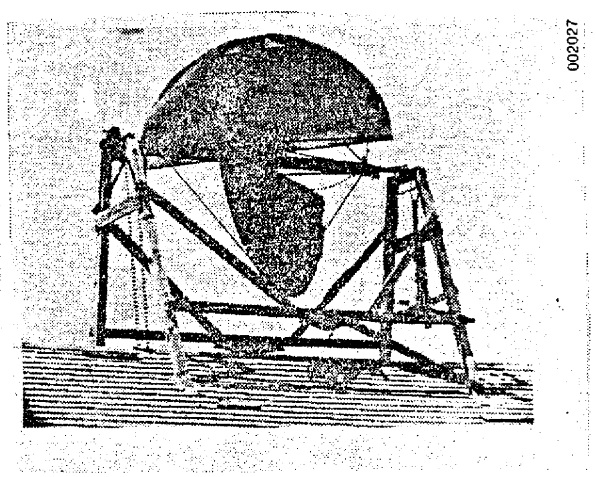
The ultimate consideration when selecting the shape for the orbital path is the net energy output per unit of cost. The most effective shape aerodynamically for a drag device is a straight-line path downwind and for a lift device is a straight-line path across the wind. But, if a straight-line path is used, the direction of motion must be reversed on some part or the part must be curved to bring the element back to the starting point.

The linear path with the element reversing its direction of motion could be used with a drag device, but the active element would have to change its drag characteristics depending on the direction of motion (i.e., high drag going downwind and low drag going upwind); this would necessitate a certain mechanical or structural complexity. Reversing the direction of a linear path has been considered for lifting elements. The disadvantages are that the lifting element must operate over a wide range of relative wind speeds and angles of attack to slow down and reverse its direction. This results in the greatest acceleration on the blade occurring at the ends of the path when the relative wind speeds are lowest so that aerodynamic loads cannot be used to reduce the stresses of the lifting element. The wide range of angles of attack necessitates the use of cyclic pitch control which can be complex; the acceleration at the ends of the straight path limits the maximum speed attainable ratio and, hence, the effectiveness of the elements.

The path consisting of straight and curved sections has certain advantages over the single linear path. For drag elements, the semicircle at each end of the straight sections reverses the orientation of the element, and a fixed shape of active element can be used. With lift elements, the changes in the angle of attack are much smaller than when the single linear path is used. If the transverse velocity of the element is high enough, no blade pitch change is required. However at speeds high enough to make lifting elements effective, the acceleration on the semicircular ends of the path can be high enough to cause problems. These deceleration problems can be reduced either by reducing the speed, and hence the effectiveness of the lifting element or by increasing the radius of curvature of the path. In the limiting case for a given total length of path, this acceleration will be at a minimum when the path is circular.

While moving in an orbital path however, the active elements will still be subjected to dynamic and aerodynamic loads, and therefore some mechanism must still be provided to support the loads and maintain the path. Probably the simplest way of maintaining a path for an active element is to move it in a semicircular path about an axis or flexure. In this type of system the structural, dynamic, and aerodynamic loads can be taken out by the axis or flexure in a relatively simple manner, and the power can be extracted by using some form of linkage to the active elements.

For circular motion either a simple axis (Figure 4-6) or a track (Figure 4-7) can be used to maintain the path. The axis is a very convenient device



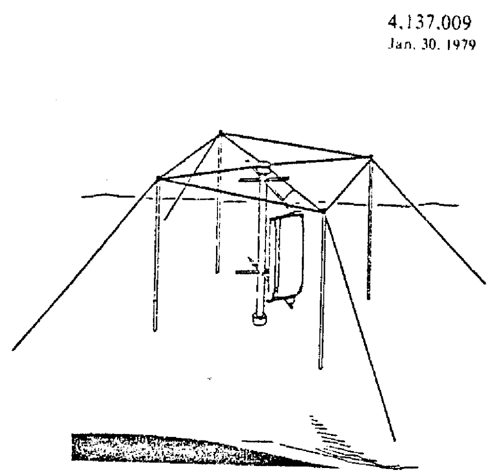
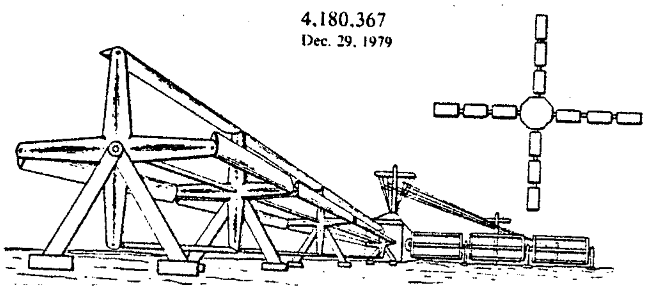


Figure 4-6. Devices Using Axes to Support the Active Elements



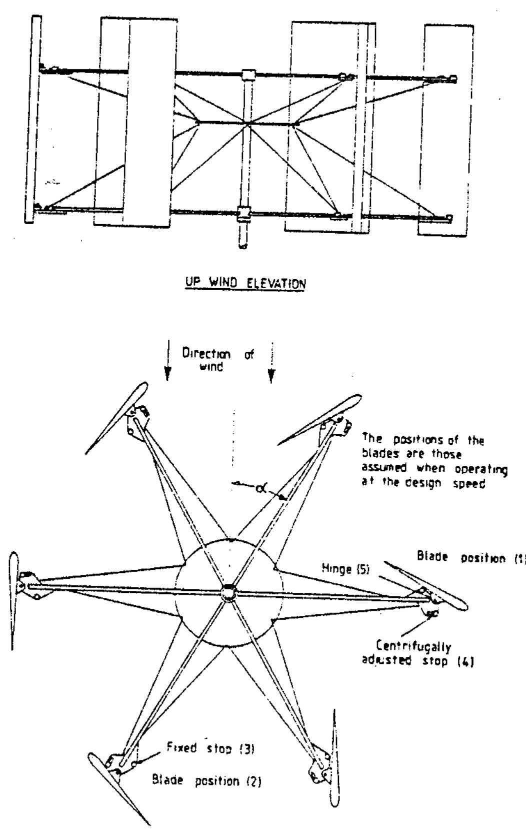


Figure 4-6. Devices Using Axes to Support the Active Elements (Continued)

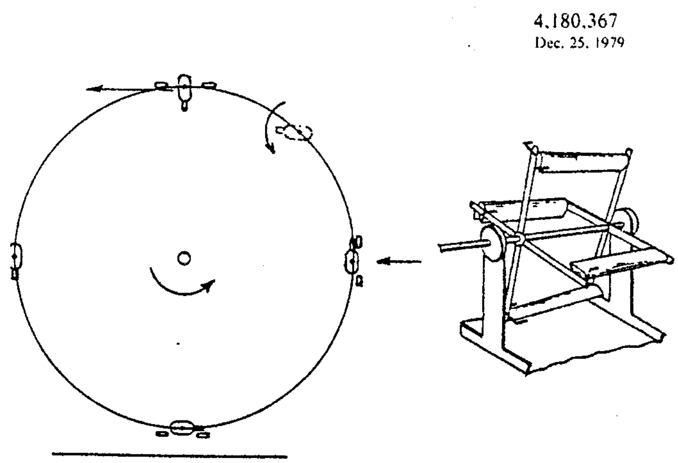


Figure 4-6. Devices Using Axes to Support the Active Elements (Concluded)

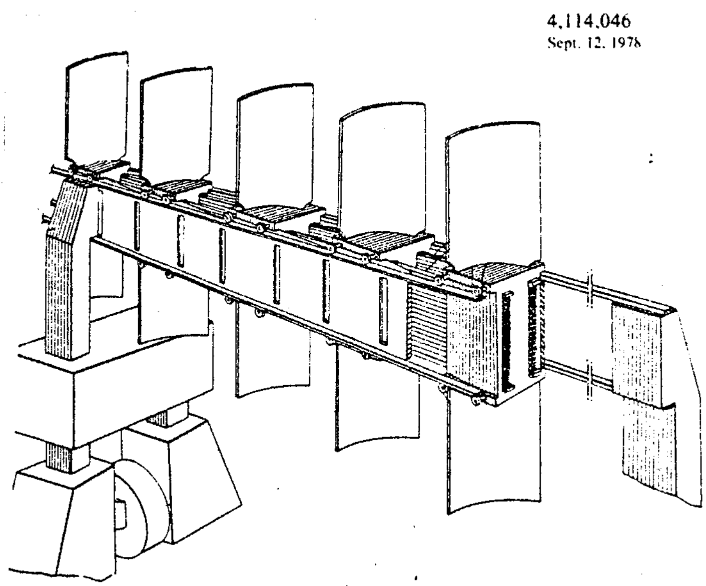


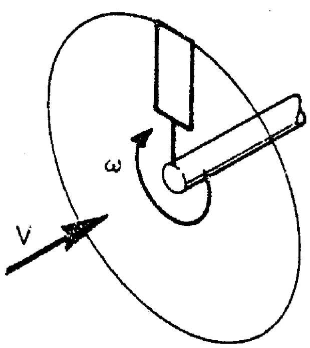
Figure 4-7. Devices Using Tracks to Support the Active Elements

because it can easily be arranged to support the structural, dynamic, and aerodynamic loads, and to transmit the power to a conversion device (see Figure 4-8). The axis is also a relatively low-cost structure that is readily oriented into the wind if necessary and usually has low friction losses. Non-circular paths will usually require the use of a track, and the problems and advantages will then be similar to those experienced on a circular track (see Figure 4-9).

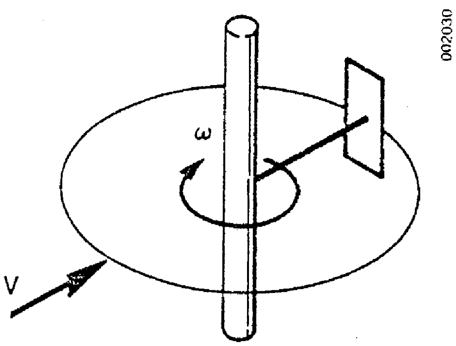
When the active elements rotate around an axis supported by a base tower, the desirable height of the tower is an economic consideration. The increased average power output that is obtained by raising the elevation of the active elements must be balanced against the cost of the base tower. The height that is most cost-effective will be reached when the cost of increasing the average power output by raising the height is equal to the cost of obtaining the same increase in average power by changing any other machine parameter.

With a track, the support of the loads is more difficult than with an axis. Generally the friction and aerodynamic losses are greater than with an axis, which results in the use of lower speeds for the active elements and hence in lower effectiveness. The power transmission of a track system is usually arranged to take advantage of the relative motion between the track and the carriage supporting the active element. The important advantages claimed for the track concept are that very large machines can be built and that power conversions can be accomplished with relatively conventional devices.

One other support system that is worthy of note is the tether. The tether can be used to overcome the drag loads on a lifting system used to increase the



(a) Axis for Supporting Lifting Elements Within Vertical Plane (HAWT)



(b) Axis for Supporting Active Elements Moving in a Horizontal Plane (VAWT)

Figure 4-8. Axis Systems Used in the HAWT and the VAWT

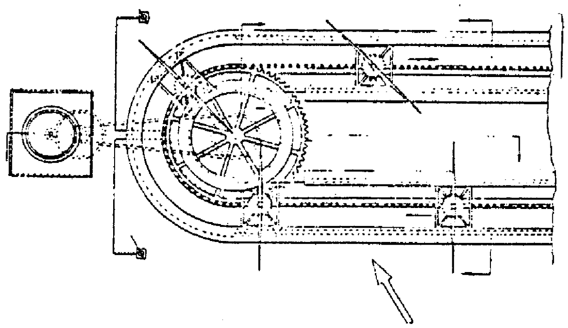


Figure 4-9. Noncircular Track

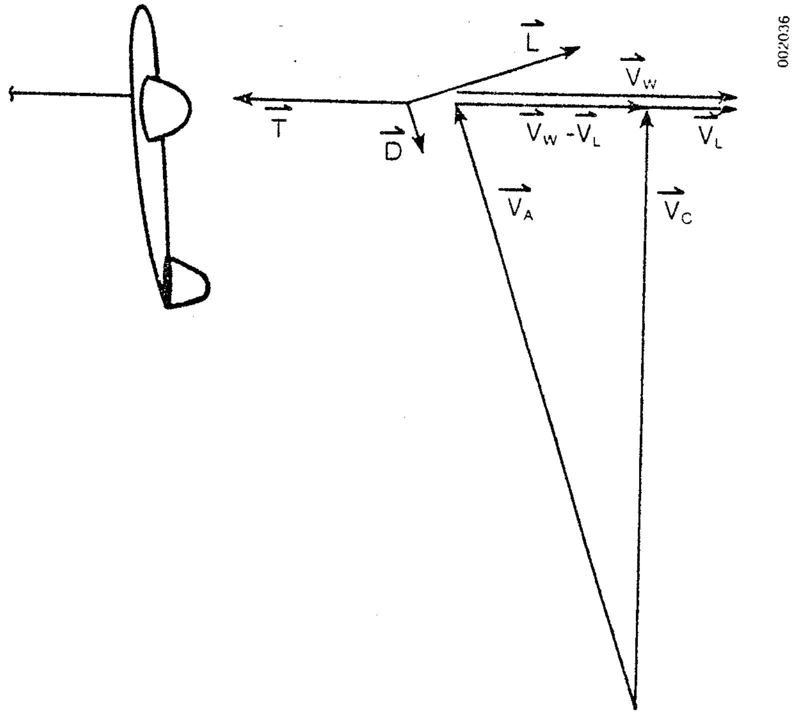
elevation of a wind machine so that it increases the available power density; or it can be used to support an active lifting device that is moving in an orbital path downwind of an anchor point, with the shape of the orbital path being controlled aerodynamically. The advantage of the tether is that it provides a relatively low cost way of allowing the active elements to take advantage of the increased wind speeds at higher altitudes, as illustrated in Figure 4-10. One disadvantage of the tether used to support an active lifting element is that the aerodynamic drag on the cable can cause severe power losses and increased structural costs. See Figures 4-11 and 4-12 for the effects of cyclic gravitational loads and cyclic aerodynamic loading, respectively.

4.2 CONVENTIONAL WECS

Conventional WECS can be defined as those types of machines that have had some commercial success. They include types that have been available on the market and many of those that have been constructed for use by their builders. All conventional machines employ active elements that are supported by an axis and move in a circular path. The active elements can operate either on aerodynamic lift or drag.

4.2.1 Differential Drag Devices

Differential drag devices are inefficient both aerodynamically and structurally, as illustrated in Figures 4-13 and 4-14. Because of this inefficiency, the commercial impact of the differential drag devices has been quite limited. However, because of their rugged simplicity and high starting torque, they are used in certain low power applications. The most common types of differential drag WECS are the Savonius rotor and the drag cup anemometer. Many variants of these models have been built by individuals for their own use.



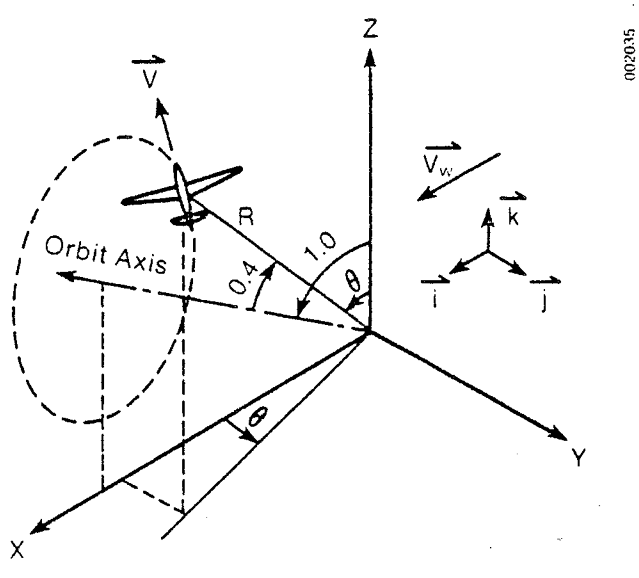


Figure 4-10. Tethers Used to Maintain Useful Orbital Paths

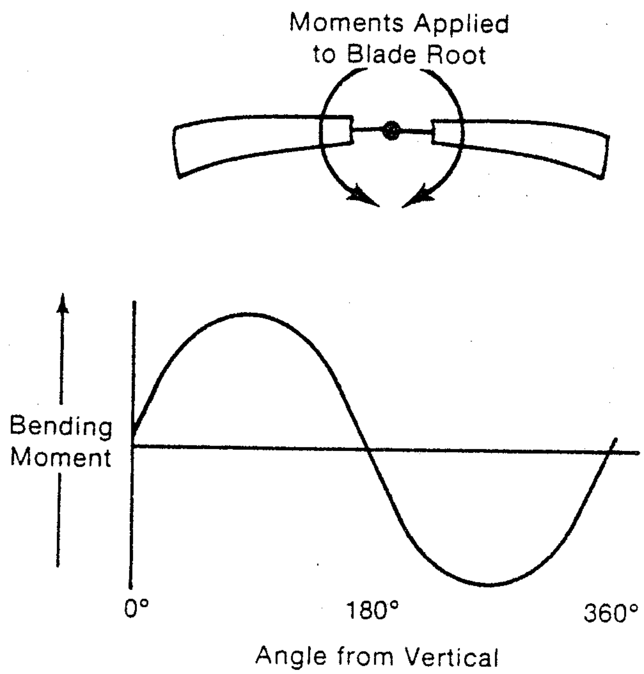


Figure 4-11. Gravitational Bending Moments Seen by Blade Roots of a HAWT

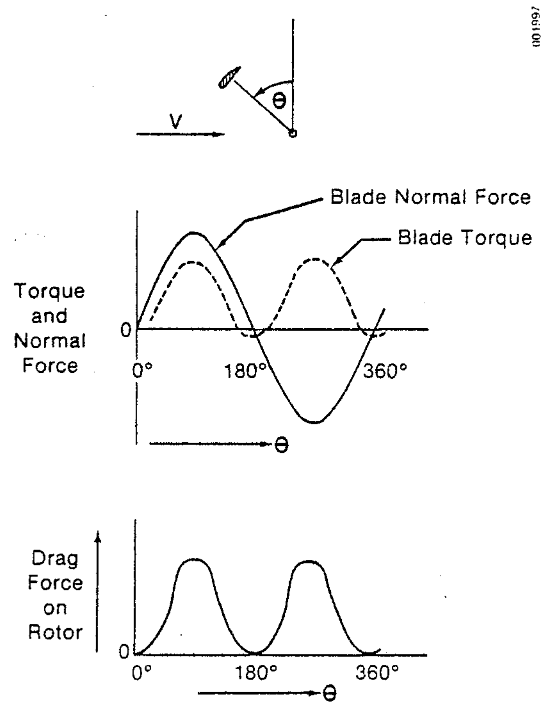


Figure 4-12. Aerodynamic Forces on a VAWT

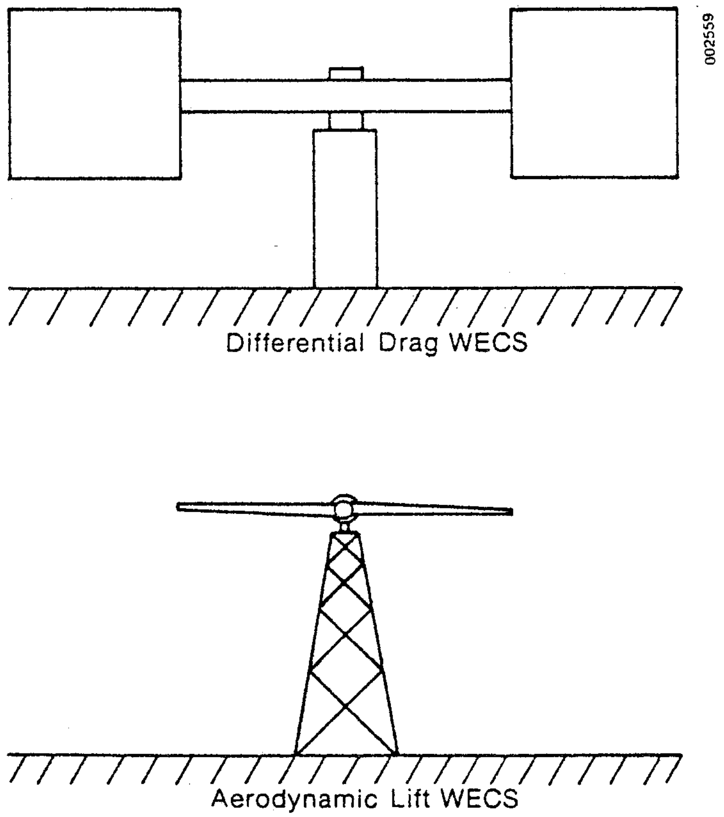


Figure 4-13. Relative Sizes of a WECS Using Differential Drag and Using Aerodynamic Lift to Produce the Same Power in the Same Wind Conditions

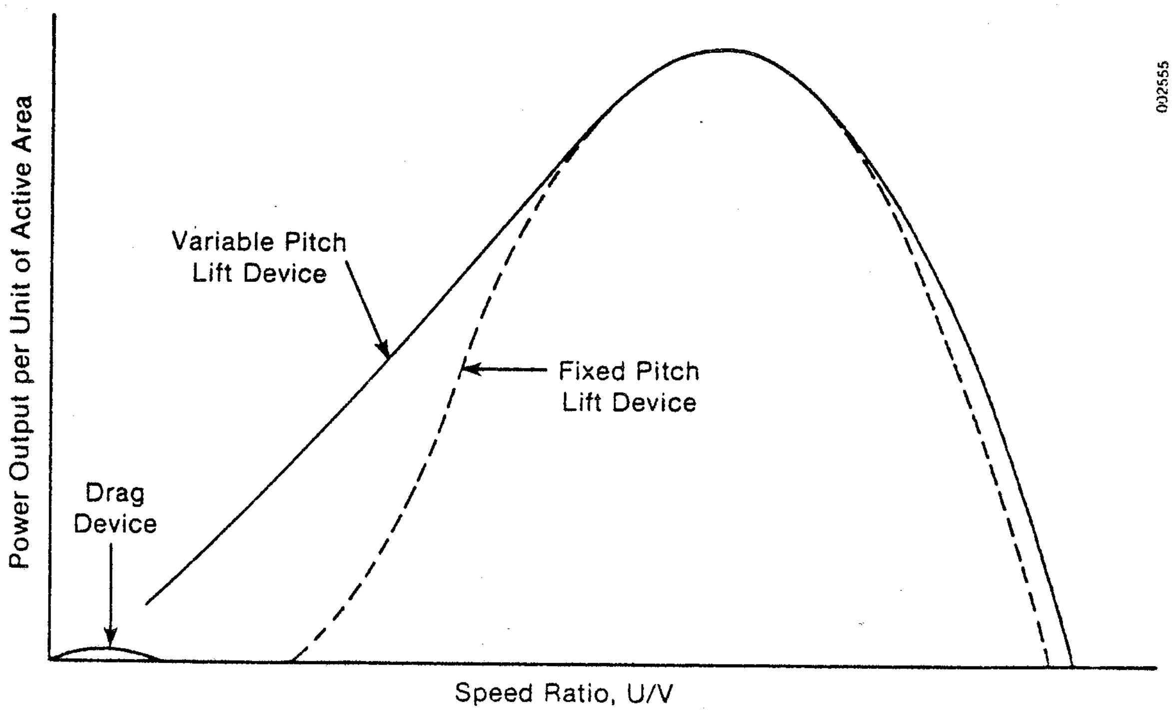


Figure 4-14. Power Output per Unit of Active Area for Differential Drag WECS and Lift WECS

The drag cup anemometer is not strictly a WECS because the constant ratio of tip speed to wind speed is the important consideration, and the device develops very low torque. But in principle it can be used to extract power from the wind. Indeed, the early Asian WECS and many homebuilt machines can be considered variants of the drag cup anemometer.

The operating principles of the differential drag WECS are shown in Figure 4-15. The maximum tip-speed ratio can be obtained when the ratio of drag coefficients of the active elements in both forward and reversed flow is at a maximum. If the drag coefficient in the reversed flow is zero then the maximum free running tip speed will approach wind speed; when the drag coefficients are similar, the maximum tip-speed ratio will be near zero. Practical differential drag devices with fixed geometry are unlikely to have a free running tip-speed ratio greater than 0.4.

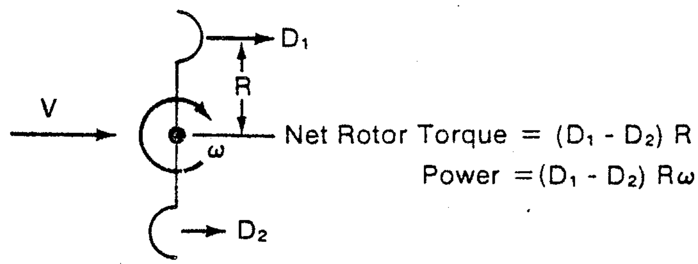
To achieve higher tip-speed ratios and greater power coefficients, variable geometry differential drag elements can be used. Some types of variable geometry elements are shown in Figure 4-16. The variable geometry adds some complexity to the WECS in exchange for increased performance. With some types of variable geometry devices, the WECS is sensitive to wind direction and requires an orienting device. Even with the variable geometry the maximum tip-speed is always less than wind speed.

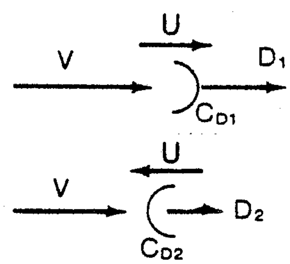
Another method for increasing the performance of the differential drag WECS is to provide a shield to prevent the wind from impinging on the forward-moving drag elements. When the shield is used, the WECS is sensitive to wind direction so that some orienting device is required. Figure 4-17 illustrates some types of shields.

The Savonius rotor, illustrated in Figure 4-18, combines the high starting torque of the differential drag WECS with a higher efficiency and higher tip-speed ratio. A properly designed Savonius rotor can have a free running tip-speed of about twice wind speed. The increased efficiency and tip-speed make the Savonius rotor superior to the differential drag device. However, it is inferior to WECS with lift elements because of the large quantity of structural materials required and the large forces that are generated in high winds. It is most often used in small sizes where its rugged simplicity and high starting torque are valuable.

The aerodynamic performance of the Savonius rotor has been studied extensively. When the rotor is started, it operates essentially as a drag device. When the rotor is turning, the flow is complex and unsteady, and the maximum tip-speed ratio of about two suggests that aerodynamic lift is being generated at higher speeds.

End plates are essential for high performance. Without end plates, the free running tip-speed ratio is about one, and the performance is reduced. There must also be a gap between the two overlapping halves of the rotor to achieve the high performance.





$$U = R\omega$$

$$D_1 = \frac{\rho}{2}(V_0 - R\omega)^2 A_1 C_{D1}$$

$$D_2 = \frac{\rho}{2}(V_0 + R\omega)^2 A_2 C_{D2}$$

Assuming that there are no losses when the drag elements are moving crosswind, maximum free running speed will occur when

$$D_1 = D_2$$

$$\text{or } (V - R\omega)^2 A_1 C_{D1} = (V + R\omega)^2 A_2 C_{D2}$$

$$\frac{A_1 C_{D1}}{A_2 C_{D2}} = \left(\frac{V + R\omega}{V - R\omega}\right)^2$$

$$\text{For } R\omega = V, \quad \frac{A_1 C_{D1}}{A_2 C_{D2}} \rightarrow \infty \quad \text{or } A_2 C_{D2} = 0.$$

$$\text{For } R\omega = \frac{V}{2}, \quad \frac{A_1 C_{D1}}{A_2 C_{D2}} = 3$$

Figure 4-15. Torque and Power Produced by a Differential Drag WECS

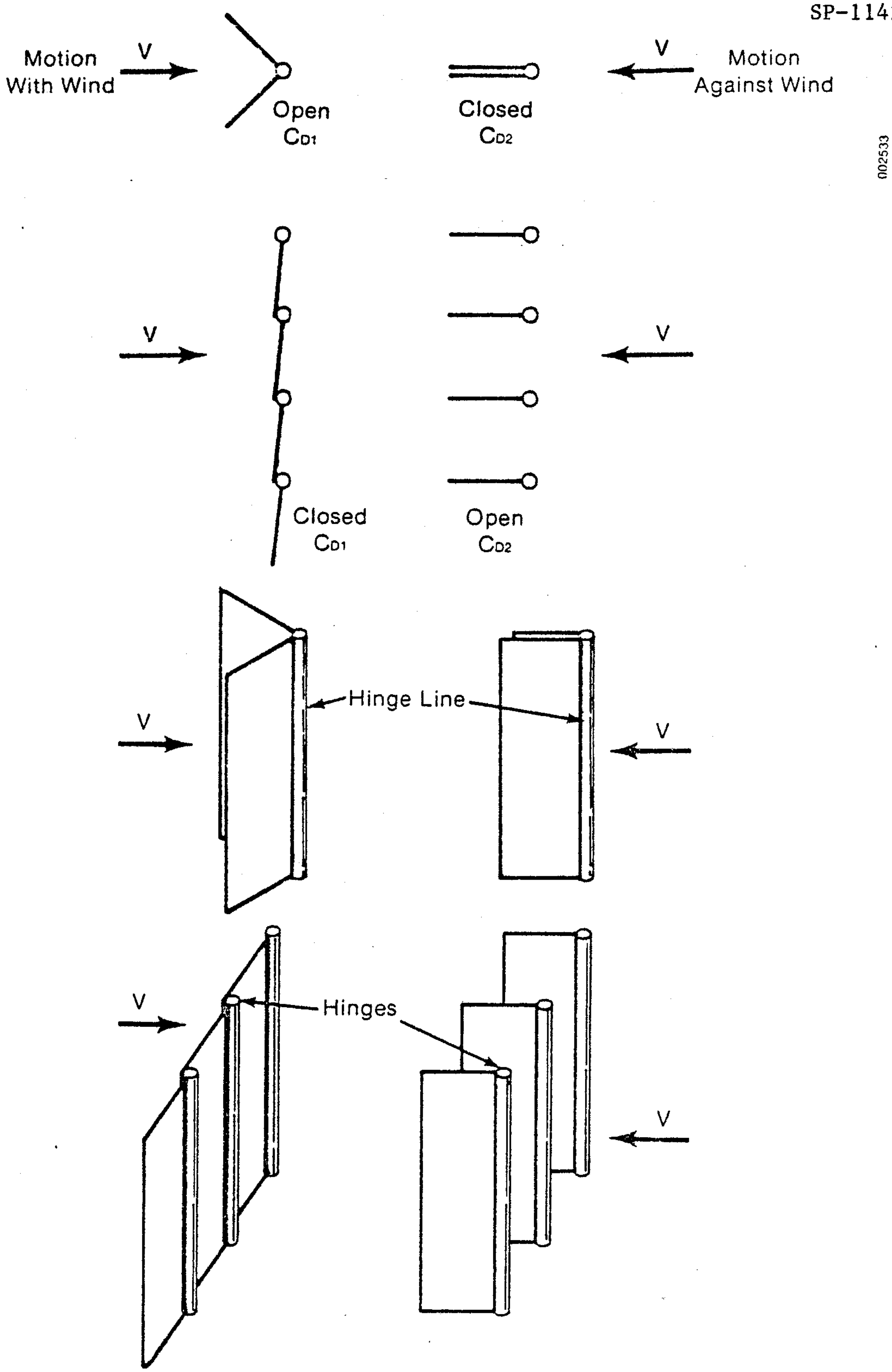


Figure 4-16. Variable Geometry Elements for Differential Drag WECS

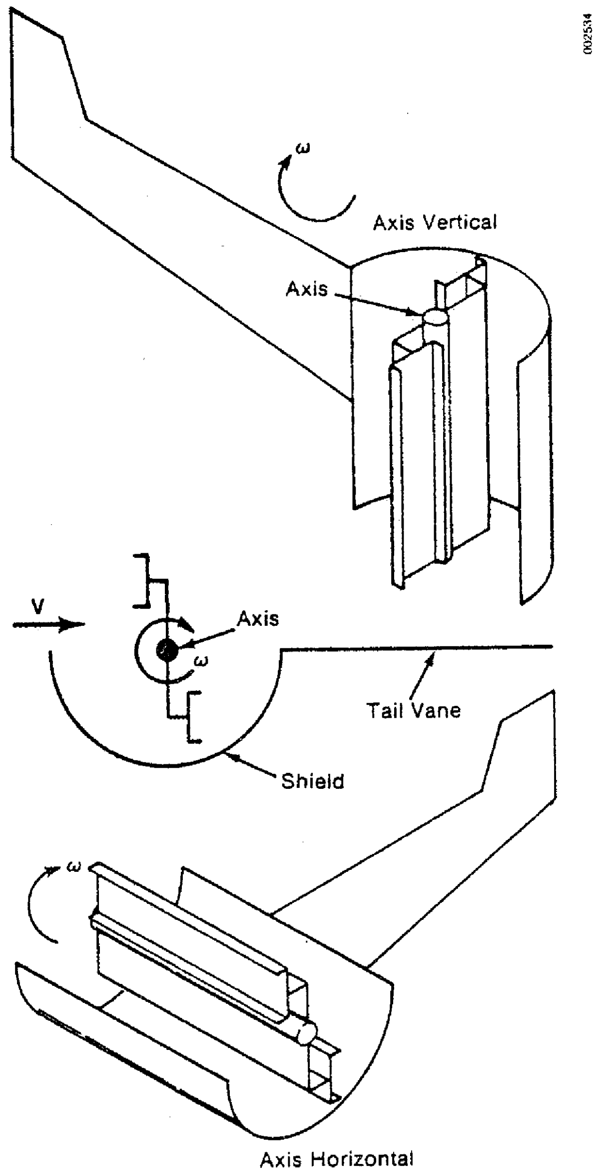


Figure 4-17. Shielded Element WECS

4.2.2 Horizontal Axis WECS

Horizontal-axis machines have received the most developmental effort and have been the most successful commercially.

The horizontal axis WECS with lifting elements [horizontal axis wind turbines (HAWTs)] has a wide variety of applications, dating as far back as early Persia, and sizes (from a few watts to a few megawatts). The system has been used to provide energy for water pumping, electrical generation, grinding grain, and other uses in many parts of the world. Some horizontal axis lifting element WECS designs are shown in Figure 4-19.

The HAWT has several essential features. It must have one or more lifting elements, or blades, attached to an axis that is aligned with the wind. The HAWT requires some mechanism to orient the axis so that it is aligned with the wind. It also requires a support structure to raise the active elements into

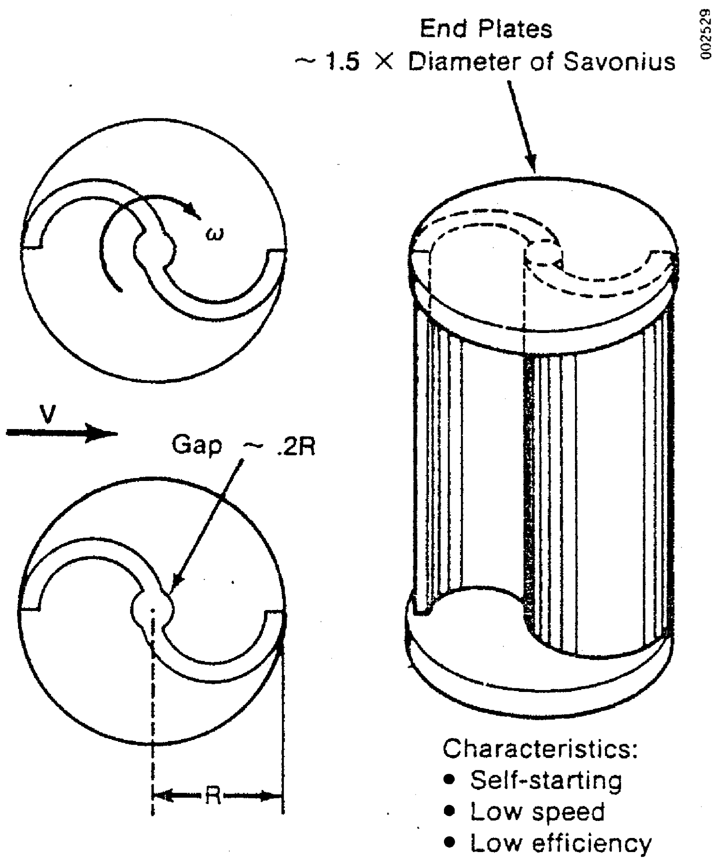


Figure 4-18. Savonius Rotor

a reasonable wind regime, and this support structure must have sufficient strength to resist the aerodynamic loads that may be applied. An energy conversion system and a control system are also required. Figure 4-20 illustrates the essential features.

A variety of performance characteristics can be obtained by using an appropriate selection of design parameters; it is not difficult to design an HAWT with relatively high aerodynamic and structural efficiencies. However when cost and reliability are also important, the design process can be difficult. When designing rotor blades, the choices that are available include the number, the shape, the airfoil section, the total solidity, whether the blade pitch is fixed or not, and the structural materials.

Rotors have been built with numbers of blades ranging from one to several. Machines with two or three blades are the most common. For the same total solidity, it is usually less expensive and more structurally sound to minimize the number of blades; but when fewer than three blades are used the moment of inertia of the rotor is not the same about two mutually perpendicular axes in the plane of the rotor. This results in a cyclical gyroscopic moment applied to the support structure when the spinning rotor is yawed (as shown in

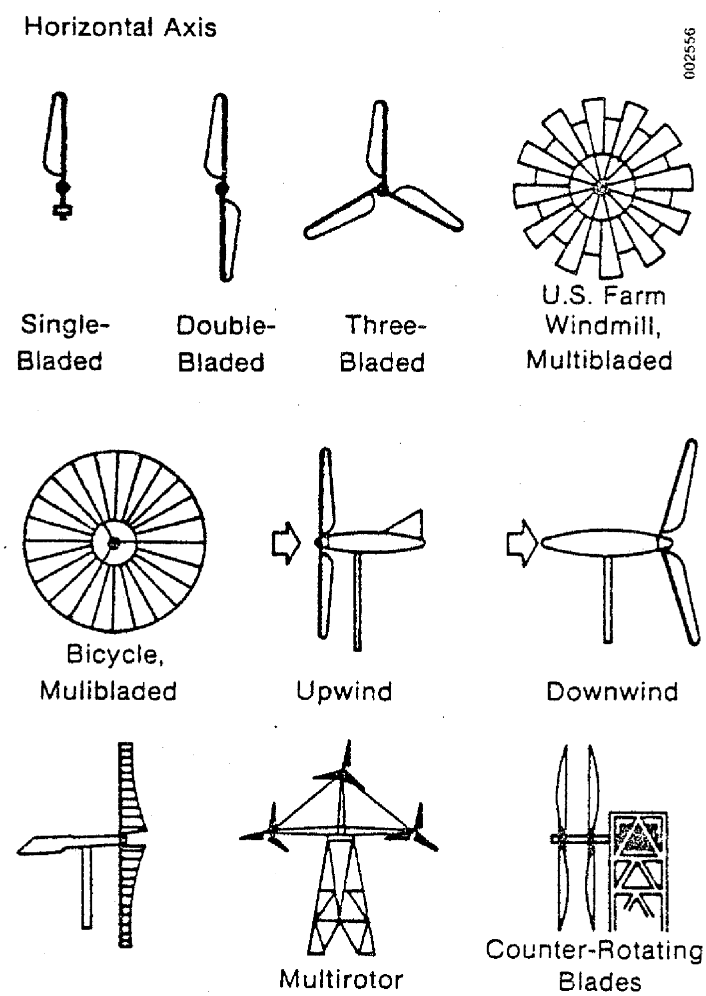


Figure 4-19. Some HAWT Configurations

Figure 4-21). On one- or two-bladed machines, the rate of yaw is sometimes limited in order to minimize these effects. With three blades or more there is no cyclical gyroscopic moment applied to the shaft. There is, however, a cyclical gyroscopic moment applied to each blade root. The choice of blade shape and airfoil section, some examples of which are shown in Figure 4-22, depends upon the particular application. For high performance the airfoil should have a high value of C_L/C_D.

The total solidity that is required depends upon the desirable aerodynamic characteristics. A high solidity was necessary for the relatively high starting torque required by the positive displacement water pumps that were used with the American farm windmill. In applications where a high starting torque is not important but overall performance and a high operating tip-speed are, a very low solidity is desirable (see Figure 4-23).

Variable pitch can be used to obtain good performance over a greater range of tip-speed ratios than fixed pitch. The variable pitch can also be used to increase the starting torque and to control the power in high winds. Against these desirable characteristics, the designer must weigh the extra cost and

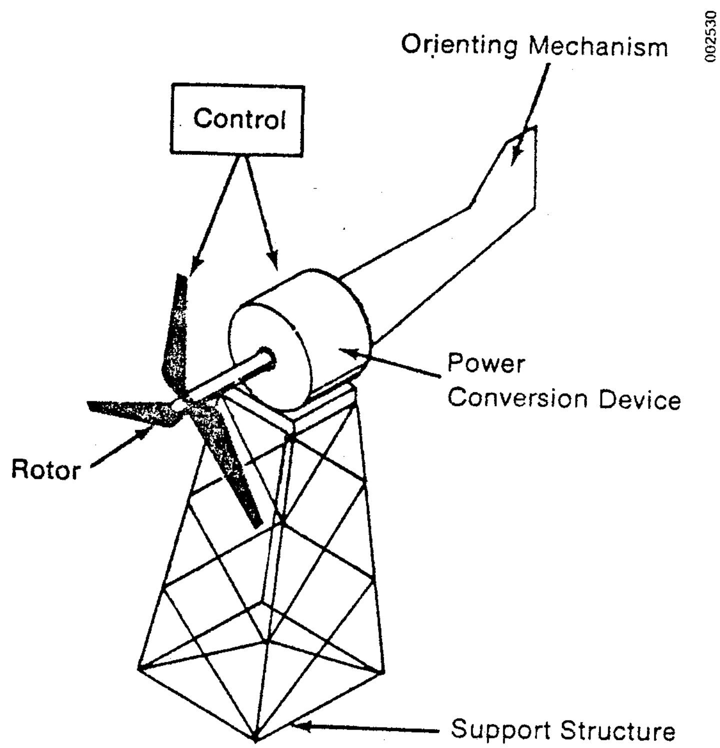


Figure 4-20. Basic Elements of a HAWT

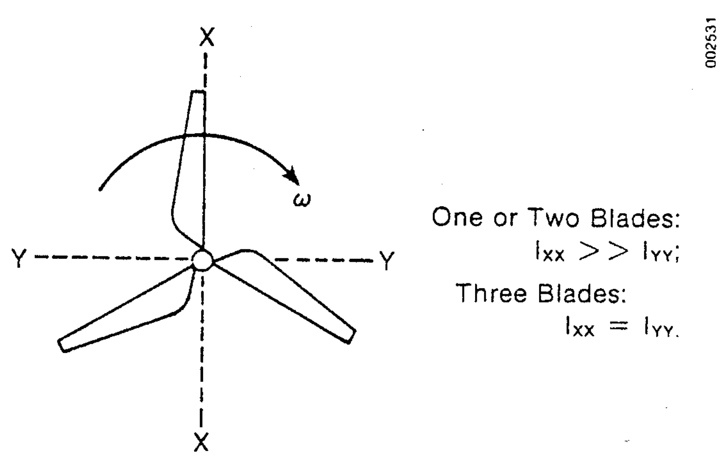


Figure 4-21. Moment of Inertia of a Rotor

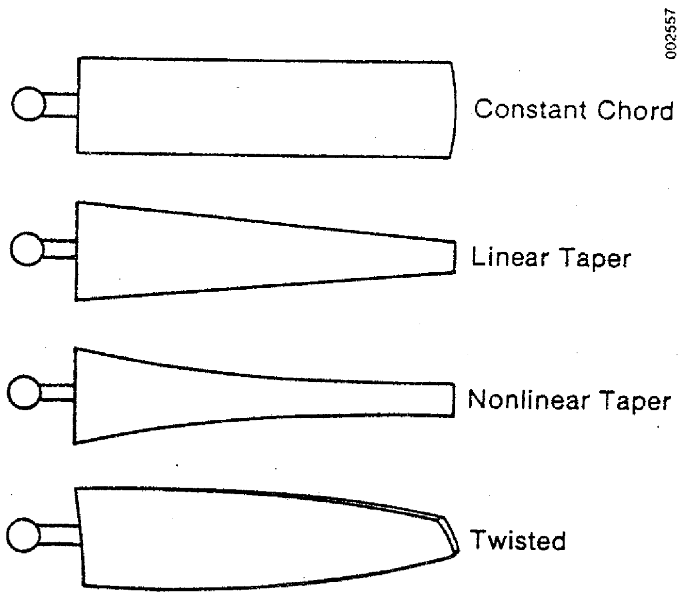


Figure 4-22. Typical Blade Shapes for a HAWT

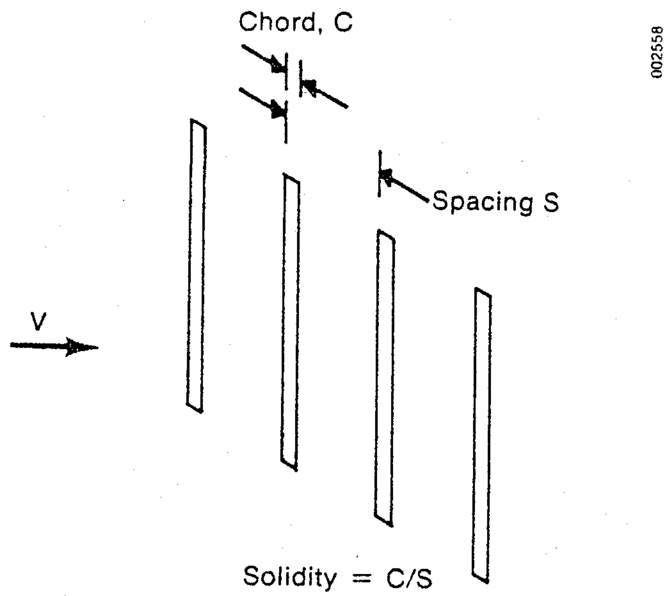
possible problems with reliability that may result from the relatively complex pitch-control mechanism. Choosing the best structural materials for the blades is very difficult. The most common materials are wood, steel, aluminum, and fiberglass, or other fiber-reinforced plastics.

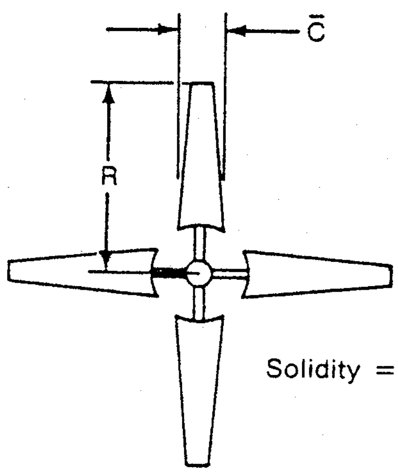
Various rotor-orienting mechanisms are available, ranging from the direct application of an aerodynamic force on a free yawing rotor to the use of a yaw drive motor responding to signals from a sensing device. Figure 4-24 shows a variety of orienting mechanisms.

The rotor support structure must hold the rotor at an appropriate height, and most have the strength to resist the aerodynamic loads that will be imposed during operation and those that may occur in high winds. The supporting structure must also have enough rigidity to enable it to resist the dynamic loads acting upon it. Figure 4-25 shows some support structures.

The most common power conversion equipment consists of a speedup mechanism driving an electrical generator. Many other drive systems have been used, some of which are illustrated in Figure 4-26. The rotor can be controlled to operate at a constant speed or at a variable speed. The constant speed machine allows the WECS to be coupled to an AC electrical network with a simple interface. A constant speed system also imposes dynamic loads that have a fixed frequency, so the structural design problem is simplified. Constant speed conversion equipment produces less energy than variable speed conversion equipment, but the reduced complexity is often sufficient compensation.

Power control can be achieved by changing the pitch of the blades, turning the rotor axis out of alignment with the wind, allowing the blades to stall, or





$$\text{Solidity} = \frac{\text{Blade Area}}{\pi R^2}$$

or

$$\text{Alternately Solidity} = \frac{(\text{No. of Blades}) \times (\text{Av Chord})}{R} = \frac{n\bar{C}}{R}$$

Figure 4-23. Effects of Solidity on the Performance of Typical HAWTs

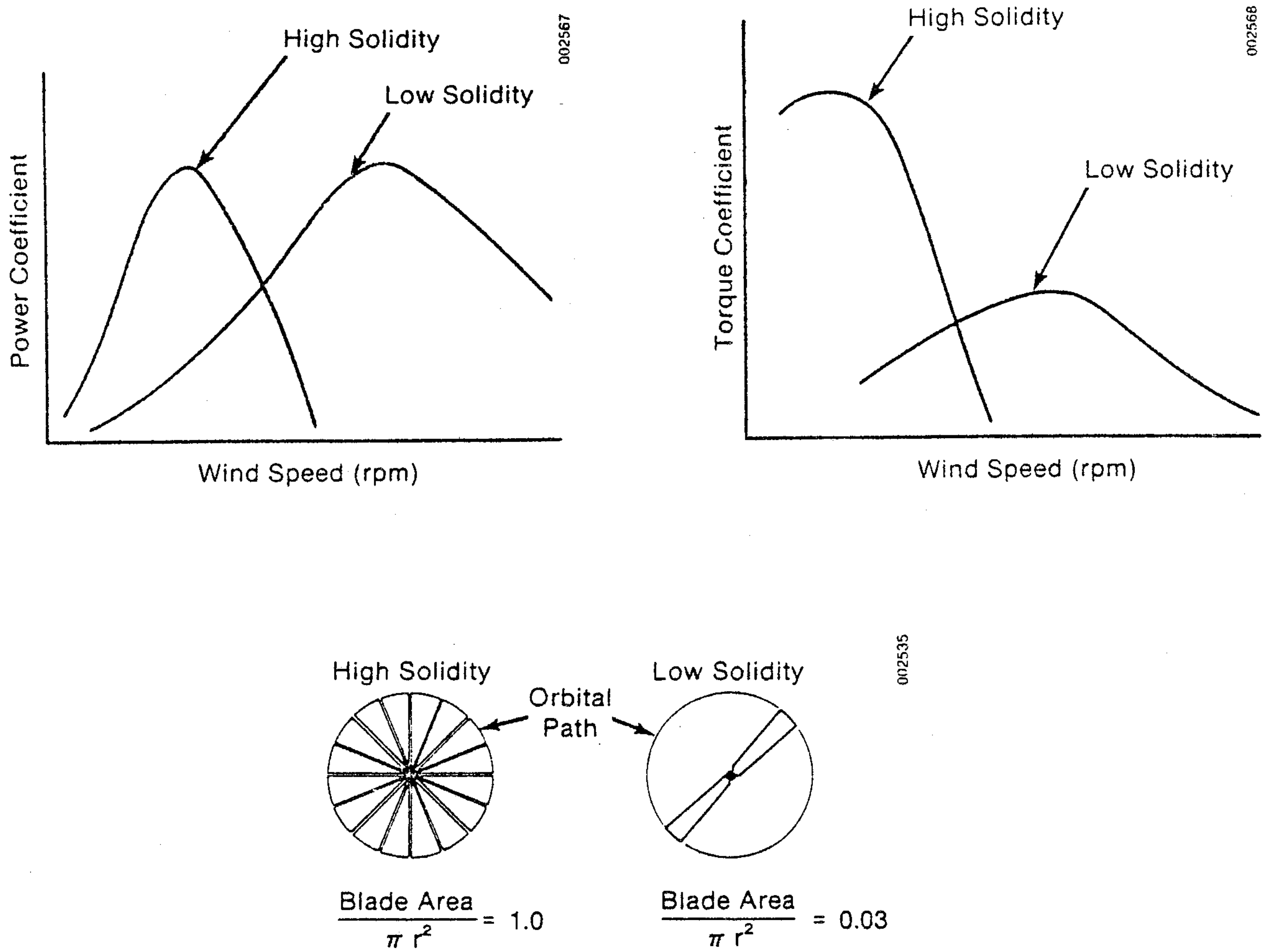


Figure 4-23. Effects of Solidity on the Performance of Typical HAWTs
(Concluded)

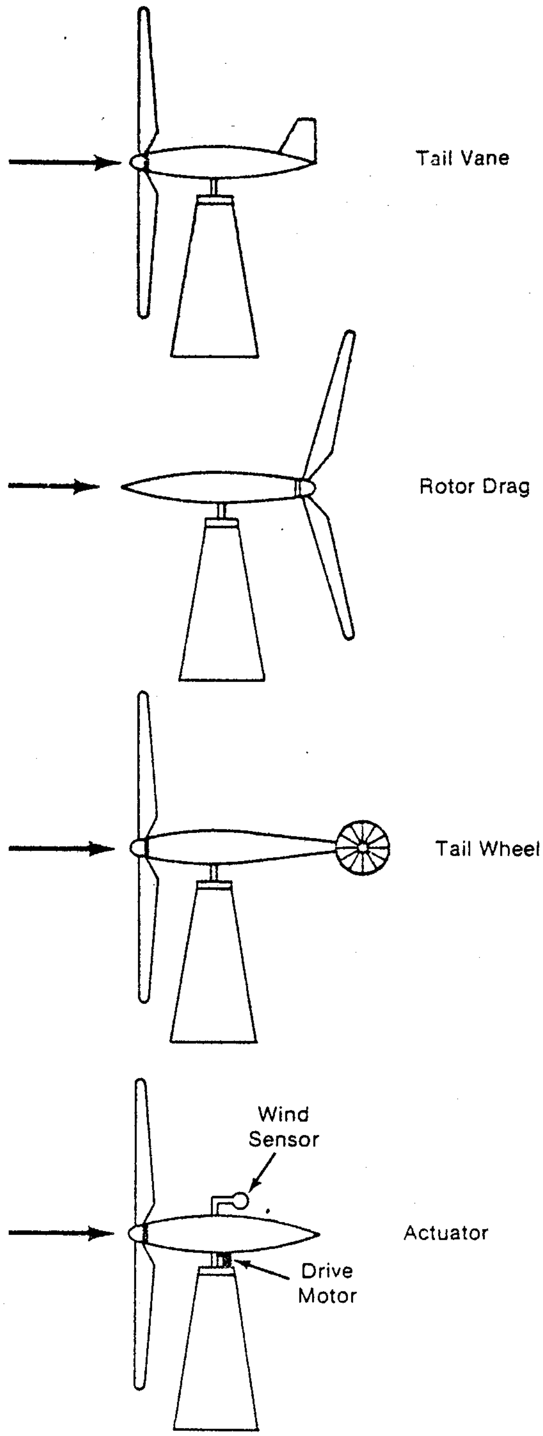


Figure 4-24. Typical Orienting Mechanisms for HAWTs

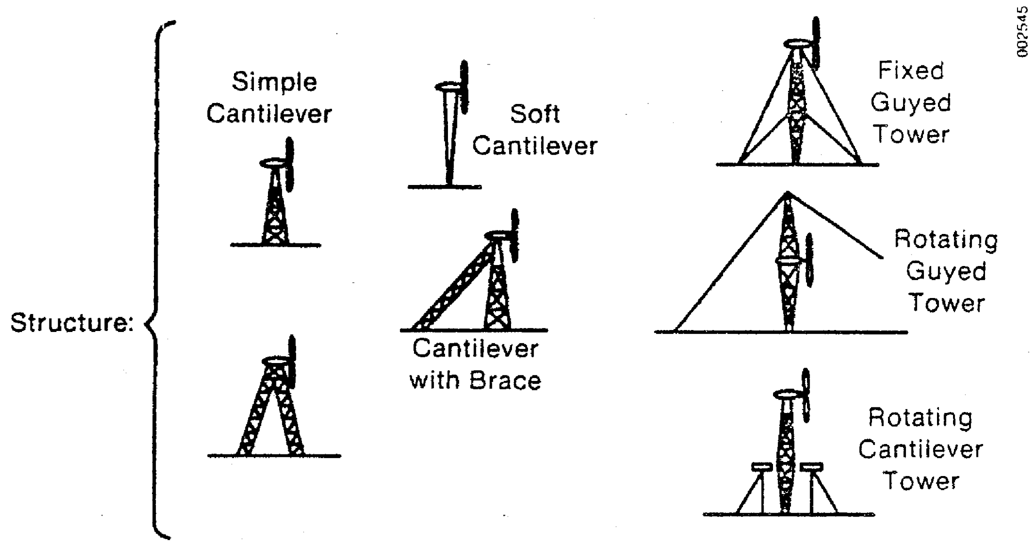


Figure 4-25. Some Rotor Support Structures

using aerodynamic spoilers. Figure 4-27 illustrates some of the power control methods, and Figure 4-28 shows some specific designs for varying blade pitch.

An inherent characteristic of the HAWT is that the gravitational loads on the blades vary cyclically and that the stresses produced by these loads increase with size (see Figure 4-11). These cyclic gravitational stresses tend to limit the maximum size of the HAWT; however, rotors as large as 300 ft in diameter have been built and operated.

4.2.3 Vertical Axis WECS

In 1925, Darrieus patented a variety of vertical axis WECS models that used aerodynamic lift. Figure 4-29 shows the concept submitted in the original patent. As with the HAWT, the vertical axis wind turbine (VAWT) uses one or more blades attached to an axis, as shown in the examples in Figure 4-30. However, in the case of the VAWT, the axis is aligned vertically across the wind. The operating principles are shown in Figure 4-31.

There are three types of VAWT: the fixed-pitch curved-blade machine, the fixed-pitch straight-blade machine and the variable-pitch straight-blade machine (Figure 4-32). All VAWTs are subject to cyclic aerodynamic loads, and the lift force reverses direction relative to the blades during each turn of the rotor so that nearly symmetrical airfoils are required. The straight-blade machines have the advantage of simple blade construction. However, the centrifugal bending moments on the blades, diagrammed in Figure 4-33, limit the blade speed and the allowable unsupported blade length. The curved-blade machines have a blade shape that a flexible element would adopt under the centrifugal load, so the blades are subjected to low bending stresses.

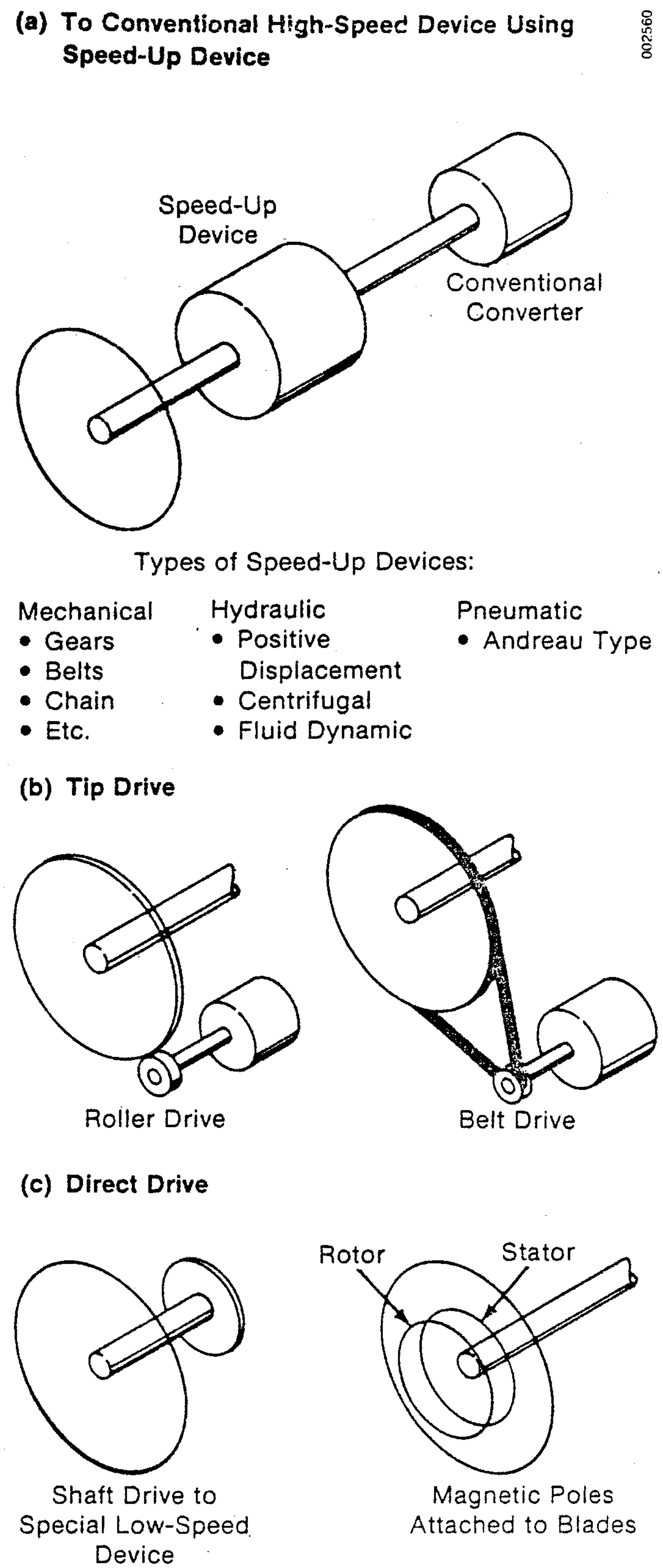


Figure 4-26. Typical Power Transmission and Conversion Mechanisms

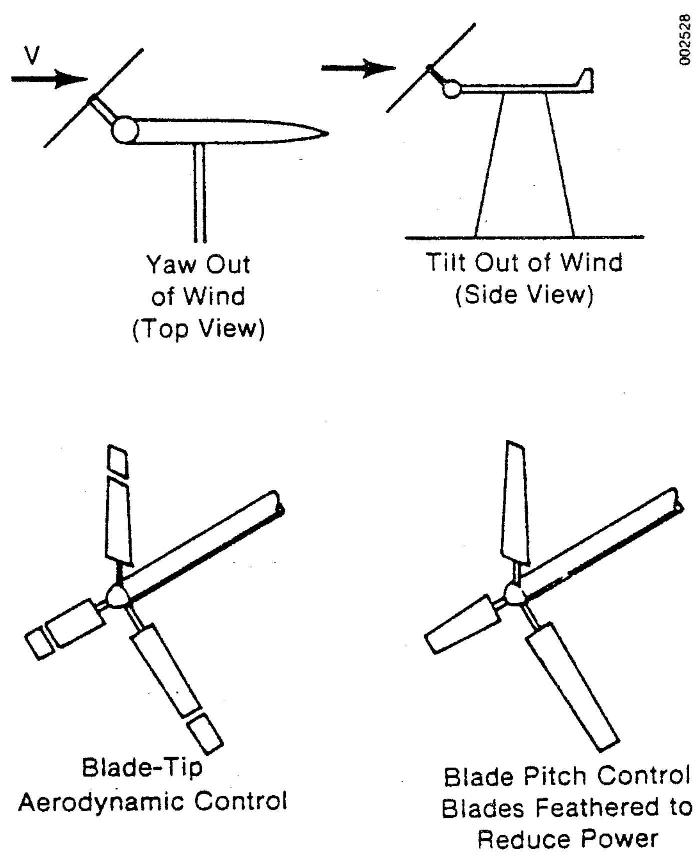


Figure 4-27. Some Methods for Controlling and Limiting the Power Extracted from the Wind

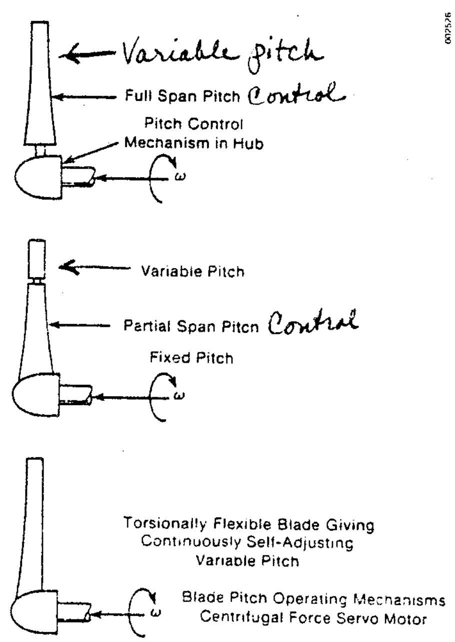


Figure 4-28. Blade Pitch Control Mechanisms

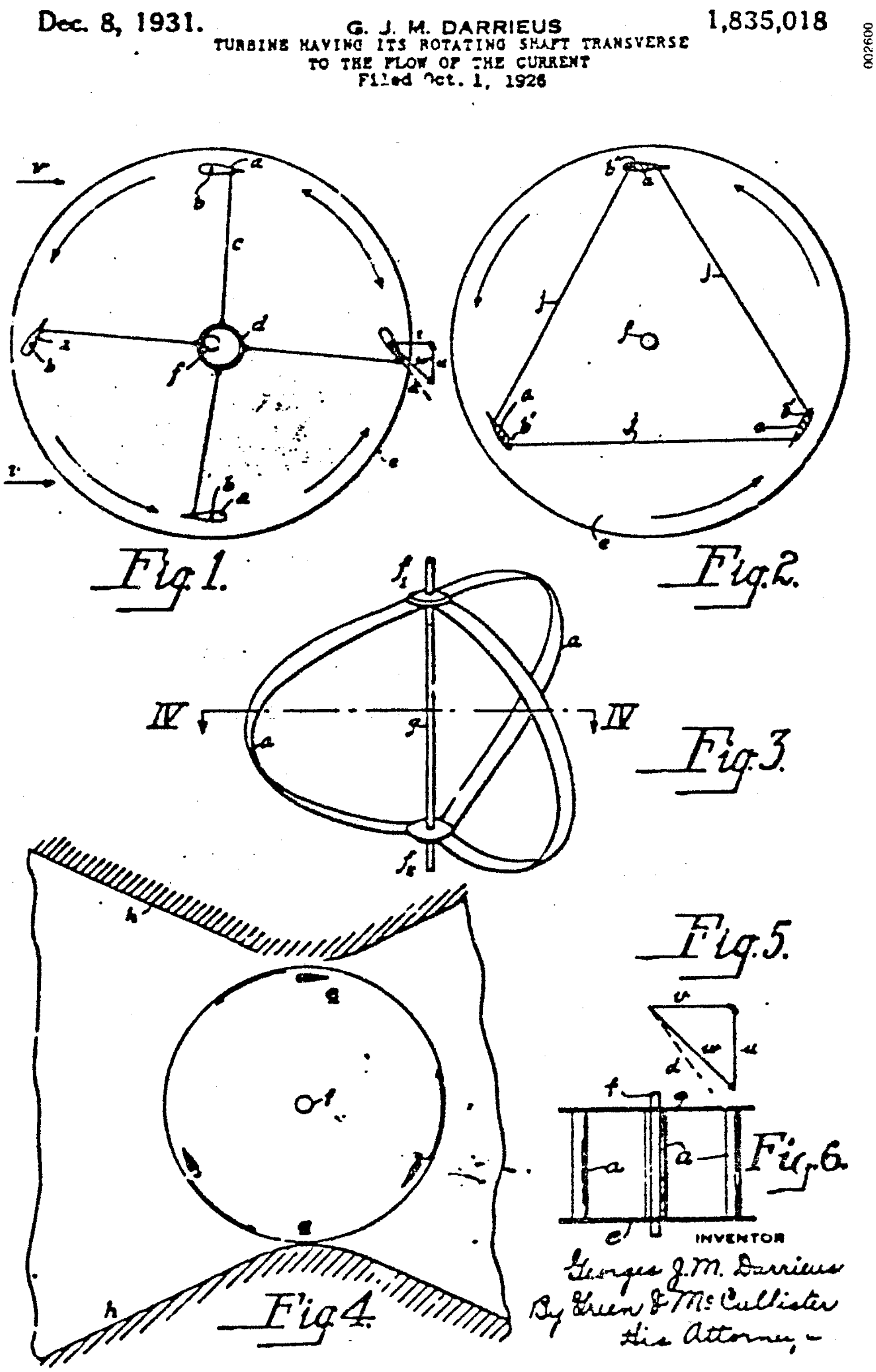


Figure 4-29. Original Patent Obtained by Darrieus

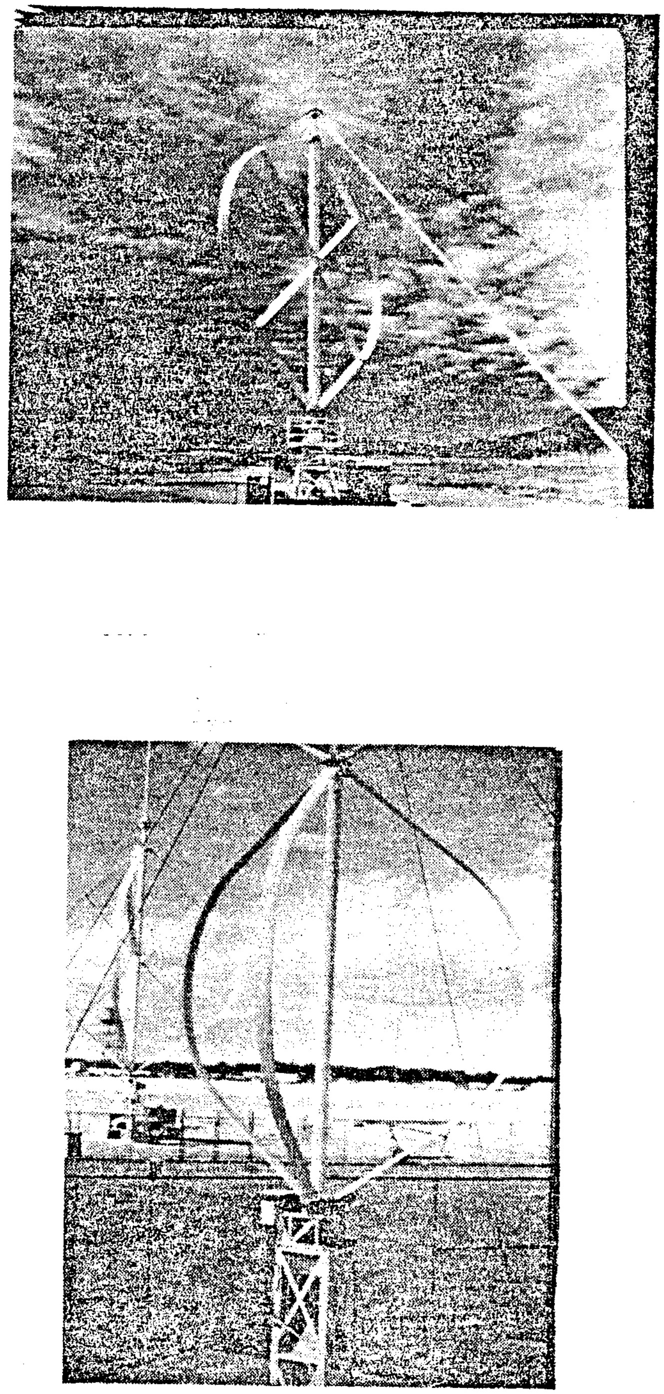


Figure 4-30. Typical Curved Blade VAWTs

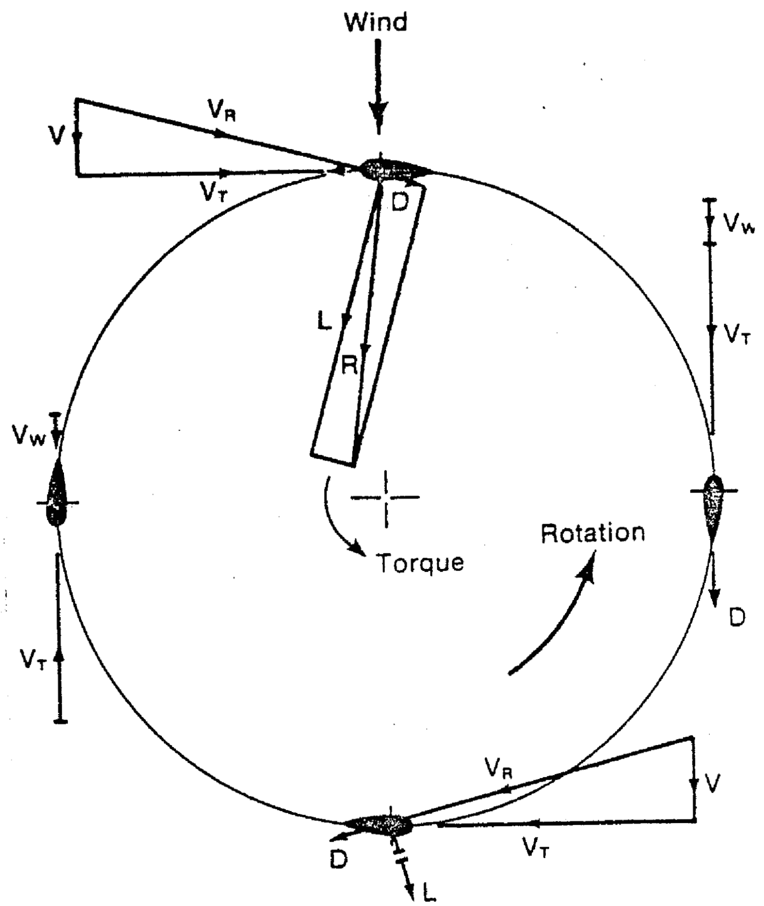


Figure 4-31. Operating Principles of a VAWT

Fixed-pitch machines are insensitive to wind direction but have a very low starting torque unless a starting device, such as the one illustrated in Figure 4-34, is used. Variable-pitch machines can develop higher starting torque and flatter power curves, but they are more complex and are sensitive to wind direction. Therefore, they require devices to orient the pitch-change mechanisms.

Since the aerodynamic loads on the blades are cyclic, the dynamic component of the overall aerodynamic loads and the torque on the rotor are functions of the number of blades. The cyclic nature of the loads is shown in Figure 4-35. With three blades, the dynamic component of the overall loads is small; however, the individual blades are affected by the full dynamic component. With one or two blades, the aerodynamic torque has a very large dynamic component. However, if a torsionally soft coupling is placed between the rotor and the conversion device, the dynamic component of the torque simply causes a small cyclic change in rotor speed and a small change in shaft torque. As illustrated in Figure 4-36, this means that the cyclic component of blade stress can also be small when one or two blades are used. The dynamic component of aerodynamic drag can also be reduced by using soft mounts on the rotor or by using centrifugal pendulums on the rotor shaft as dynamic absorbers, like those shown in Figure 4-36.

With three blades and fixed pitch, the rotor must be designed to withstand the maximum wind loads that will exist when the rotor is stopped in extreme wind

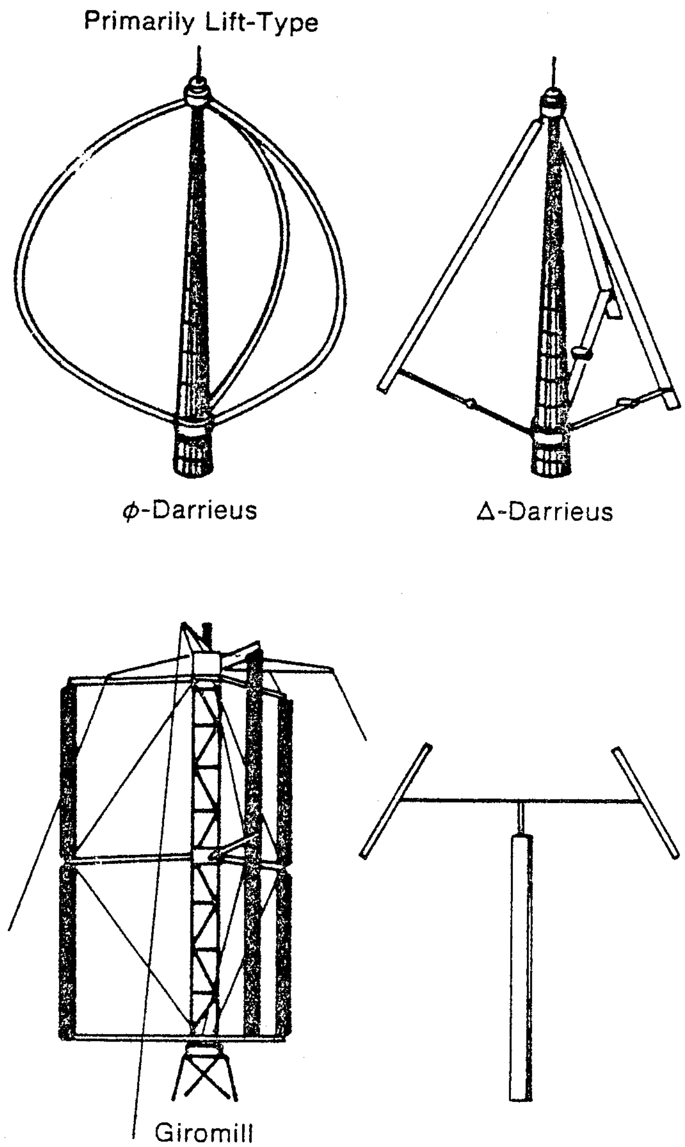


Figure 4-32. Various Types of VAWTs

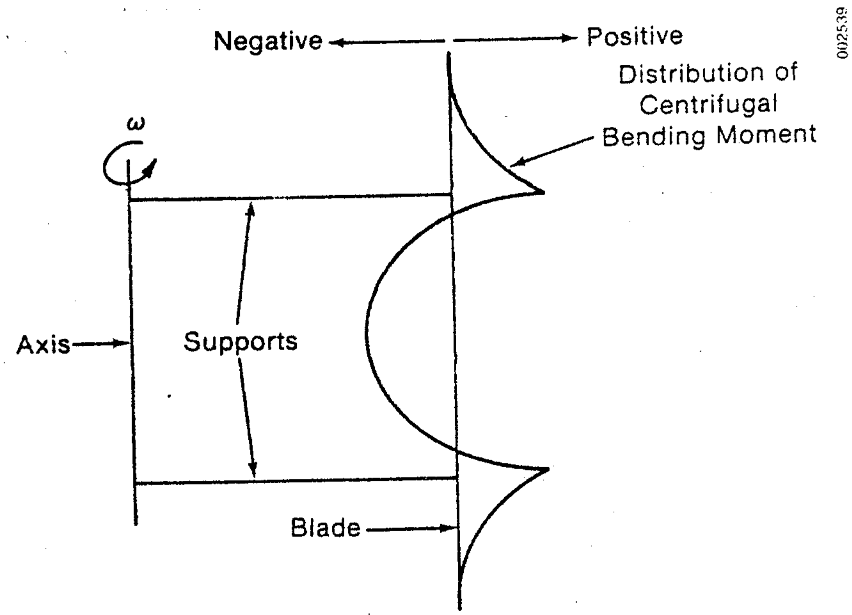


Figure 4-33. Distribution of Centrifugal Bending Moment on a Straight Blade VAWT

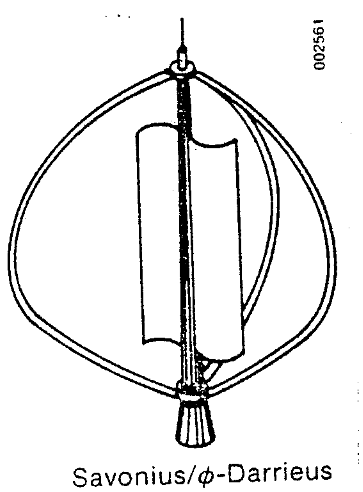


Figure 4-34. Savonius Rotor Used to Increase Starting Torque on a Fixed Pitch VAWT

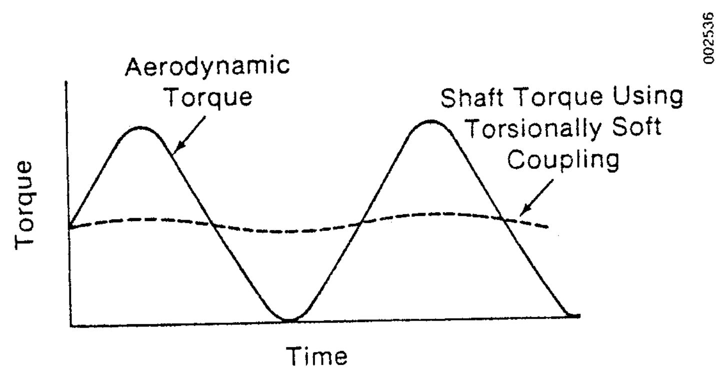
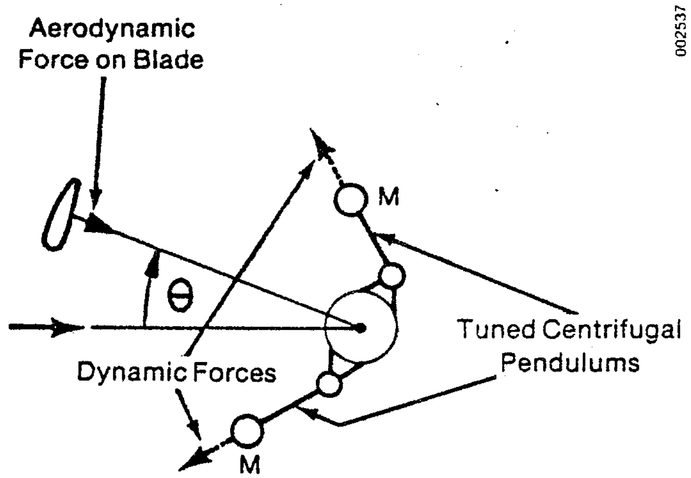
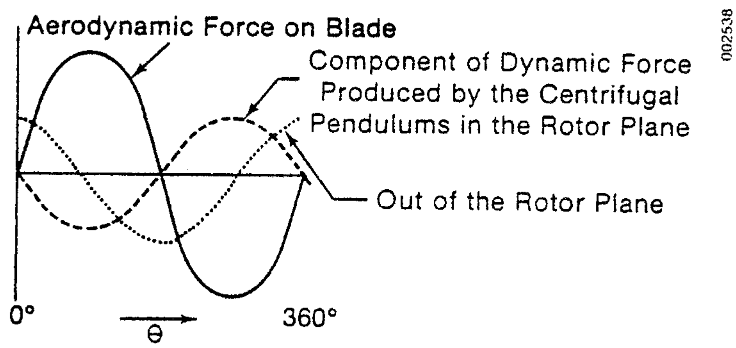


Figure 4-35. Cyclical Aerodynamic Torque and Shaft Torque that Exists when a Torsionally Soft Coupling Is Used





Relative to a fixed axis system, the sum of the Aerodynamic blade forces and the centrifugal pendulum forces can be an approximately uniform drag force.

Figure 4-36. Use of Centrifugal Pendulums to Reduce Dynamic Drag Loads Seen by Supporting Structure

conditions with one blade upwind. With the curved-blade machine, a critical design case occurs when the rotor is parked with one blade upwind, since it is then subjected to a buckling load and the allowable buckling stress is much less than the allowable tensile stress (shown in Figure 4-37).

With two blades, there can be a choice of automatically orienting the rotor into a low-drag configuration, like the design shown in Figure 4-38, or designing the blade to withstand the maximum buckling load.

The single curved-blade rotor can be oriented so that it is always under tensile stress and hence presents a simpler design problem than a multiple-blade rotor. However, a counterweight is needed to balance the single blade. The torque characteristics of the stopped single-bladed rotor are illustrated in Figure 4-39, showing both the stable and unstable equilibrium positions.

When two vertical-axis machines have the same overall solidity, the one with the smaller number of blades will have larger individual blade chords and therefore greater blade strength, as shown in Figure 4-40. Solidity for a VAWT is defined as $n\bar{c}/R_m$, where n is the number of blades, $\bar{c}$ is the blade chord, and R_m is the maximum rotor radius (see Figure 4-37).

The buckling strength of the curved blades can be increased by using struts (like those shown in Figure 4-41) that also increase the axial stiffness of the blades, reducing fatigue problems with a rotor that is parked in a turbulent wind.

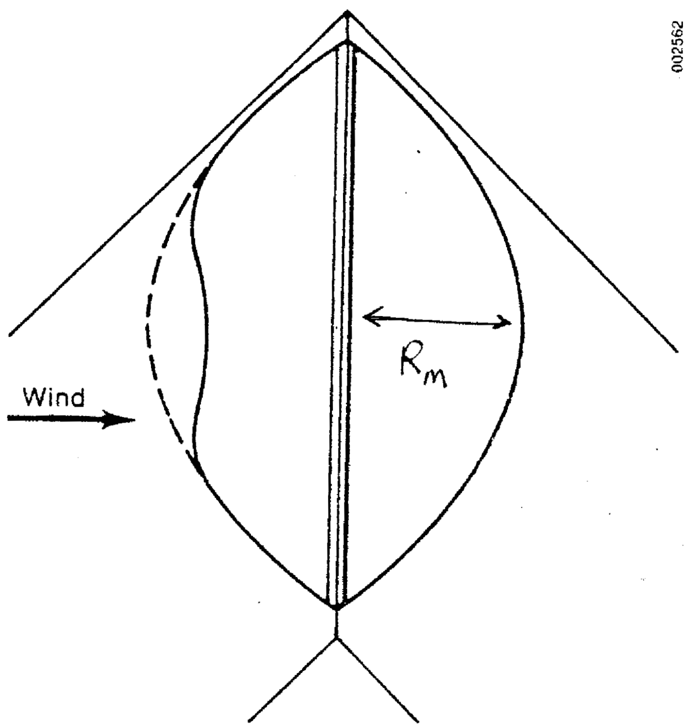


Figure 4-37. Buckling of the Upwind Blade of a Parked VAWT Rotor in an Extreme Wind

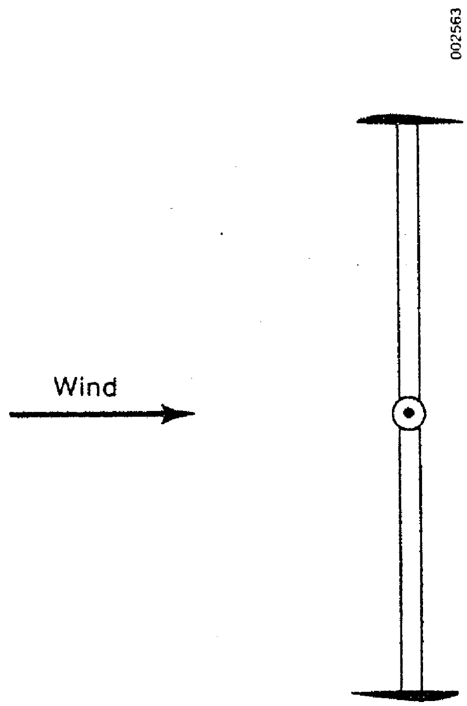


Figure 4-38. A Two-Blade VAWT Rotor Parked in a Low-Drag Orientation

The power control for a variable-pitch machine can be accomplished by varying the blade pitch. With fixed-pitch machines power control can be accomplished either by using a driven unit that is sufficiently large to stall the rotor or by using aerodynamic spoilers that reduce the power output of the rotor.

The rotor can either be operated at essentially constant speed or at variable speed. Variable-speed designs can operate at near-maximum efficiency over a range of wind speeds. A well designed constant-speed machine can produce energy at about 80% of the capacity of a variable-speed machine, and the decrease in complexity of the constant-speed machine can justify the decrease in energy production.

With multiple-blade rotors, the dynamic loads can excite a blade lead-lag resonance that may cause fatigue problems. These dynamic problems can be greatly reduced with a single-blade rotor.

The most desirable blade section characteristics have not been accurately determined, but they probably include a low drag coefficient, a limited maximum lift coefficient, a smooth stall, a thick section, and a shape that is easy to manufacture.

For a specific blade section drag coefficient, the maximum power coefficient is almost directly proportional to solidity. At very low but significant solidities, the effect of increased solidity can be minimal and can result in the same power coefficient at a lower tip-speed ratio. The variation of the power coefficient with solidity is graphed in Figure 4-42. When the limiting effects are reached, the main effect of increasing solidity will be to increase power transmission problems because of the low tip-speed ratio. For a given design condition, there will be a minimum solidity per blade that will

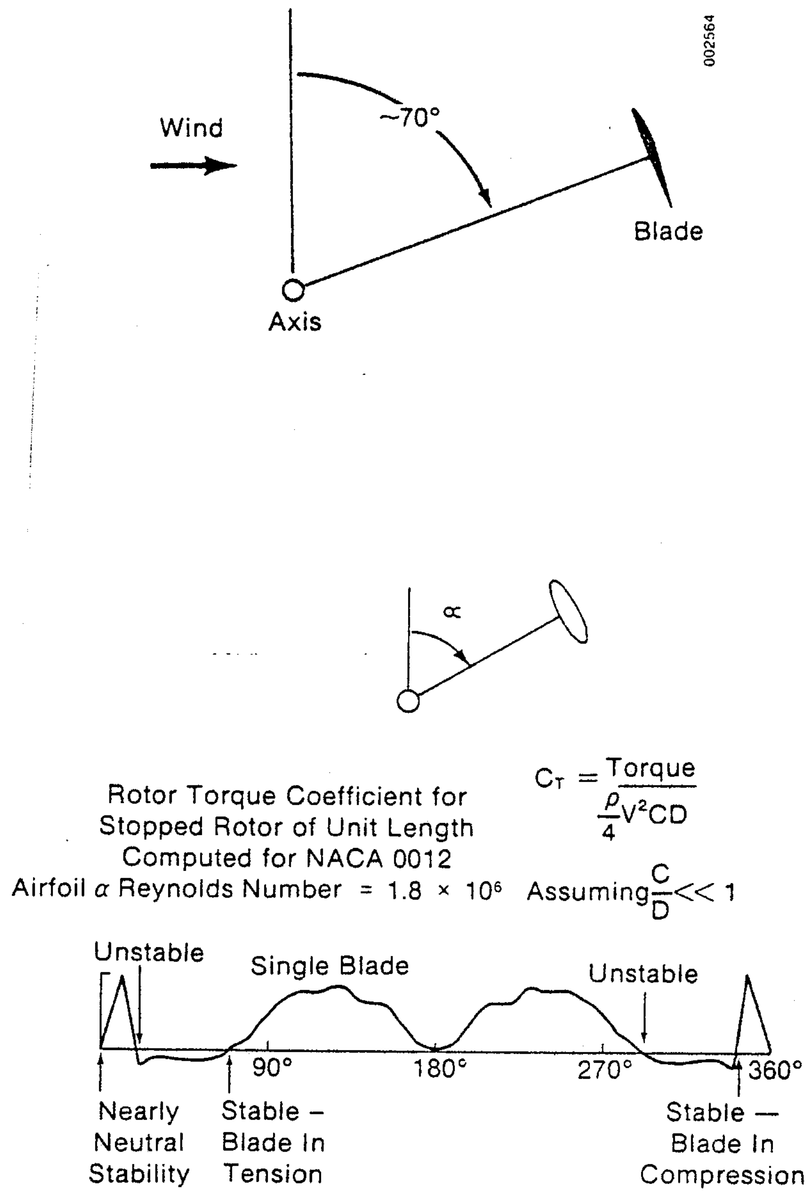


Figure 4-39. Torque Characteristics of a Stopped Single-Blade VAWT Rotor

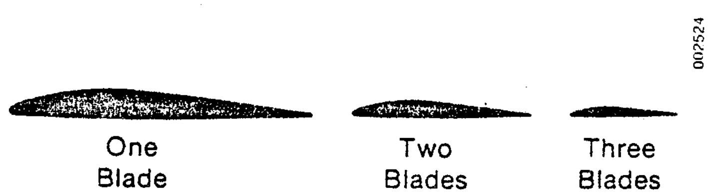


Figure 4-40. Relative Chord Sizes for One-, Two-, and Three-Blade Rotors Having the Same Solidity

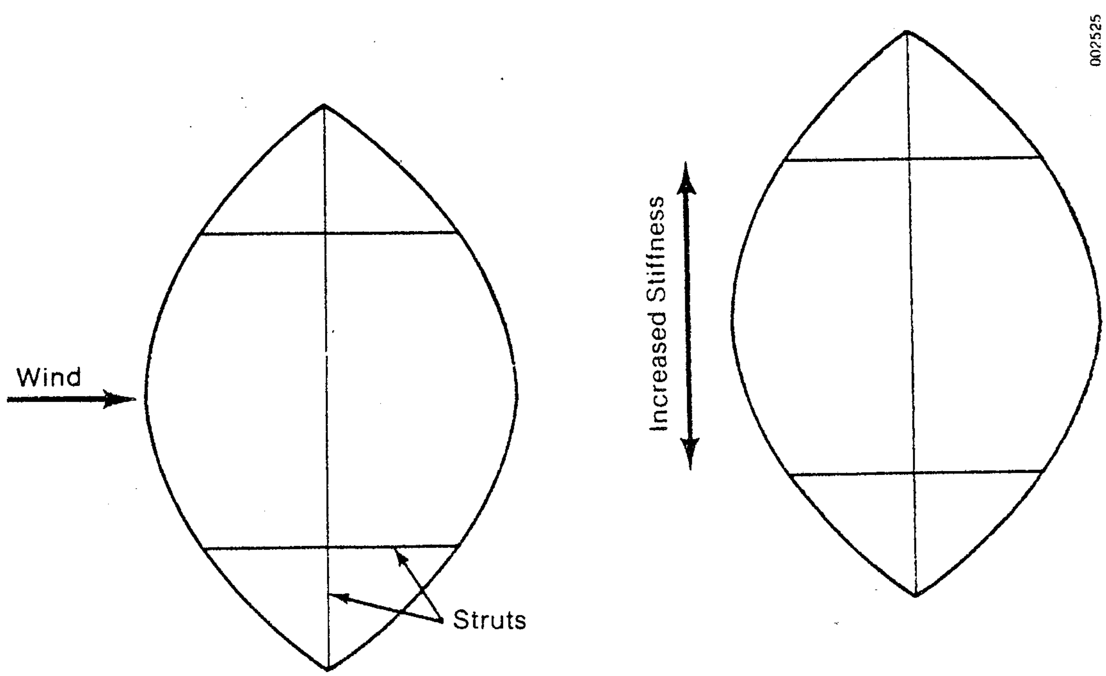


Figure 4-41. Use of Struts to Increase Resistance to Buckling and to Increase Blade Axial Stiffness

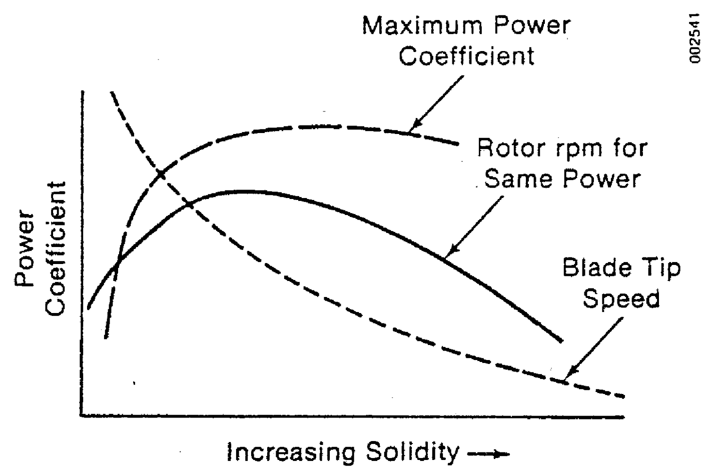


Figure 4-42. Effect of Solidity on Some of the Important Rotor Properties

be structurally allowable. This minimum solidity will be a function of the size of the rotor, the maximum wind speed, the expected ice loading, and similar factors.

A decrease in the zero-lift drag coefficient for the blade is always beneficial to performance since the drag represents a parasitic power loss. For a given rotor, a decrease in the drag coefficient means an increase in the power coefficient and also an increase in the maximum tip-speed ratio. The parasitic power loss is approximately proportional to the cube of the tip speed. When there are discontinuities in the rotor shape--at the strut junctions or the ends of straight blades, for example--there is some evidence that the discontinuities result in losses that reduce the power coefficient and that the losses are greater than would be expected intuitively.

An increased maximum lift coefficient results in an increased power coefficient at low tip-speed ratios. It does not necessarily increase the maximum power coefficient, but for a constant-speed rotor it causes the power output to continue to increase with wind speed, making it necessary to increase the size of the driven device or, alternatively, to decrease the rotor speed to obtain the same maximum power. The decreased speed causes increased power transmission problems. High blade section lift coefficients are rarely desirable. In fact, efforts are being made to tailor VAWT aerodynamic properties to limit the power output.

The rotor height-to-diameter (H/D) ratio is another parameter under the control of the designer. For curved-blade machines with an upper bearing supported by guy wires, a rotor H/D of 1.5 is reasonable. On the other hand, if the rotor is cantilevered from a bearing at the base of the rotor, an H/D of less than one might be more acceptable for structural reasons.

The gravitational loads on the blades of a VAWT are constant, unlike those imposed on HAWT blades, but the aerodynamic loads are cyclic, in contrast to the nearly constant loads affecting an HAWT. Since the VAWT rotates about only one axis, there are no gyroscopic moments to contend with; and since the fixed pitch rotor can accept winds from any direction, its response to changing wind direction should be essentially instantaneous.

SECTION 5.0

FLOW AUGMENTATION

One problem faced by the designer of a wind energy converter is the diffuse nature of the resource. Natural wind has a low power density per unit of area. With an average wind speed of 5 m/s and a value of $0.05 per kWh for the energy, an efficient wind energy converter would extract $15 worth of energy per square meter of swept area per year (as illustrated in Figure 5-1). Although it is true that at higher wind speeds this value would be considerably higher, it should also be noted that regions with high average wind speeds are not too common. In regions with lower wind speeds, it would seem desirable to concentrate the power in the wind to make it more economical to convert. This concentration of power is commonly called flow augmentation.

5.1 SUMMARY

In streamline flow, the maximum amount of energy that can be extracted from a given mass of wind is equal to its kinetic energy in the free stream. Hence, the power augmentation that can be achieved is directly proportional to the increase in mass flow through the device and therefore to the increase in the speed of the flow. In real fluid flow, the wake downstream of the wind energy converter can mix with the external flow and increase the change in total pressure that can be achieved.

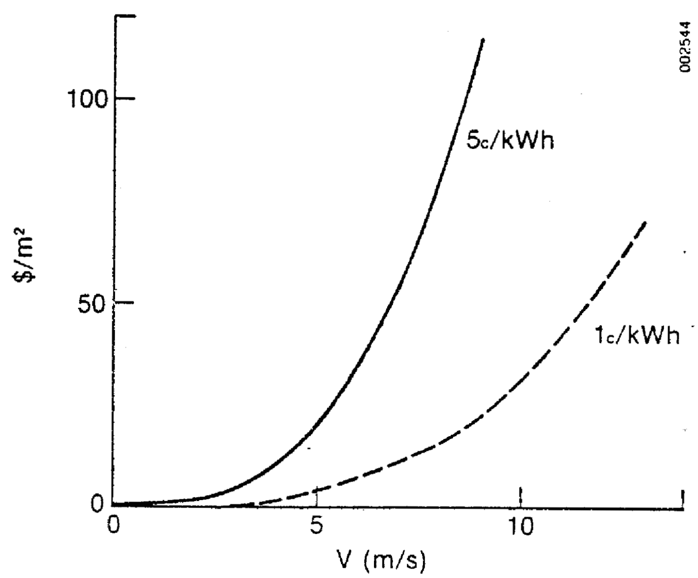


Figure 5-1. Annual Value of a WECS

Increasing the flow causes an increase in the dynamic pressure and a corresponding decrease in the static pressure (as shown in Figure 5-2). Since discontinuities in the static pressure are not physically possible, it is necessary to provide some physical boundary between the accelerated flow and the external flow or to create some flow condition that provides a stable static pressure gradient. Stable static pressure gradients can exist where there is a curvature in the flow, as there is in a vortex.

The elementary axial flow augmentor shown in Figure 5-3 consists of a mechanism to accelerate the flow, a power extraction device, and a diffuser to decelerate the flow and raise the static pressure to the free stream condition. The analysis given in Appendix D shows that the axial flow augmentor must carry a significant axial load, and this implies that it must have a significant axial extent. If pressure loading on the augmentor is similar to that on the actuator disk, the diameter of the diffuser exit must be similar to that of the unaugmented actuator disk that it replaces.

It is easy to exchange static pressure for dynamic pressure or to accelerate the flow, but it is quite difficult to reverse the process. A diffuser is considered to be any form of duct that increases in cross-sectional area in a downstream direction. In order for there to be a significant static pressure recovery for a diffuser, the flow must remain attached to the walls. When a flow enters a zone of adverse pressure--where the static pressure increases in a downstream direction--there is a tendency for the boundary layer to separate from the walls and for the diffuser to become ineffective due to the energy losses associated with this turbulent flow. One of the most important factors influencing the tendency for the flow to separate is the rate of change of static pressure or adverse pressure gradient. The tracing of an actual water

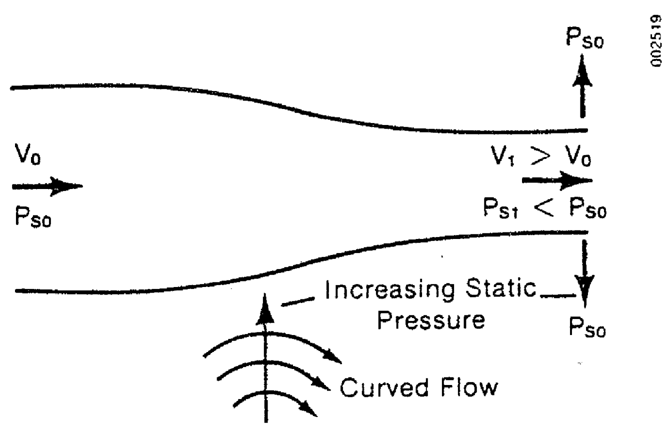


Figure 5-2. Reduction of Static Pressure in the Flow Associated with an Increase of Speed

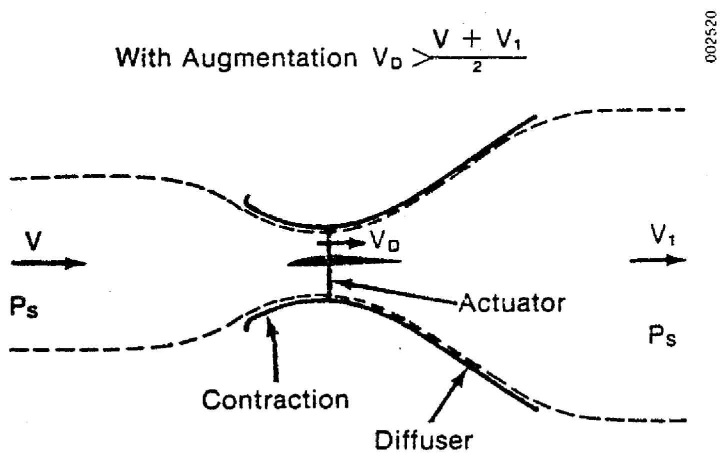


Figure 5-3. An Elementary Axial Flow Augmentor

tunnel experiment shown in Figure 5-4 illustrates such a flow separation. Diffusers can be made to operate by ensuring that the adverse pressure gradient is not severe. However, this approach results in a very long diffuser, and the additional materials costs are usually not economically acceptable on a wind machine.

The external walls of the diffuser are not the only surfaces in a diffuser that are exposed to an adverse pressure gradient in a diffuser. Usually there will be a nacelle or a tail cone associated with the wind turbine, and the flow can separate from these surfaces if the adverse pressure gradient is severe enough. This type of separation is shown diagrammatically in Figure 5-5, and an actual situation is shown in the tracing in Figure 5-6.

The diffuser walls can either be passive or active surfaces. Examples of each are shown in Figure 5-7. If a passive surface is used, the diffuser wall must be essentially continuous, while active surfaces can have a much smaller surface area.

The axial flow augmentor can produce a secondary benefit by reducing the tip losses that normally exist on an open wind turbine and hence improving the performance by a greater amount than that attributable to augmentation alone.

Placing two actuator disks in series (see Figure 5-8) in a duct is often considered a means for augmenting a WECS. In this concept, one disk is used to pump an increased amount of flow through the other disk. The analysis given in Appendix D shows that the sum of the change in total pressure across both disks cannot exceed the free stream dynamic pressure, and the mass flow rate depends only upon the properties of the duct and is unaffected by the pumping disk. Since the pumping disk will put power into the stream that must be

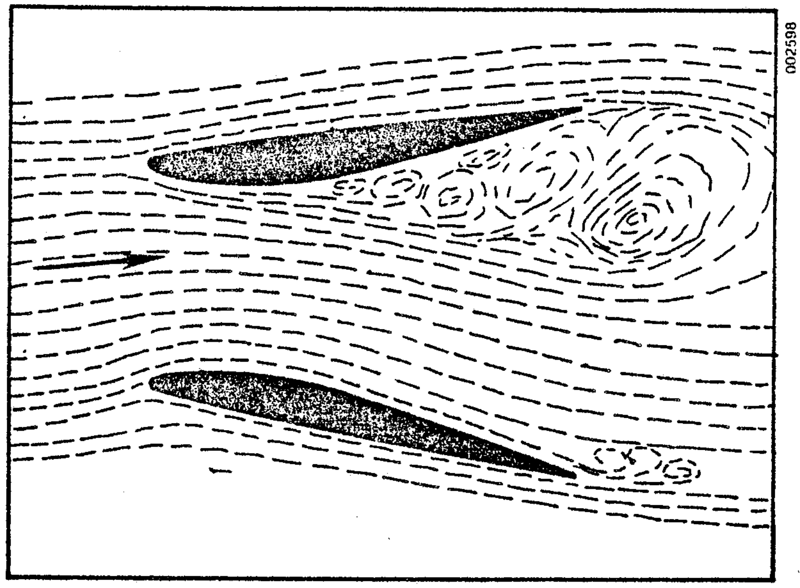


Figure 5-4. Flow Separation from the Walls of a Diffuser

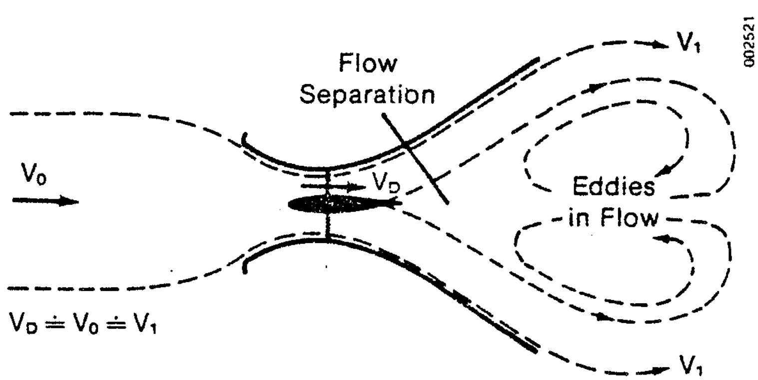


Figure 5-5. Flow Separation from a Nacelle

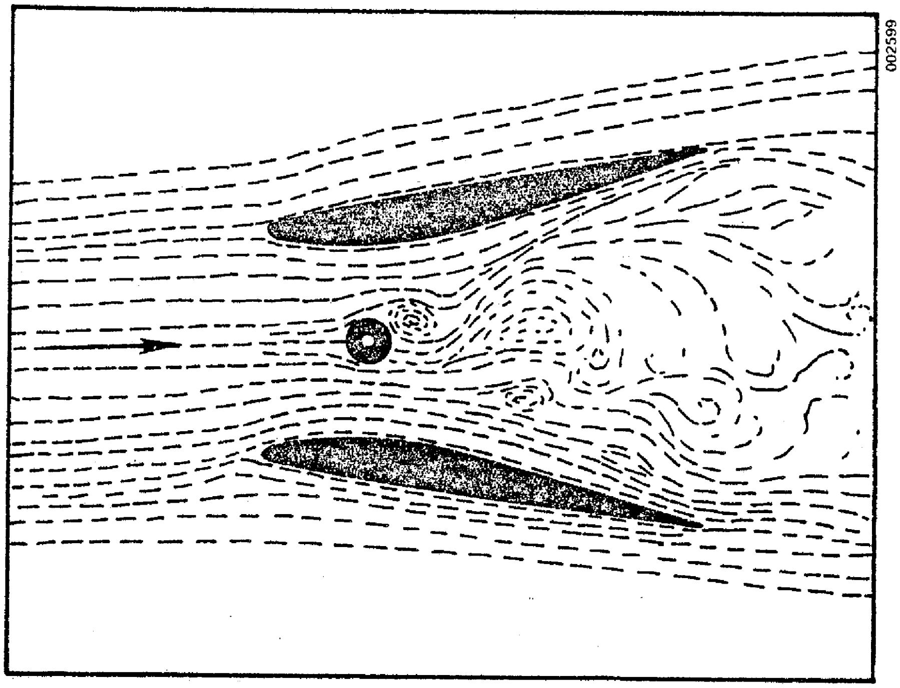


Figure 5-6. Water Tunnel Flow Visualization of the Flow Separation from a Simulated Nacelle in a Diffuser

supplied by the second disk, there is an increase in the overall power level, but not in the power output. The losses in the system are likely to be related to the overall power level, and the net power output of the system will be reduced by using the pumping disk.

Another type of axial flow augmentor has a wind turbine submerged in a vortex that has been created by some device. The idea behind this concept is that the turbine could extract a significant amount of power from the high velocity swirling flow in a vortex. The device shown in Figure 5-9 operates in this manner. The major problem with this type of augmentor is that the vortex is a very delicate phenomenon and can burst when disturbed. If the swirl velocity is decreased by the wind turbine, then the radial static pressure gradient behind the turbine will decrease, and hence the static pressure on the axis behind the turbine will increase. The increased static pressure behind the turbine will prevent the flow through turbine. So far, there is no known experimental evidence of an open vortex augmentor producing a power coefficient higher than those obtained by conventional, unaugmented wind turbines.

The low-pressure region in the core of a vortex can also be used to draw air through a wind turbine. One device designed to perform in this way is shown in Figure 5-9. In this design the vortex flow is not directly acted upon by the wind turbine, but the secondary flow that passes through the turbine is exhausted into the vortex core. The change in total pressure that can occur across the turbine disk is a function of the flow rate through the disk. At very low flow rates the vortex is undisturbed, and the pressure drop can approach the difference between the external flow and the pressure in the undisturbed core. However to extract power, the flow rate must be significant, and then the presence of the secondary flow modifies the core and can greatly increase the static pressure, significantly reducing its ability to

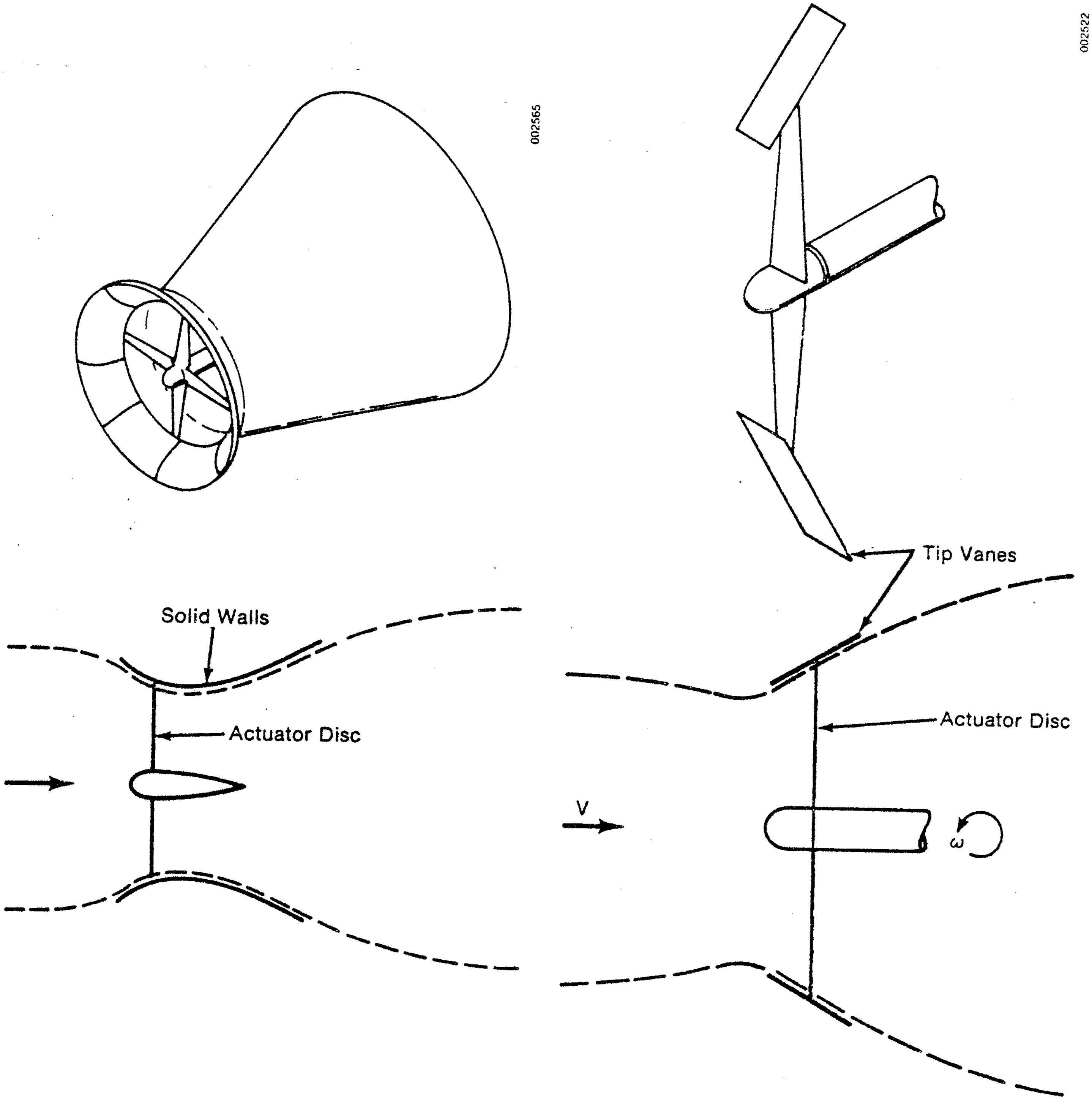
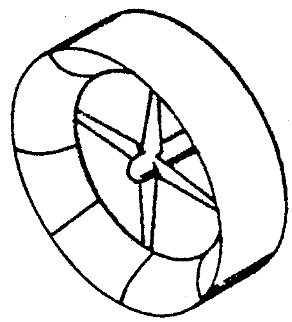


Figure 5-7. Examples of Diffusers Using Either Active or Passive Walls, or Combinations of the Walls



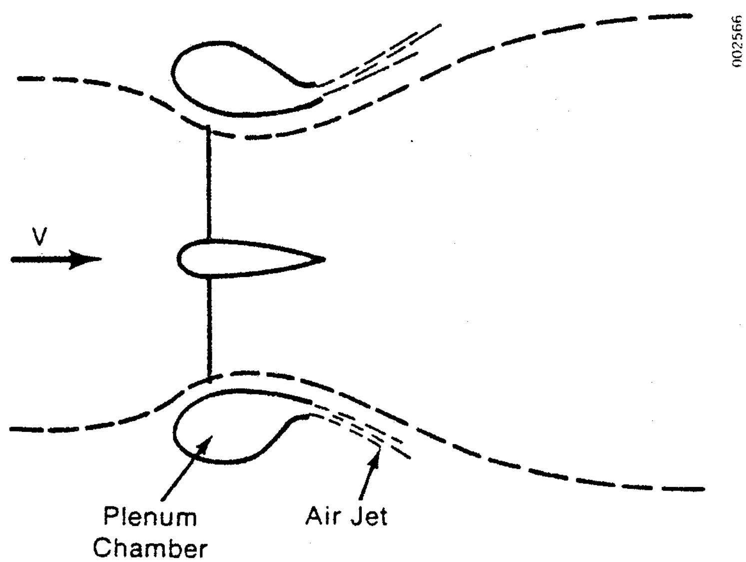


Figure 5-7. Examples of Diffusers Using Either Active or Passive Walls, or Combinations of the Walls (Concluded)

draw air through the turbine. The drop in total pressure that can exist in a vortex augmentor of this type can be greater than the free stream dynamic pressure, because the stable vortex can exist for a considerable distance downstream of the turbine and in this distance, energy can diffuse to the core to raise its total pressure above the free stream static pressure. A simplified analysis of a vortex augmentor is given in Appendix D, and this analysis suggests the important parameters.

With either of the vortex flow devices shown in Figures 5-9 and 5-10, it may be possible to obtain very high power coefficients when these coefficients are based on the disk area of a very small turbine. But when the coefficient is based upon the more realistic system frontal area, the power coefficient is likely to be quite small.

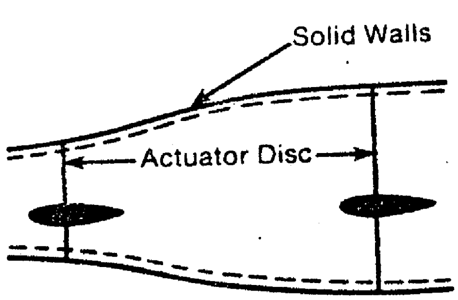
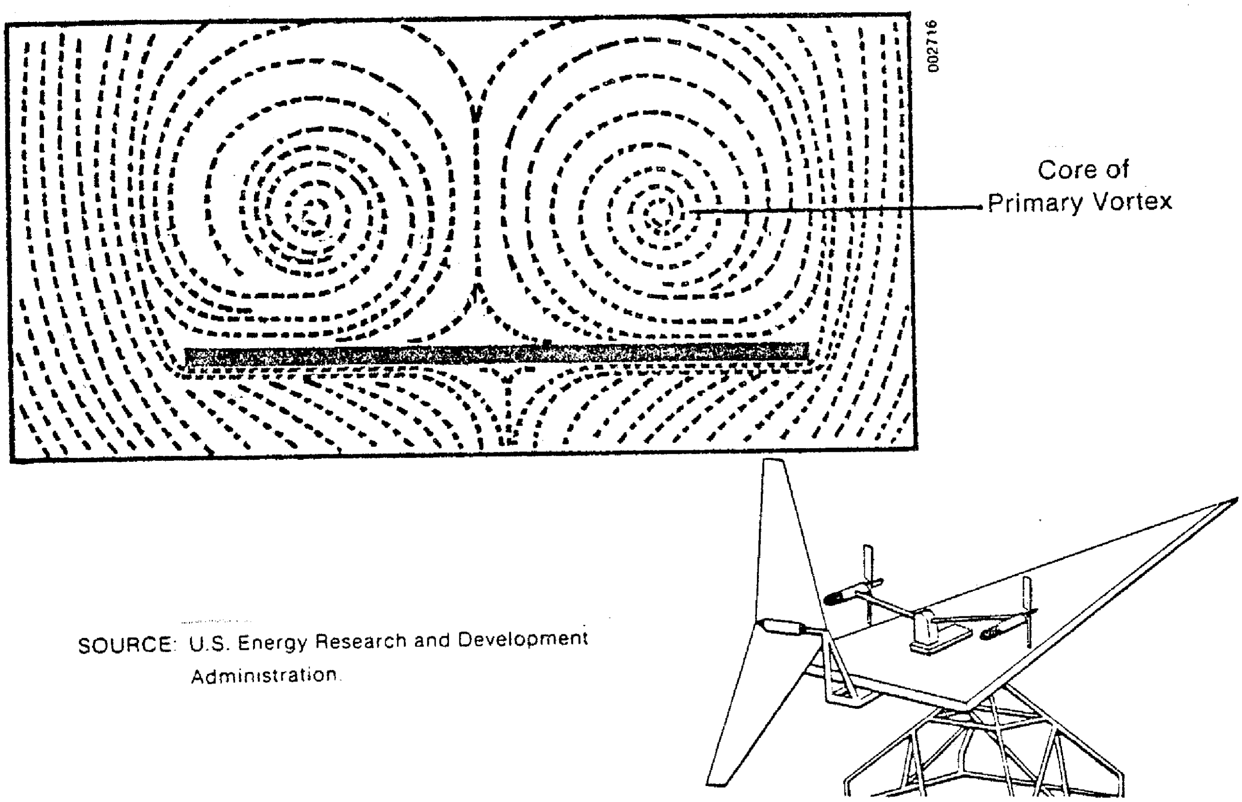


Figure 5-8. Augmentor Using Two Actuator Disks in Series



SOURCE: U.S. Energy Research and Development Administration

Figure 5-9. Turbines Placed in the Accelerated Flow of a Vortex Produced by a Delta Wing

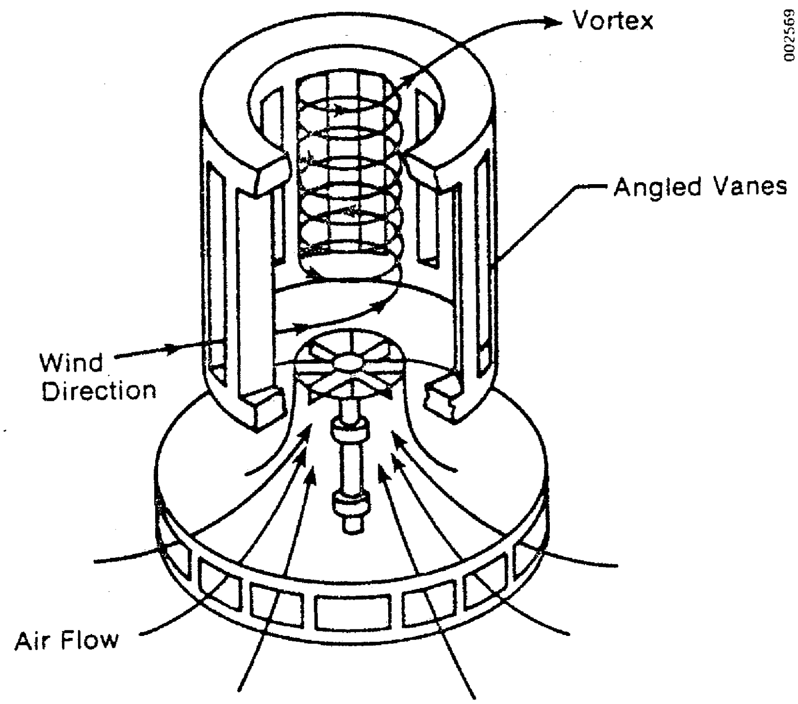


Figure 5-10. Use of a Vortex to Draw a Secondary Air Flow Through a Turbine

The theoretical analysis in Appendix D suggests that the amount of power that can be extracted is proportional to the square of the vortex strength, and hence the most productive research area might be directed toward increasing the vortex strength. One method of increasing the vortex strength is to use powered airfoils. For example the tower could be converted to a high lift airfoil as shown in Figure 5-11.

The moving actuator disk augmentor is another device for increasing the mass flow through the disk. An example of such a system is shown in Figure 5-12, and conceptually diagrammed in Figure 5-13. This type of device has been studied in the past because of its application to early aircraft, which often used electrical generation powered by wind. The analysis given in Appendix D shows that if the actuator disk is moved in still air, the power output of the ideal system will always be less than the power input. However, when the disk is moved into a wind there will be a power augmentation in the ideal system. In a real system, the inefficiencies in the various components will seriously limit the amount of augmentation that is available.

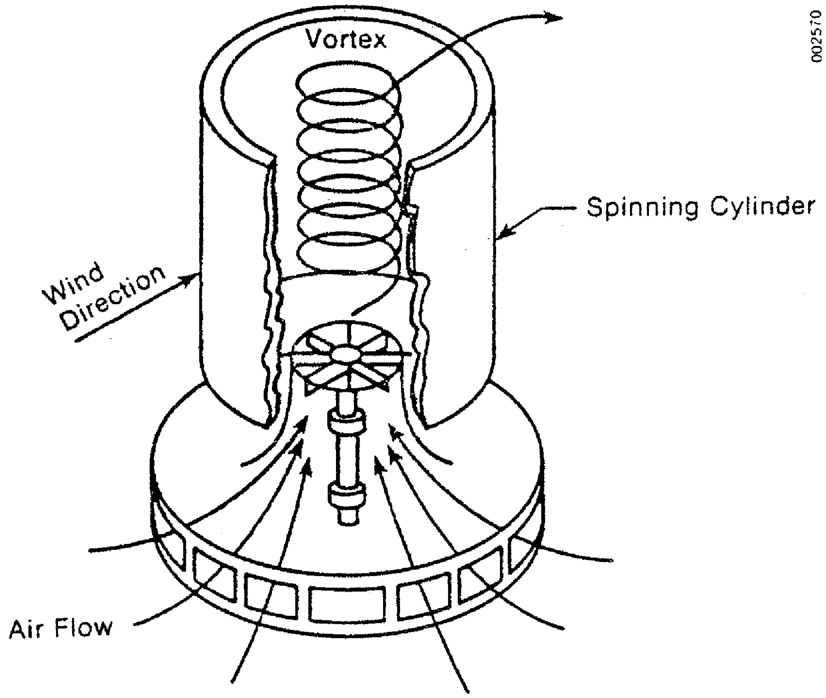


Figure 5-11. Use of a High Lift Airfoil to Increase the Strength of a Vortex that Is Used to Draw a Secondary Flow Through a Turbine

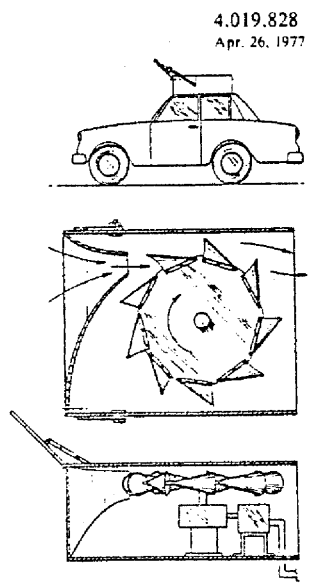
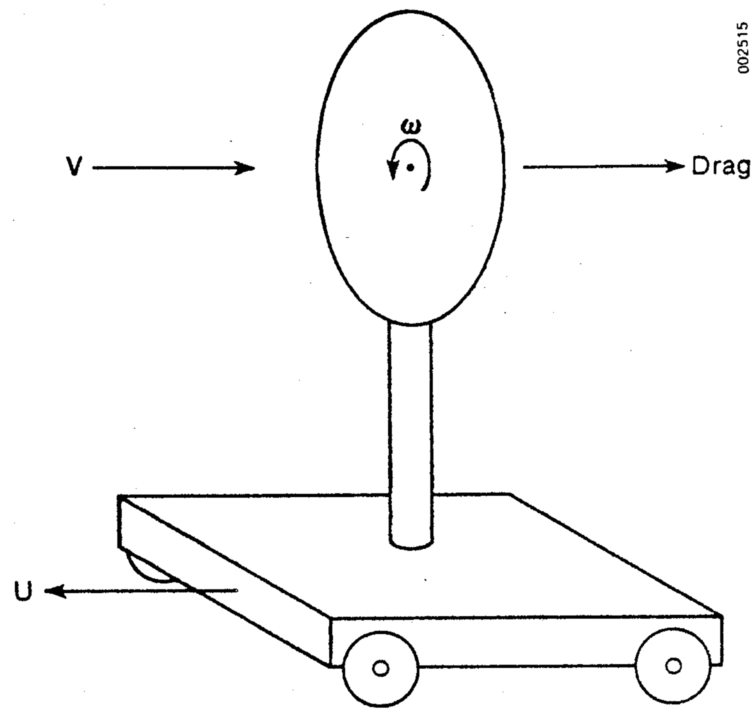
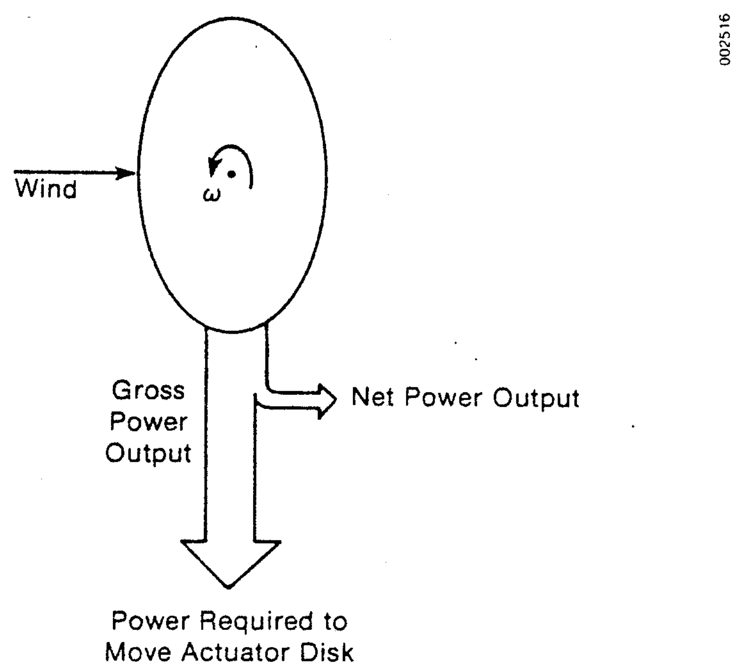


Figure 5-12. A Moving Actuator Disk Augmentor

Placing wind turbines in the accelerated flow that occurs around an obstruction is often proposed as a method for augmenting the power output, as in the examples shown in Figure 5-14. If the wind turbine is small compared with the size of the obstruction (e.g., a wind turbine is placed on the top of a rounded hill, as shown in Figure 2-10), augmentation can be significant because the relatively small wake of the WECS can mix with external flow to get sufficient energy to enter the region of increased static pressure that exists downwind of the obstruction (Figure 5-15). Under these circumstances, the power output can be proportional to the cube of the wind speed. If the obstruction is not large when compared with the WECS, there is little mixing of the wake with the external flow, and the presence of the WECS can cause flow separation over the obstruction if



a)



b)

Net Power Output = Gross Power — Power Required to Move Actuator Disk

Figure 5-13. A Conceptual Moving Actuator Disk Augmentor

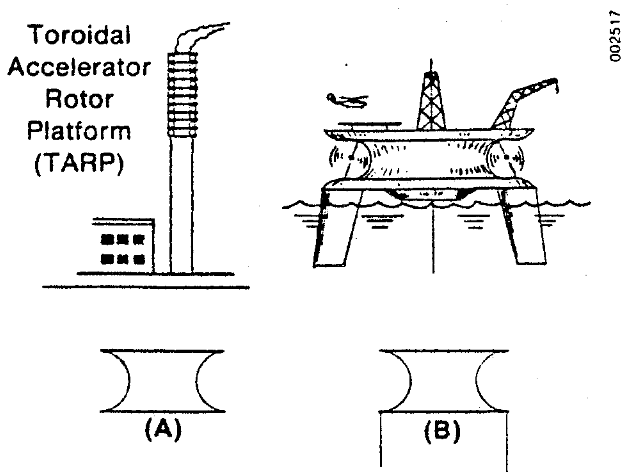


Figure 5-14. Wind Turbine Placed in the Accelerated Flow Caused by an Obstruction

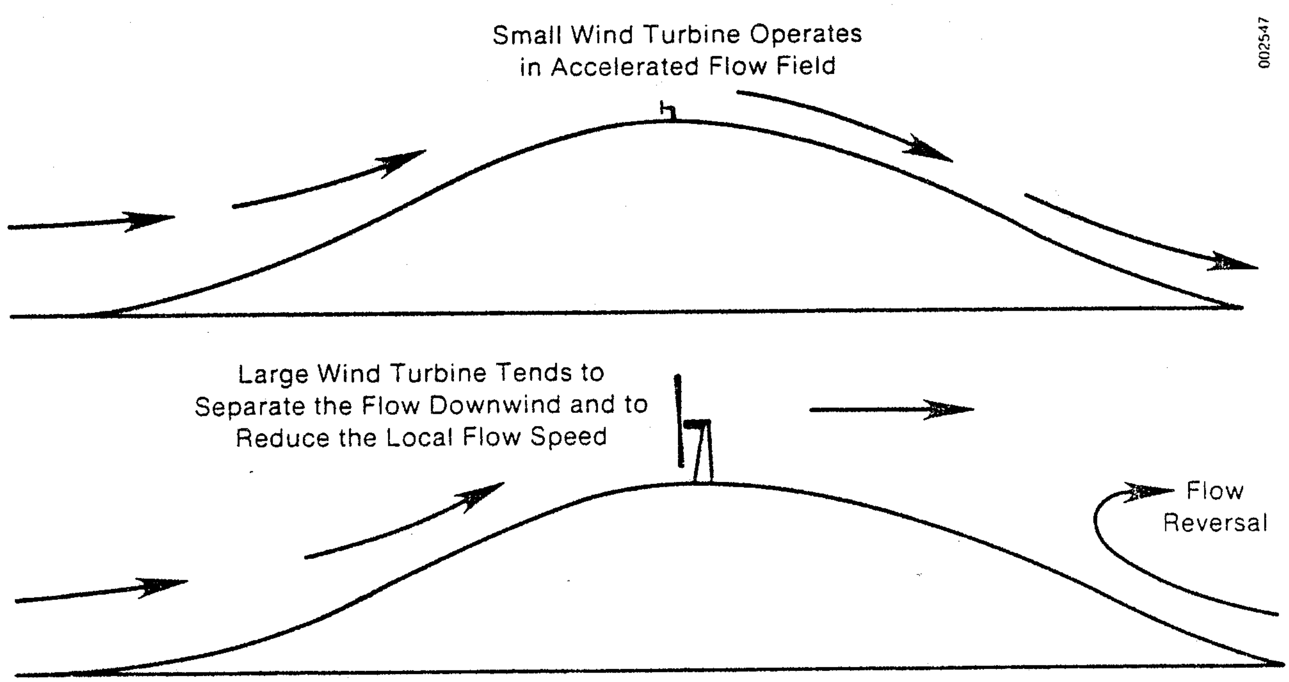


Figure 5-15. Effects of Installing a WECS on an Obstruction that Is About the Size of the WECS

there is a significant static pressure change through the WECS. With separation, the flow over the obstruction below the WECS can be quite different from the flow over the obstruction above, resulting in a reduced speed-up of the flow. When the obstruction is not large compared with the WECS, it will probably be impossible to support a total pressure decrease across the WECS that is as large as the free stream dynamic pressure. Under these circumstances, the increase in power output is likely to be more nearly directly proportional to the speed than to its cube.

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SECTION 6.0

WECS OPTIMIZATION

The process of optimizing a wind energy conversion system is very complex. It involves selecting the combination of parameters that will give the greatest benefit-to-cost ratio. Since varying almost any parameter will have both negative and positive effects on the system, optimization is a process of tradeoffs. Apart from the obvious requirement that the WECS perform reasonably well for long periods, it must also be capable of withstanding storm loads, must not have a significant environmental impact, and must be safe.

Theoretically it is easy to write the expression for the optimum configuration of a WECS and to show that a given system will be optimized when the ratio between incremental benefits and incremental costs is the same, regardless of which parameter is varied. This ratio has the same value as the overall benefit-to-cost ratio of the system. In practice, the situation may be so complex that optimization techniques can be used only as guides to ensure that any particular parameter is not overemphasized.

The Darrieus type curved-blade high-speed VAWT illustrates the problem of optimization. Even the choice of this basic configuration presupposes some selective process that we must ignore to make a comparison between the optimized configuration and other types of machines. The types of basic choices include the type of rotor support (cantilever, rigid external frame, guy wire, fixed base, rotating base support); ratio of rotor height to diameter; number of blades; airfoil section; solidity; construction materials; height above ground; installed power rating; and overall size.

The desirable rotor H/D ratio is influenced by the type of rotor support. For example, an H/D of ~ 1.5 is useful for guy-supported structures while H/D < 1 is more appropriate for a cantilevered structure. Among other factors, the increased H/D usually increases rotor rpm for the same swept area and power, hence it reduces power transmission problems. At the same time it increases blade root stresses. The increased height of the central column in the rotor and the increased rpm requires greater stiffness in this column to prevent dynamic problems. The increased height also decreases the resistance of the blades to buckling when the rotor is stopped with a blade upwind in a severe storm. One other advantage to a greater H/D ratio is that with the same base tower, the increased rotor height brings the device into a slightly higher wind regime resulting in slightly increased energy production.

Choosing the best number of blades is a controversial issue. It seems unnecessary to use more than three blades but there are arguments for using one, two, or three blades. Since the aerodynamic loads on the blades are approximately sinusoidal, using three blades makes the aerodynamic torque and drag approximately constant. A price must be paid for the approximately constant aerodynamic loads, including increased blade root dynamic stresses and a greater possibility of blade lead-lag resonance. In addition, a machine of the same total solidity will have a smaller blade chord and hence a weaker blade, and it will be necessary to design the blade to withstand a buckling load when it is upwind in high winds. With a three-blade machine operating at higher frequencies, there is also a reduced amplitude in the cycling force that is applied to the support structure and drive train, compared with one- and two-blade rotors.

With the two-blade rotor, the aerodynamic torque moments and drag forces are approximately sinusoidal. The effects of the dynamic components of both torque and drag can be essentially eliminated by using fairly simple low-frequency dynamic insulators and dynamic absorbers; therefore, they do not constitute a real problem. The use of a soft drive train can greatly reduce the dynamic stresses on the blade roots caused by cyclic aerodynamic torque. There is still the possibility of blade lead-lag resonance, but damping can be introduced outside the rotor. With the same total solidity, the blades are stronger than for the three-blade rotor. When using two blades, it is possible to align the rotor across the wind during extreme storms, in order to reduce the buckling load.

The single-blade rotor is the oddest and yet probably the most interesting configuration. As with the two-blade rotor, the aerodynamic torque and drag are sinusoidal but the effects can be reduced in the same way. There is an unbalanced centrifugal force that must be either counterbalanced or supported. The possibility of blade lead-lag resonance can be eliminated. The single blade is the strongest for the same total solidity, and it can be arranged so that it is not subjected to severe buckling loads when parked. With the single blade it is possible to seriously consider rotors with low total solidity.

The choice of airfoil section depends upon performance, structural requirements, manufacturing techniques, and cost. A low section drag coefficient is always beneficial to aerodynamic performance if it can be obtained at a reasonable cost; very high lift coefficients are rarely desirable. The low drag coefficient reduces the fixed losses and allows the machine to operate at a higher tip-speed ratio and lower solidity, while the higher maximum lift coefficient results in the rotor extracting approximately the same power at a reduced tip-speed ratio and higher torque, causing increased power transmission problems. The airfoil section must have sufficient depth to meet structural requirements and it must be easy to manufacture.

Increasing the solidity usually results in an increased power coefficient at a reduced tip-speed ratio and lower rpm. The increased solidity per blade gives greater strength. The optimum solidity would probably be between 0.075 and 0.15.

When choosing construction materials, the designer has the widest range of variables with no simple way of deciding which materials are the best. One interesting combination uses aluminum for the vertical members and steel guy wires with a guyed rotor. If the guy wires have a slope of 45°, then the tension will remain approximately constant regardless of temperature.

The height above the ground must also be chosen by the WECS designer. As the elevation is increased, the wind speed increases and so does the average power output. The economic height is reached when the incremental increase in benefit obtained from an incremental increase in investment to raise the height of the WECS is the same as that obtained by varying any other parameter.

The installed power is still another variable. As shown in Figure 6-1, the average power tends to increase with installed power up to some limit. Like any other parameter, the installed power is at an optimum when the incremental gain in benefit for incremental rise in cost is the same as for the other parameters.

In summary, WECS optimization is a complex process requiring analysis of the tradeoffs between many interrelated performance, structural, and cost parameters. The maximum benefit-to-cost ratio is generally achieved by minimizing the cost of energy (COE). Life cycle costing, which incorporates capital, installation, operation and maintenance (O&M), and component replacement costs, should be used in the analysis. The replacement costs will be dependent on the design lifetime of each component in the system.

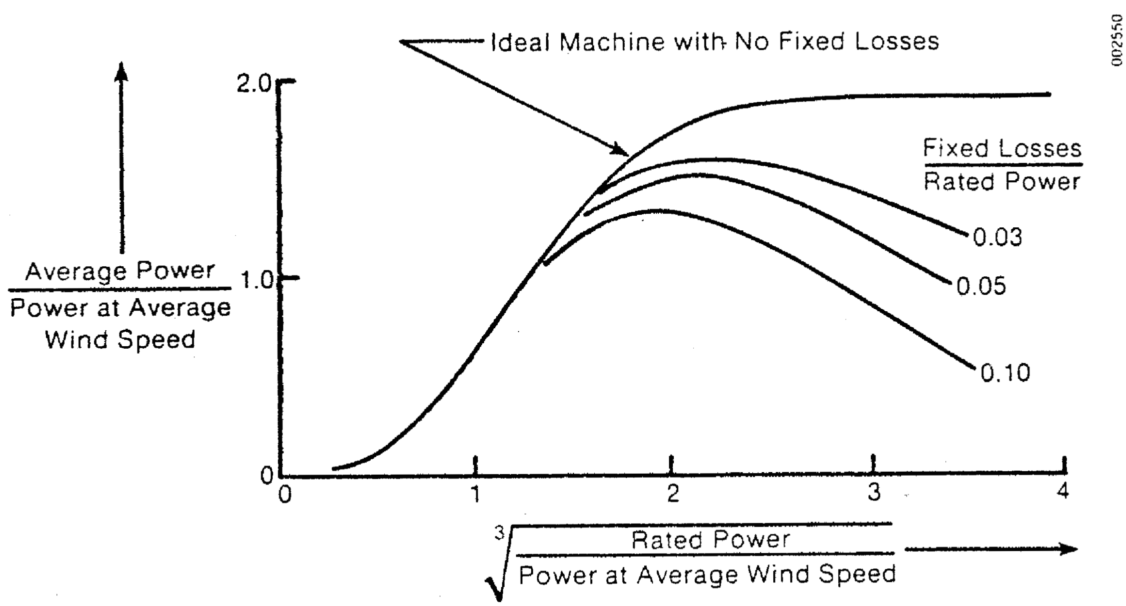


Figure 6-1. Typical Relationship Between Average Power and Rated Power for a WECS Having Some Fixed Losses

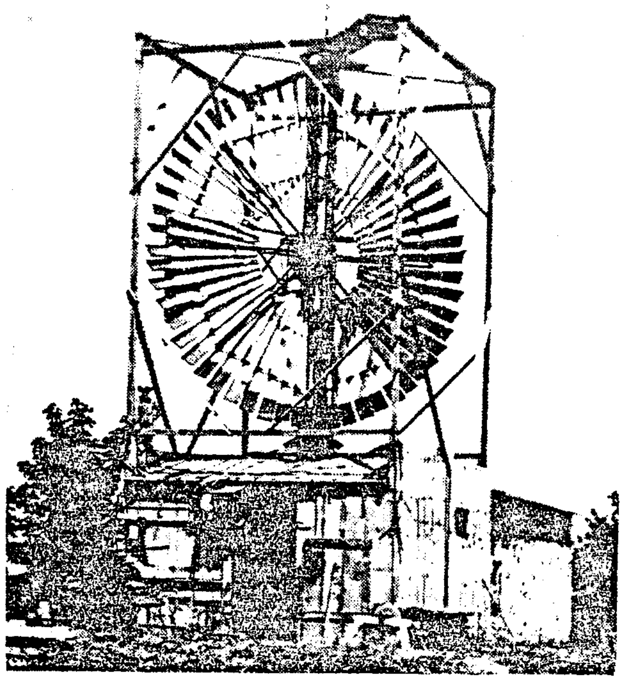


Figure 6-2. Example of an Old WECS Model

SECTION 7.0

TYPES OF SYSTEMS

Advances and innovations in WECS models may be difficult to compare to conventional systems. If new systems are classified accurately as advanced or innovative, they will necessarily be quite different from conventional systems. Advances and innovations generally occur in transmission systems, generator systems, support structures and yaw mechanisms, and wind energy extraction mechanisms. The majority of the earlier innovations have been concentrated in the last category, with major emphasis on the configuration of those mechanisms. This concentration has often obscured innovations in the other areas (McConnell 1980; South and Jacobs 1980).

Often an advanced or innovative concept is so different from conventional systems that it is not considered a modification of a conventional system. The Enfield Andreau machine, shown in Figure 7-1, is an example of a system that may have several classifications. From one viewpoint, this machine is a horizontal-axis rotor system used as an augmentor for a small, high-efficiency turbine in the hollow tower. However, it may be more accurately described as a conventional HAWT with an unconventional power transmission. Instead of having a mechanical drive from the rotor shaft to the generator, it has a pneumatic drive. The centrifugal force in the rotating blades is used to pump air out of the blades and draw air through the hollow tower past a relatively small diameter turbine that drives the generator. This technically interesting machine was, however, not commercially successful due to low efficiency and high costs.

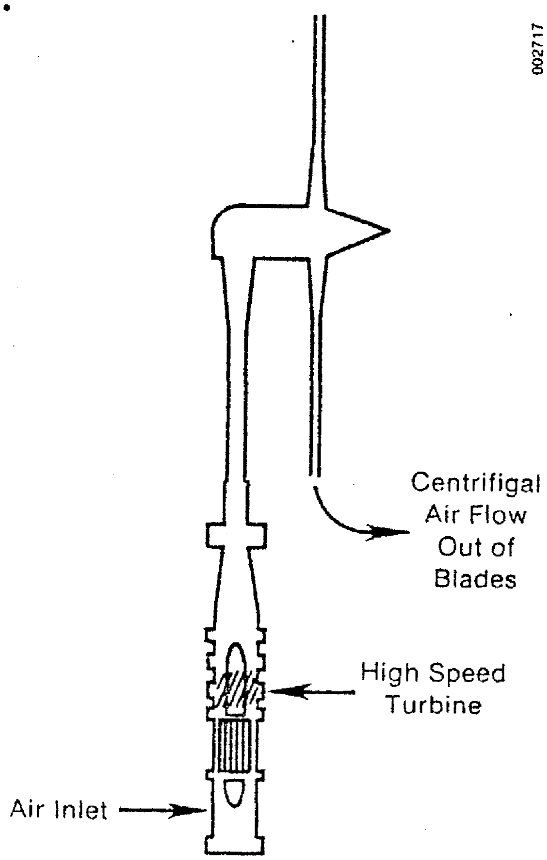


Figure 7-1. The Enfield Andreau Machine

Confusion often arises when designers try to describe advanced systems in terms of well-known conventional systems. Even grouping by advances in transmission, generator, support, and yaw adjustment systems may be difficult to apply to a particular concept. However, the exercise is valuable to an expert who is attempting to understand and evaluate an advanced concept; it provides an important perspective and frequently illuminates aspects of an advanced or innovative concept that would not otherwise be apparent. Therefore, the following discussion treats the majority of the advanced and innovative wind energy concepts from a perspective of the classifications mentioned.

7.1 TRANSMISSION SYSTEMS

Changes in a conventional WECS transmission system are usually undertaken to improve the cost of the entire system. Available transmissions and drive train assemblies may be too massive, may be situated in an inefficient location, or may not be designed to perform efficiently in a specific WECS (Thornblad 1979; Whitford et al. 1979). Designers trying to improve these features of conventional WECS may address the engineering possibilities by proposing new transmission and drive train assemblies that alter both the transmission location (reducing structural support costs) and the transmission itself. A designer may even completely eliminate the physical transmission, as with the Enfield Andreau machine. Several fluid drive transmissions have also been suggested. Many of these may be promising while others will suffer from the same cost and efficiency problems encountered by the Enfield Andreau machine.

7.2 GENERATOR SYSTEMS

Another area of possible innovation is the generator system (Crosno 1977; Hinrichsen 1979; Menzies and Mathar 1980). This area has a long history of investigation independent of its WECS applications; but several concepts have also been proposed that could improve or eliminate the generator and/or transmission systems in a WECS (Proceedings 1979; Proceedings 1980). One such concept is the loop generator.

The loop generator is a conducting loop rotating in a magnetic field so that it will cut the lines of magnetic force. This induces a current to flow in the loop. A Darrieus-type VAWT with two curved blades can be used as a conducting loop rotating in the earth's magnetic field. This field is far too weak to produce a significant amount of power. However, if the idea is carried one step further and a much stronger magnetic field is generated by a large coil surrounding the rotor, the loop generator may be possible. A practical configuration might be a two-bladed rotor with an imbedded superconductor that circulates an electrical current to produce a magnetic field; this field then rotates within a set of three fixed coils that are used to generate power. These fixed coils would also need to use superconductors to be effective. The low-frequency, three-phase power could be converted to conventional 60 Hz for connection to the commerical grid. The use of superconductors requires a refrigeration plant and hence would probably require a large installation--a condition that may be prohibitive.

Other generator systems have been suggested that eliminate the transmission by increasing the number of the generator poles and the generator diameter, as in the system illustrated in Figure 7-2. The modification reduces the need to convert WECS shaft rpm from a low rate to a higher one in order to run a conventional generator efficiently. Still another group of innovations uses the drag on an aerosol in the atmosphere to extract power from the wind and eliminates the need for both transmissions and conventional generators. (The atmosphere may either be natural or artificial.) Two such concepts, shown in Figures 7-3 and 7-4, respectively, are the Charged Aerosol Wind Driven Generator by Marks Polarized Corporation (Proceedings 1979; Proceeding 1980) and the Electrofluid Dynamic Wind Driven Generator by the University of Dayton (Minardi et al. 1980). These systems charge different types of aerosols and let the wind drag these aerosols against an induced electrical potential, up a potential hill, where they are collected. They are basically drag devices that use aerosols as the active element traveling in a linear path that is oriented in the direction of the wind. These systems have no moving parts but they would probably require a large-scale pumping system for the aerosols, and their construction might require numerous materials.

7.3 SUPPORT SYSTEMS

Concepts for advanced or innovative support structures may either be aimed at increasing performance or reducing costs. Some of the concepts involve the trade-off of increased material requirements (higher tower structures) for an increase in available power (higher wind velocities at greater heights). Tethered systems are examples of designs based on this general approach (Furuya and Mackawa 1981; Baily et al. 1982).

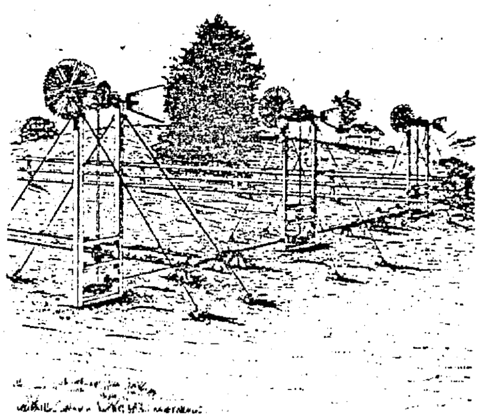


Figure 7-2. A Direct-Drive Generator

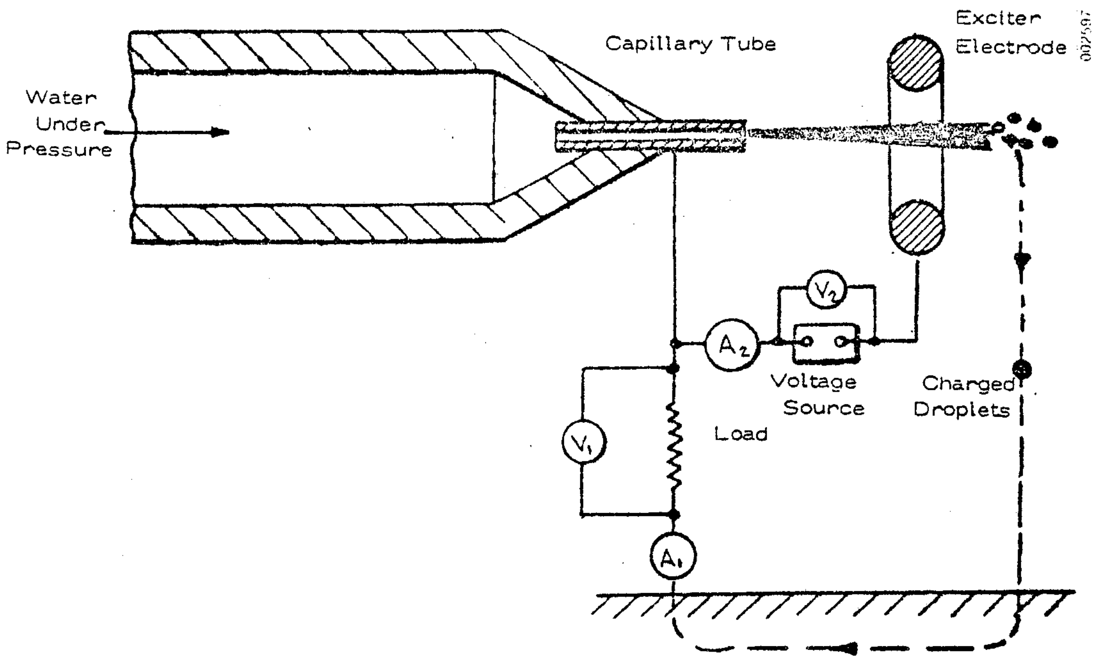


Figure 7-3. The Charged Aerosol Wind-Driven Generator

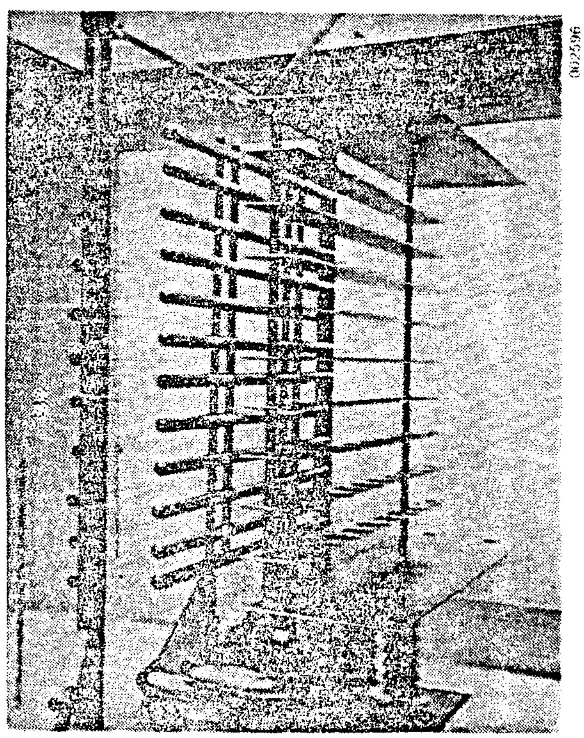


Figure 7-4. Electrofluid Dynamic Wind-Driven Generator

The tether is an interesting method for raising the active part of a wind energy converter to an altitude where the power density in the wind is much greater than at surface levels. This power density difference may come from either a geographic augmentation, a wind shear phenomenon, or from the jet stream. The tethered system must include a lifting device, a power conversion device, a means of transmitting the power to the ground, and a tether to overcome the system drag load that is necessary for the power conversion. The lifting device can be a balloon, a fixed wing, a lifting rotor that can combine the functions of both lift and power generation, or any combination of these. Balloons are stable and very simple, and they provide the required lifting forces independent of the wind, but they are costly to fill with gas and are quite vulnerable. Fixed wings provide lift and stability (and in some cases augmentation), but they require a lot of materials. The lifting rotor is advantageous because it can use a single element for both power extraction and lifting force. However, it also requires a more complicated control system. Some example of tethered systems are shown in Figure 7-5. In order for a tethered concept to be viable, increased power production must overcome the increased cost of the tethering, the power transmission devices, and the support structures.

At the other extreme of design innovations in support structures, tracked systems are often suggested because they would permit a large increase in the number and area of extraction elements and would require only a small increase in supporting structures (see Figure 7-6). This would provide good scale-up potential. These concepts call for relatively low support height for a large number of WECS models, [such as tracked airfoils or magnus-effect rotors (Whitford et al. 1979)] like those shown in Figure 7-7. Unfortunately, the track support structure usually requires a lot of materials; and the extraction elements are in a high wind shear region of the earth's boundary layer, causing lower average yearly power output per square meter of swept area.

Another method suggested to reduce support structure costs is multiple WECS machines. In this concept, several WECS machines are attached to the same support structure. This type of design can simplify support structures, but it may cause mutual interference, increased structural loads, and higher transmission costs. As with other innovative systems, to be successful, the entire system must result in reduced costs per kilowatt generated. The WECS shown in Figure 7-8 gives an idea of the variety of these structures that have been proposed.

7.4 DRAG DEVICE SYSTEMS

Innovations suggested for drag devices are usually either associated with the shielding of the returning drag element, or changing its drag coefficient on the upwind or downwind portion of the path it travels. This may involve increased cost and must always be outweighed by a sufficient increase in power output.

Many methods have been proposed for modifying the drag coefficients (C_D) of the active elements. Some of the simpler systems, such as the cupped system shown in Figure 7-9 and the Savonius rotor, have constant shapes that allow different C_D's on the upwind path than on the downwind path. Others, like

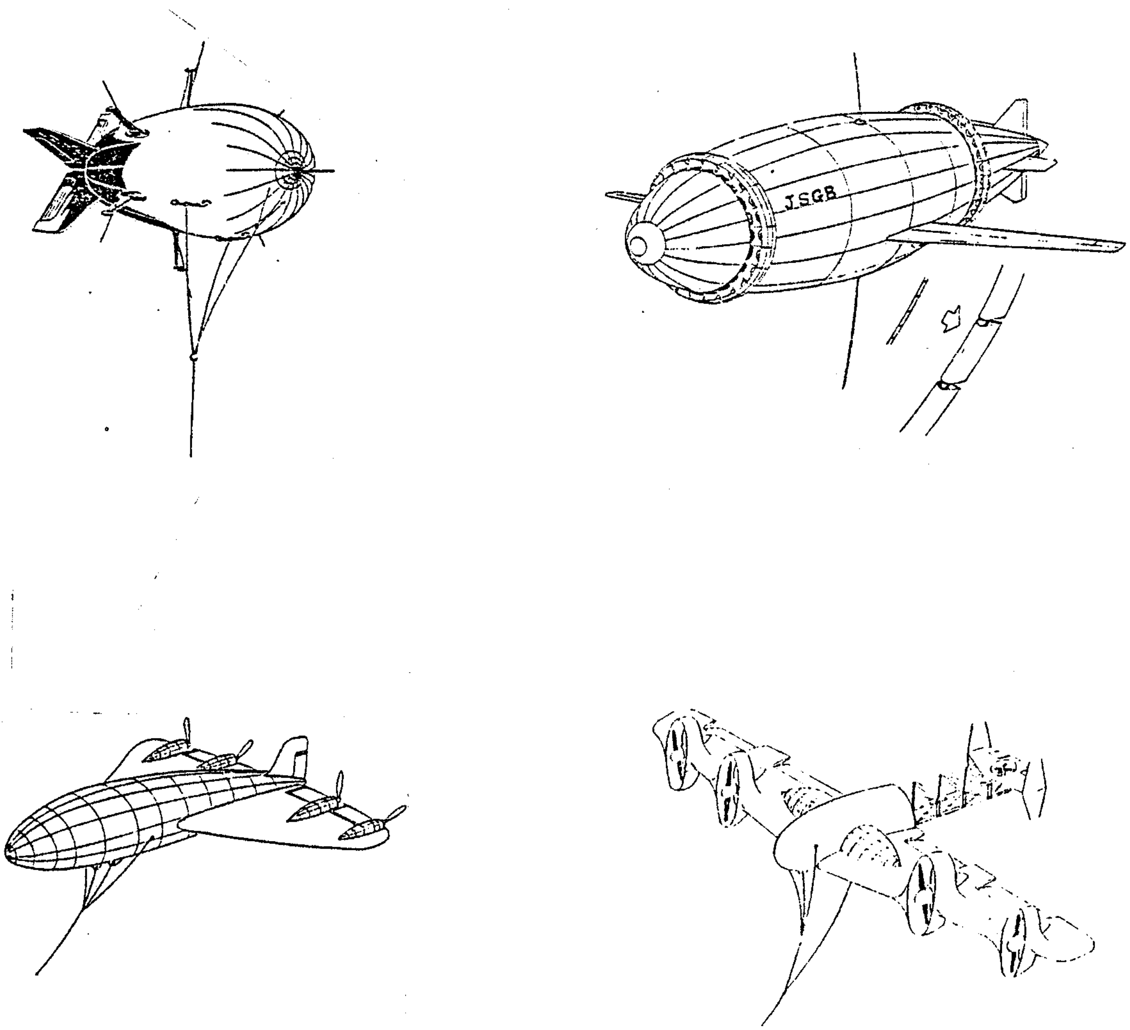
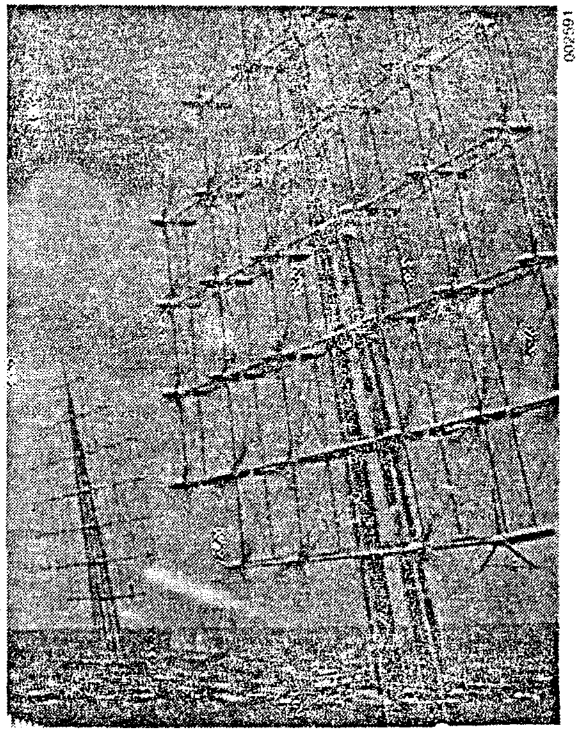


Figure 7-5. Some Examples of Tethered Systems



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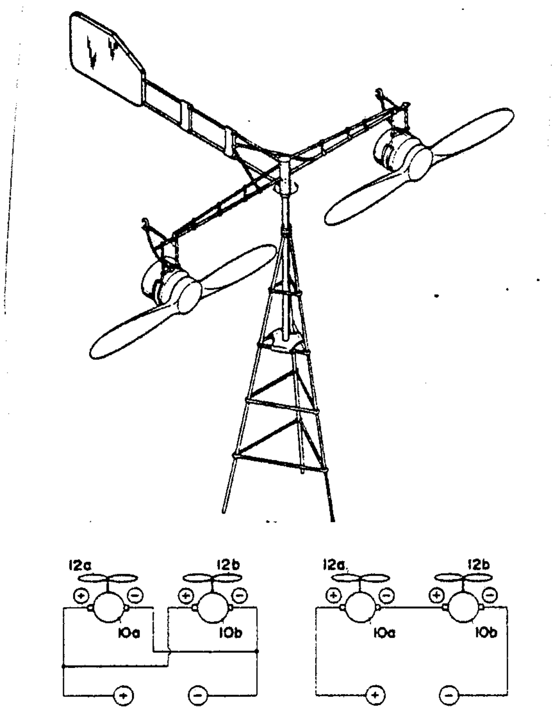
Jan. 15, 1980



4,110,631
Aug. 29, 1978

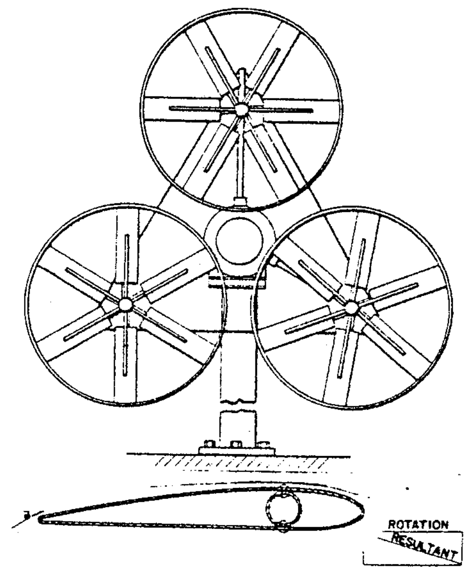


Figure 7-6. Multiple WECS Models on a Single Support

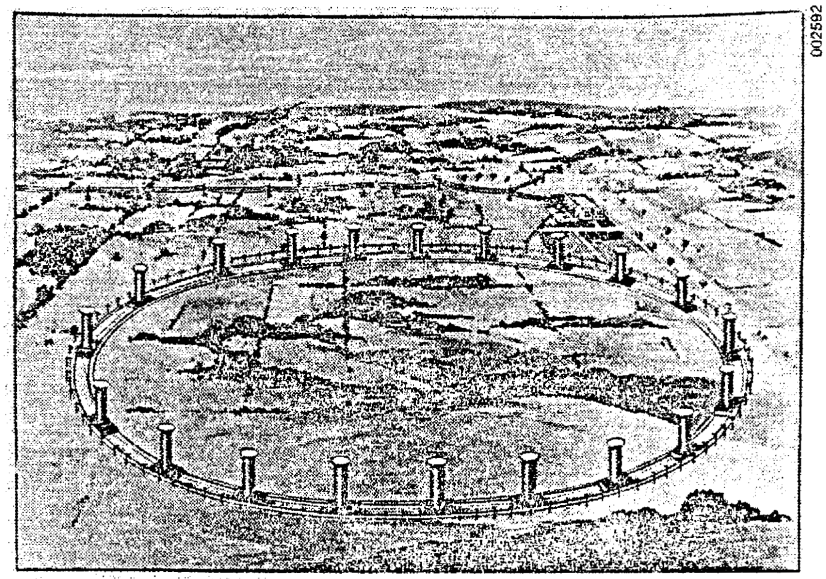


Figure 7-7. The Madaras System Using Magnus-Effect Rotors Moving on a Track

those in Figure 7-10, use hinged or flexible devices as active elements. These devices may be actuated by either pitch scheduling or the force of the mind so that they take on different shapes when traveling upwind than when moving downwind, thereby changing the C_D of the active element.

Shielding the active element is also often suggested to reduce the aerodynamic drag during the upwind motion of the system. Two examples of this concept are illustrated in Figure 7-11. This concept may also be used to design flow augmentation devices under certain circumstances.

The charged particle systems discussed in Section 7.2 can also be considered shielded drag systems because they extract energy from the wind due to drag on active elements (aerosols) that are then not subject to drag forces necessary to return them to the downwind path starting point (water pumping).

7.5 LIFTING DEVICE SYSTEMS

A number of advanced and innovative concepts have been suggested to improve or better utilize lifting elements. A lifting system may be oriented to use a vertical axis, horizontal axis, linear path (Bielawa 1980), or oval path, as illustrated in the examples in Figures 7-12 through 7-18.

The largest area of innovation for lifting systems is in the power coefficient (C_p) modifications. The maximizing of the lift coefficient (C_L) by circulation control has been suggested by West Virginia University (Proceedings 1979; Proceedings 1980; Walters et al. 1979; Walters et al. n.d.1; Migliore and Wolfe 1980; Walters et al. n.d.2) as one method, but it has some drawbacks and usually results in little or no increase in the effective maximum power coefficient over that obtained with good conventional

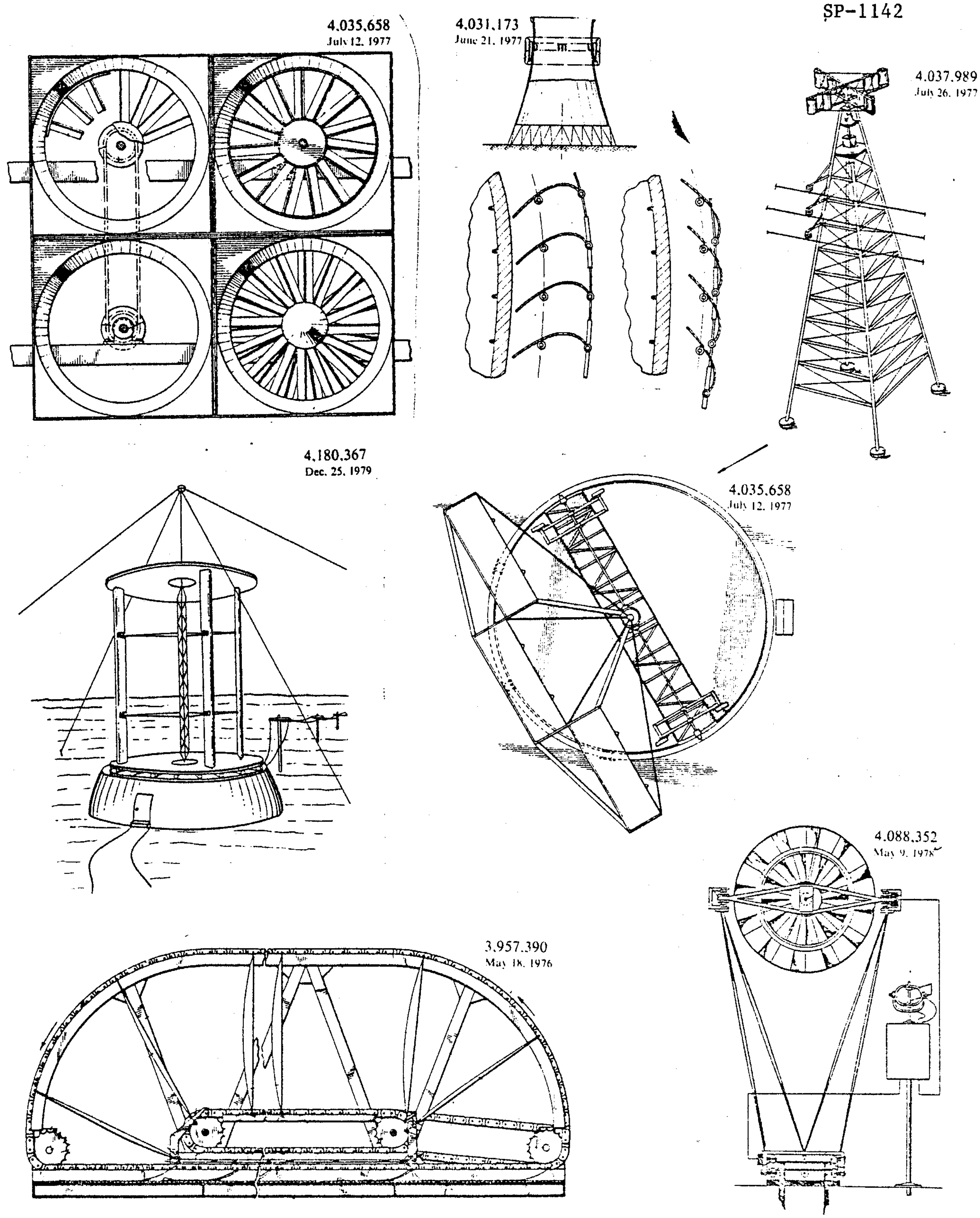


Figure 7-8. A Variety of Proposed WECS Structures

airfoils. The maximum power coefficient is obtained at a lower tip-speed ratio when high lift is used. The higher torque associated with the lower speeds increases the power transmission problems; unless this cost is compensated by some reduced costs in other areas, it is not beneficial.

Pitching schedules and rotor orientation (yawing), either to adjust rotor loads or to maximize airfoil angle of attack, have been applied in many ways, such as the Washington University Passive Cyclic Pitch Concept shown in Figure 7-15 (Hohenemser et al. 1979; Hohenemser and Swift 1981). Mechanically actuated cyclic or collective pitch may be applied to both VAWT and HAWT systems. Power airfoils are also used to adjust the C_L of systems either collectively or cyclically collectively or cyclically (see Figure 7-16), as in the West Vir ginia University system and the Madaras system.

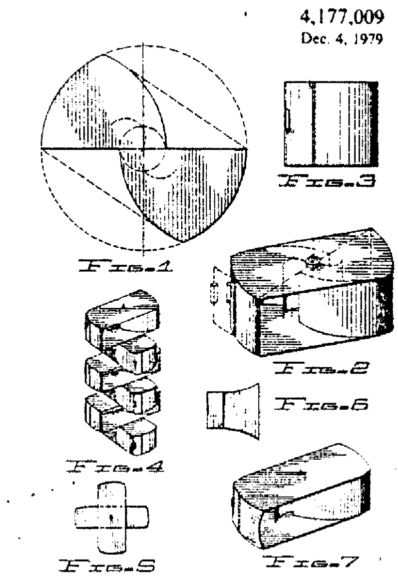


Figure 7-9. Cup Type Differential Drag WECS

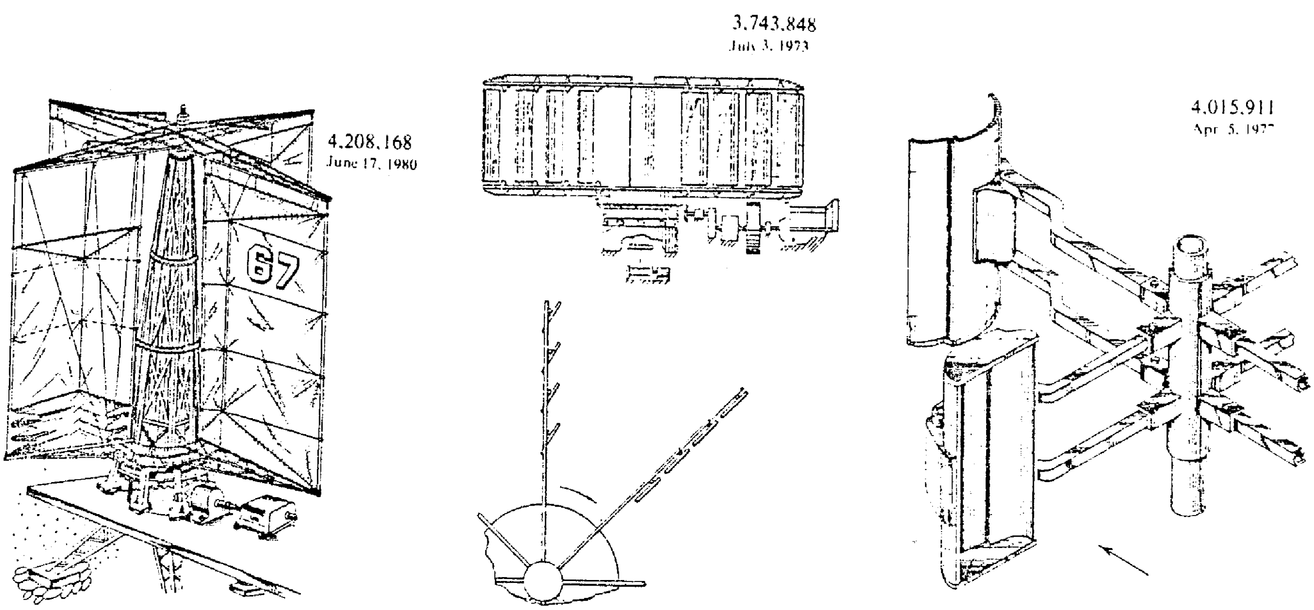


Figure 7-10. Some Proposals that Have Been Made for Variable-Geometry Drag Type WECS

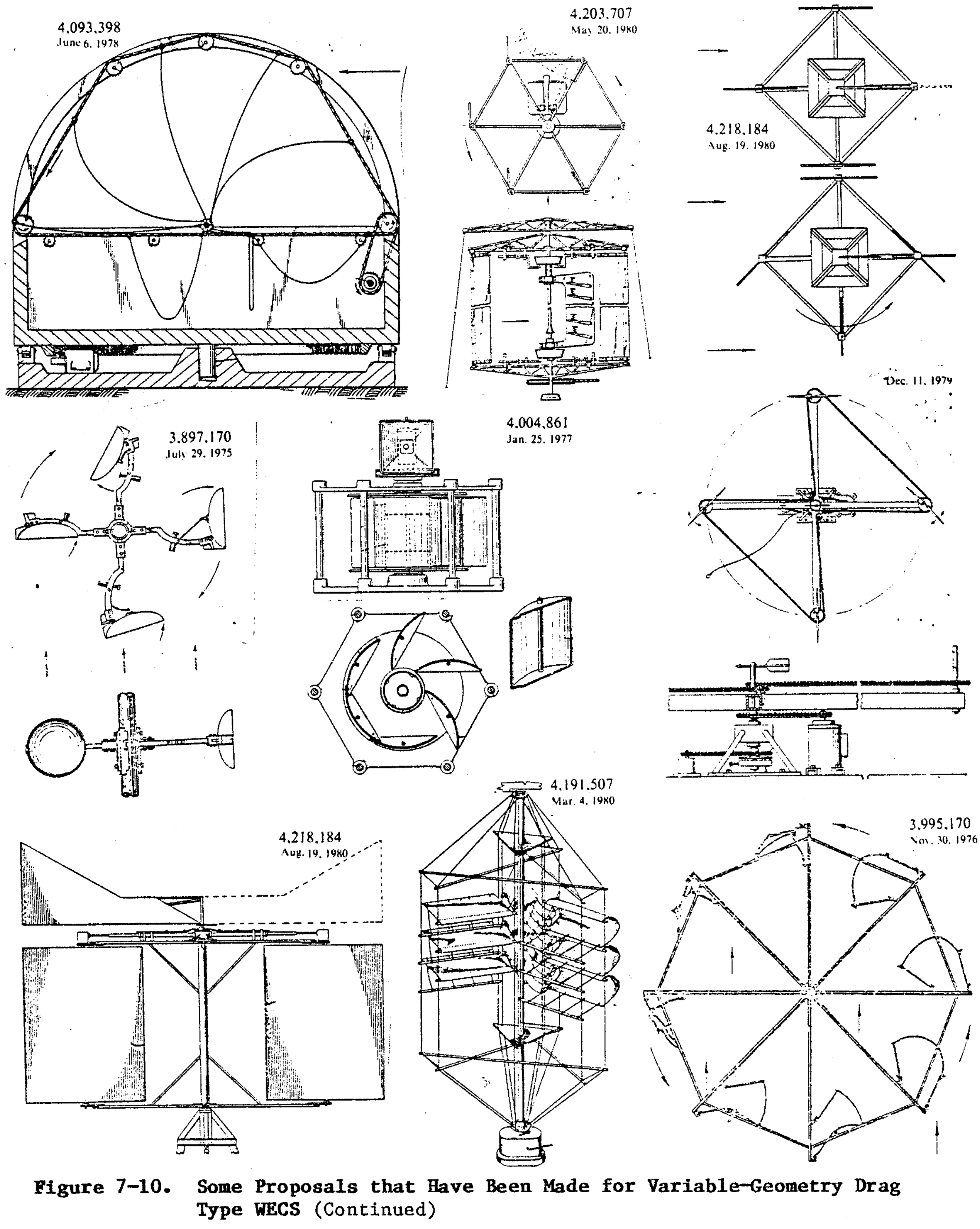


Figure 7-10. Some Proposals that Have Been Made for Variable-Geometry Drag Type WECS (Continued)

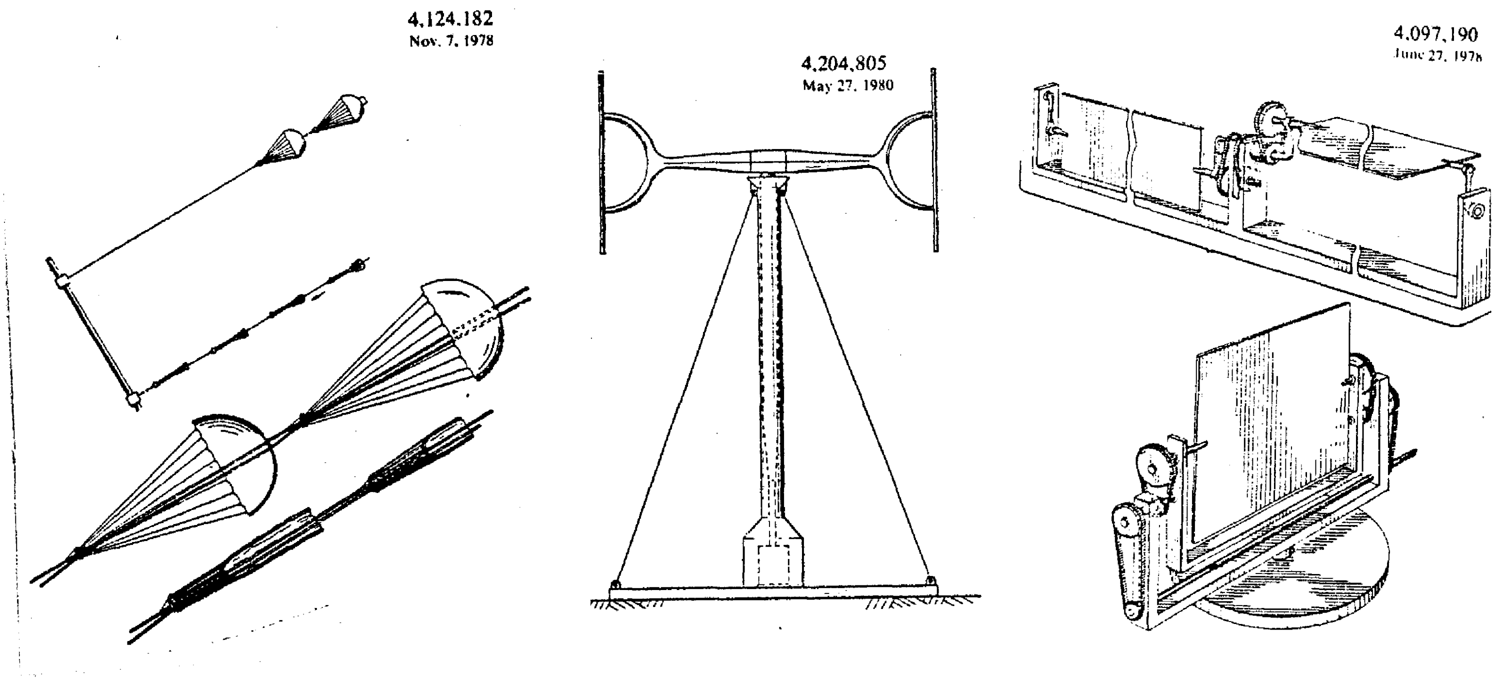
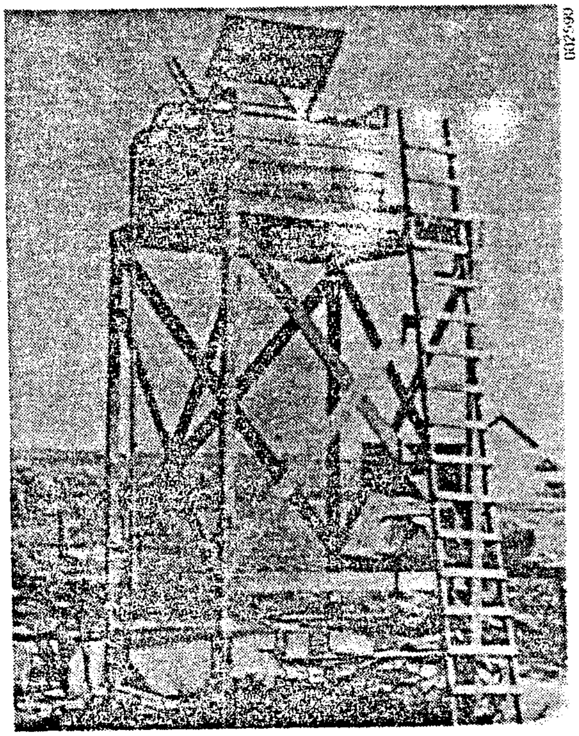


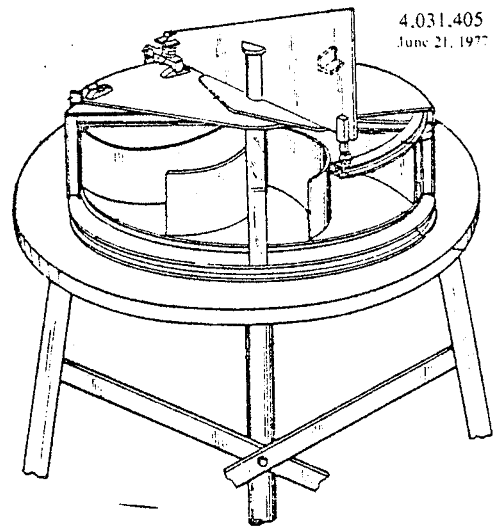
Figure 7-10. Some Proposals that Have Been Made for Variable-Geometry Drag Type WECS (Concluded)

The lift translator, an example of which is shown in Figure 7-17, is a tracked airfoil system that is oriented in a horizontal plane with the axis of rotation perpendicular to the wind. The orbital path is essentially a race track. The lifting elements move in the direction of the lifting force. Although based on the analysis in Appendix C it initially appears to optimize the force, the lift translator provides less power per unit of wing area than other lifting devices due to blade speed limitations. The system also has a much more material-intensive orbital constraint system because of the track shape than other more simple orbital configurations.

The Passive Cyclic Pitch concept (Hohenemser et al. 1979; Hohenemser and Swift 1981), shown in Figure 7-19, has two lifting airfoils traveling in a circular path with the axis normal to the wind. The airfoils are teetered on a fixed hub about a hinge that is oriented 23 degrees ahead of the chord line of the blades. This angle allows any movement of the blades out of the plane of rotation (blade flap) to be translated into a change in the angle of attack of both blades. The result is that a restoring aerodynamic force is applied to the rotor disc until it is evenly loaded.

The Madaras system, illustrated in Figure 7-19, is a variant of the VAWT (Whitford et al. 1979). In this system, the magnus-effect cylindrical airfoils are mounted vertically on rail cars that move around a track and extract power from the wind whenever they move across the wind. The power conversion is accomplished through generators driven by the wheels on the rail cars. The airfoils proposed for the Madaras system are spinning cylinders, and the direction of spin must be reversed for each half of the track (see Figure 8-6) to change the direction of the lifting force on the cylinder. Studies suggest





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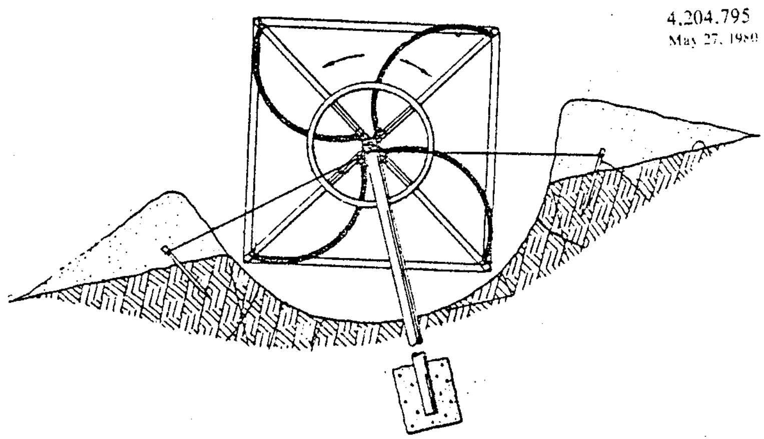
June 21, 1977



4,204,795
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Figure 7-11. Some Examples of Shielded, Drag-Type WECS

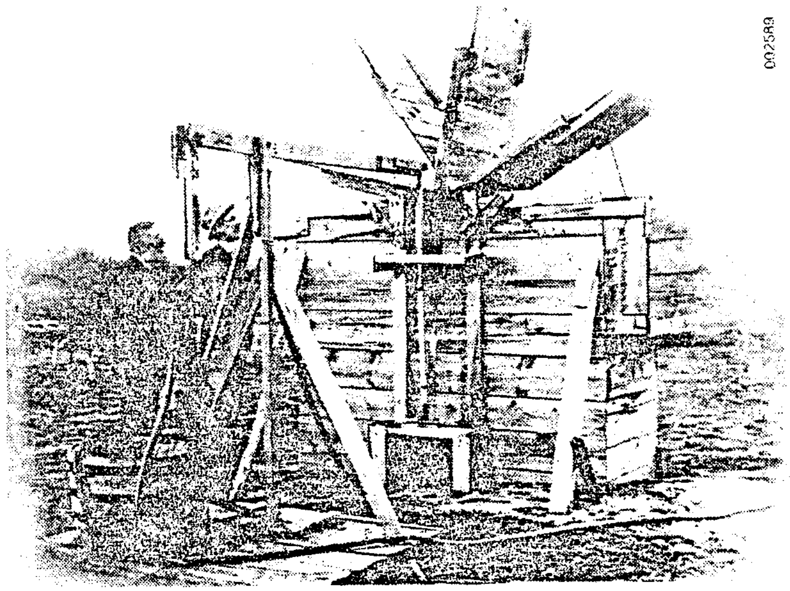

Figure 7-11. Some Examples of Shielded, Drag-Type WECS (Concluded)

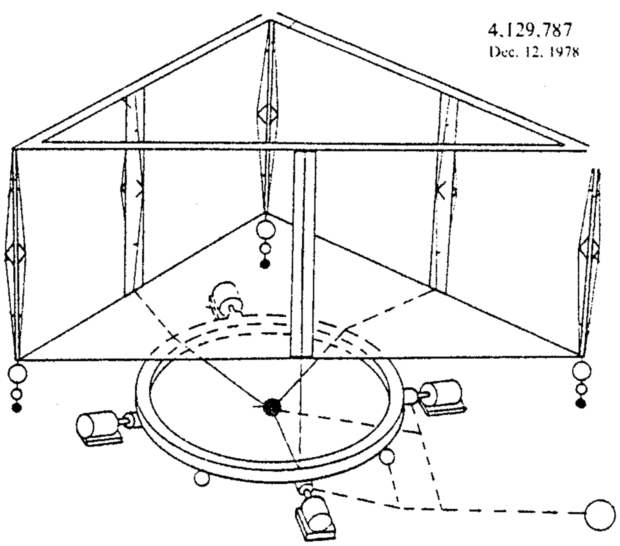

Figure 7-12. WECS Using Lifting Elements

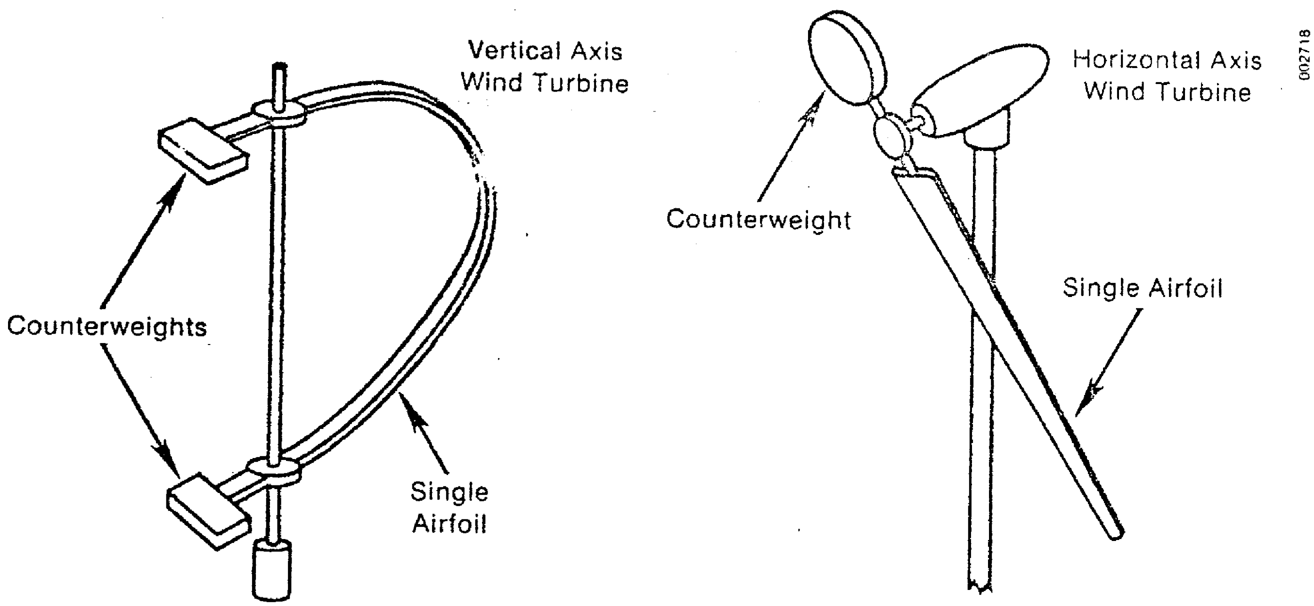

Figure 7-13. Low Solidity/High Tip-Speed Ratio WECS

that the Madaras system would be more expensive than conventional WECS and would also have limited applicability.

One of the many other innovative configurations for maximizing C_p is the multiple in line wind energy extraction system, such as the contra-rotating rotor system shown in Figure 7-20. The concept extracts a portion of the energy still in the stream tube after it passes through the first rotor. Concepts of this type can increase the power output of the rotor system but the cost of the additional rotors are usually not compensated for by the low percentage of power increase available (see Appendix B).

Tethered airfoils have also been proposed that both modify conventional support structures, as previously discussed, and change the orbital path of the extraction elements. These systems usually have a linear path: back and forth, from side to side--similar to the oscillating vane WECS (see Figure 7-21); up and down like the lift translator (see Figure 7-22); and traveling back and forth along the axis of the tethering cable (see Figure 7-10). When, as in most cases, the power extraction is to be provided by the airfoil itself, the transmission of this power is accomplished by the cable. This approach is often prohibitive because of system losses from drag on the cable and losses in extraction efficiency at the ends of the orbital path. When the motion of the airfoil is to augment the inflow velocity of the wind for other extraction devices, the system usually encounters large drag losses on the support cable. The most useful method is, however, a conventional extraction element supported on a platform, like the one shown in Figure 7-23. Regardless of the configuration, these concepts must provide a significant increase in the power output to make up for the increased drag losses and increased material requirements they impose.

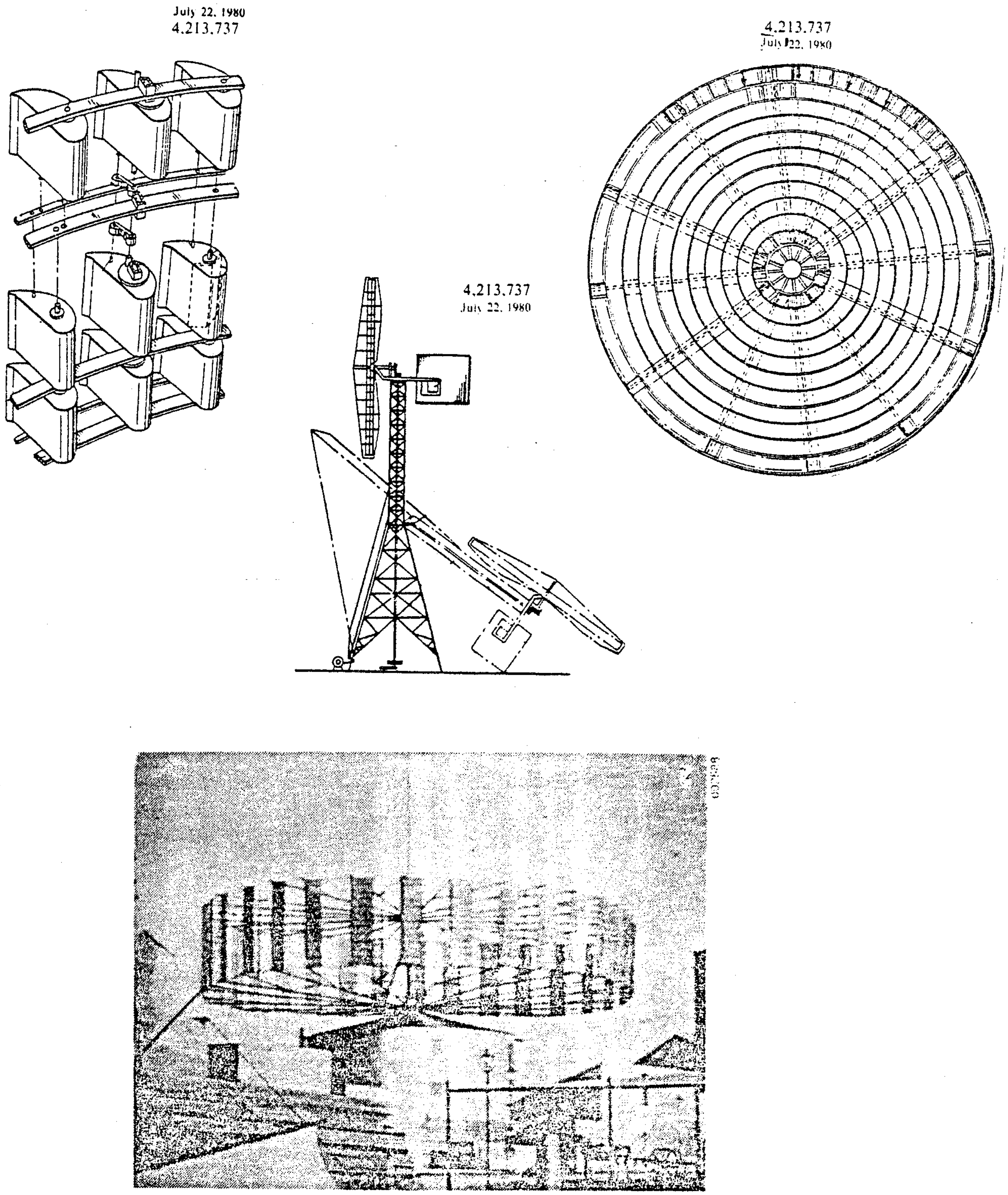

Figure 7-14. High Solidity/Low Tip-Speed Ratio, Lifting Type WECS

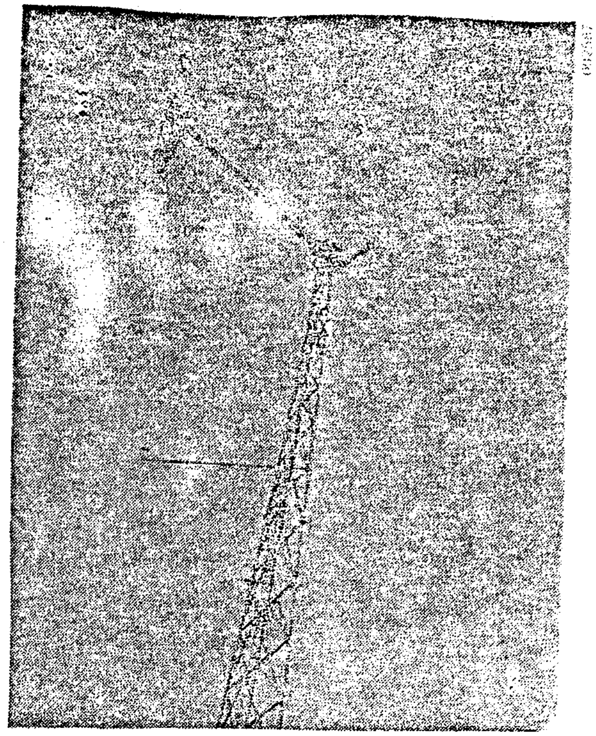

Figure 7-15. Power Control by Yawing the Rotor and Using Passive Cyclic Pitch Control to Minimize Blade Root Dynamic Loads

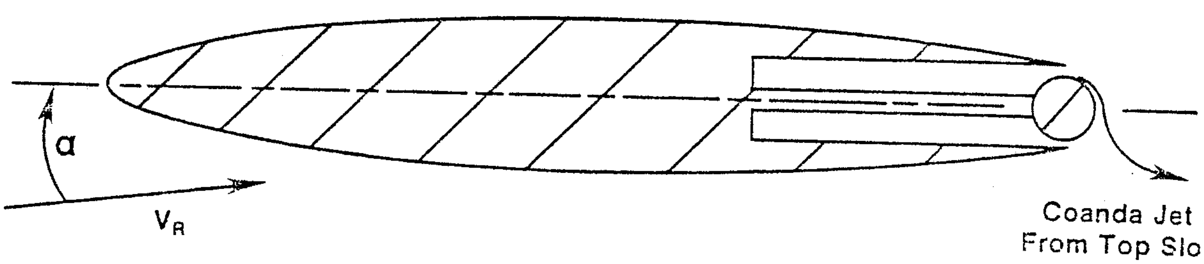

Figure 7-16. Active Symmetrical Airfoil Using Trailing Edge Jets to Produce Either a Positive or a Negative Lift Force

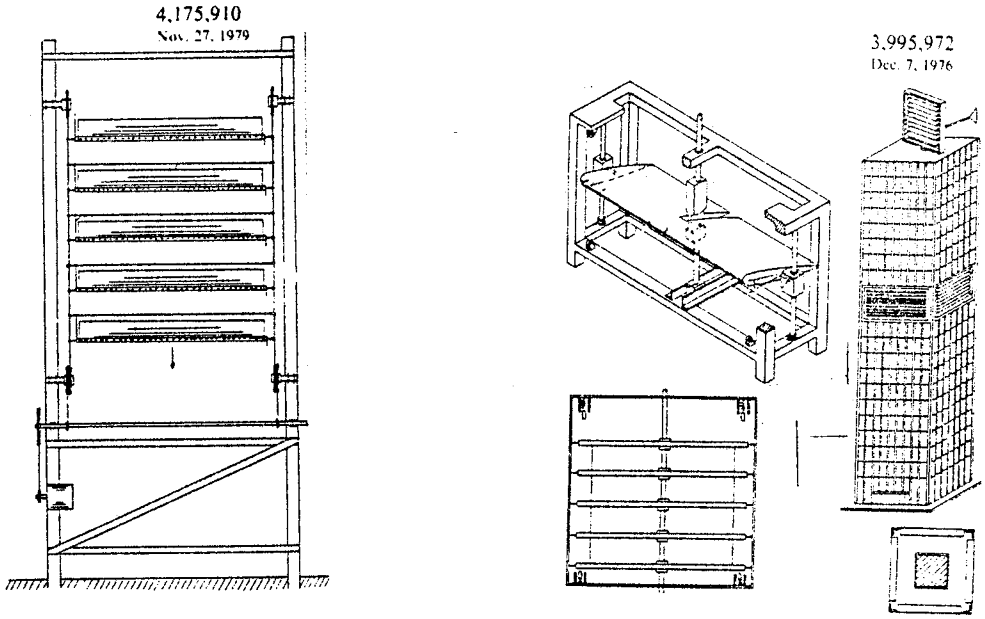

Figure 7-17. A Lift Translator WECS

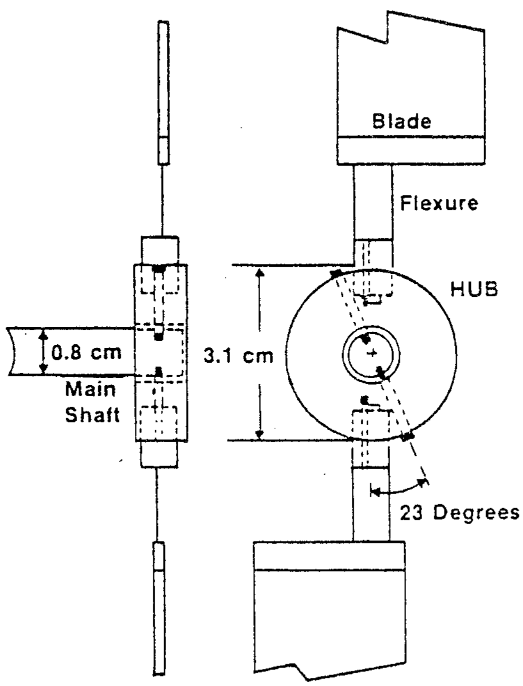

Figure 7-18. Hub of the Passive Cyclic Pitch Control Rotor

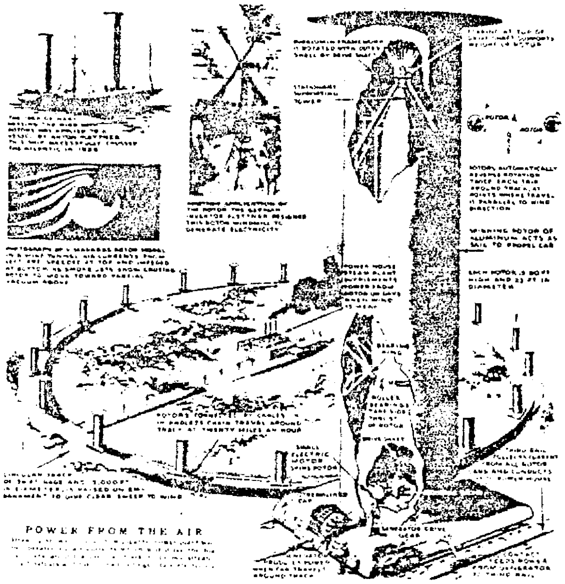

Figure 7-19. The Madaras System

7.6 LIFT AND DRAG SYSTEMS

Special consideration should be given to innovative concepts that, at various times, use active elements of lift and drag. At low tip-speed ratios, the devices operate as drag devices. But at higher tip-speed ratios, some aerodynamic lift comes into use. The measured performance of a split savonius rotor (shown in Figure 7-24) illustrates that it must use some aerodynamic lift since its maximum power coefficient is too high for a simple drag device, and also at tip-speed ratios greater than one, the outermost parts of the rotor would see only a retarding flow.

If the devices use different elements to produce lift and drag or different orientations of the same elements, the effective area and operating radius of the drag elements must be at least as great as those of the lifting elements if they are to produce a power output that is significant compared with that of the lift elements. While the lift elements are not likely to have a serious impact on the drag elements, the presence of the drag elements can have a serious adverse impact on the performance of the lift elements unless some geometric changes can be made to reduce the parasitic losses of the drag elements. In general, mixed systems do not perform well in the lift regime and are relatively complex devices. However there are certain applications where high torque at low tip-speed ratios and higher free running tip-speed ratios are more important than the differential drag devices and outweigh other considerations. These systems must be evaluated for the benefit-to-cost ratio that is obtained in the particular application. The WECS shown in Figure 7-25 illustrates a combined lift and drag machine designed for a special application.

7.7 AUGMENTATION SYSTEMS

The area of advanced and innovative wind energy concepts addressing augmentation is probably more active than any other area. These concepts are usually designed around rather conventional WECS machines with the idea that a natural or manmade structure can induce a higher mass flow rate through a wind energy conversion device. To be practical, these concepts must have lower cost than that of a larger capacity system, whether this system would be a larger WECS or a larger number of WECS machines. In other words, the conventional WECS and augmentor together must have an improved benefit-to-cost ratio.

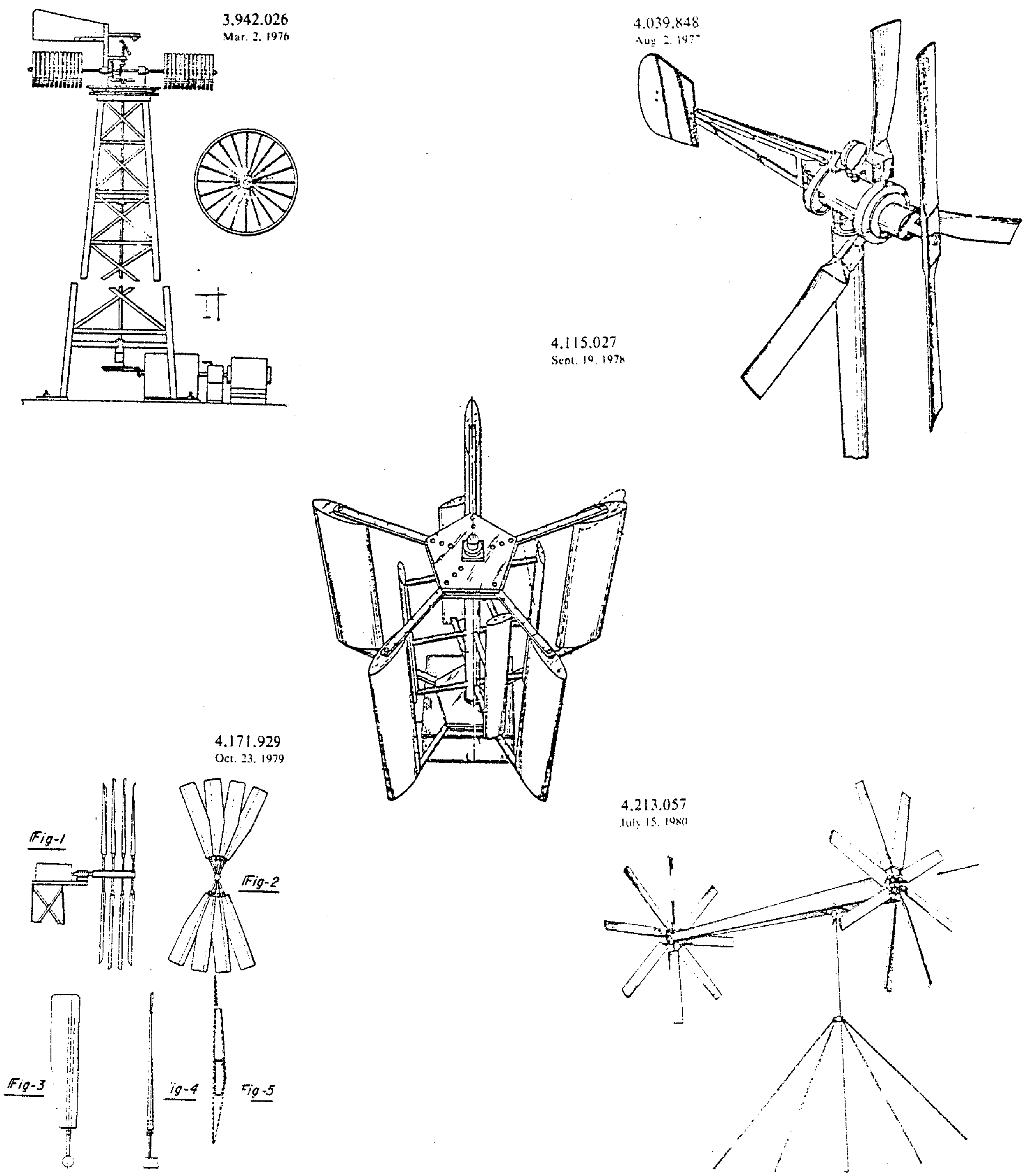

Figure 7-20. Examples of Devices Designed to Increase Maximum Power Coefficient

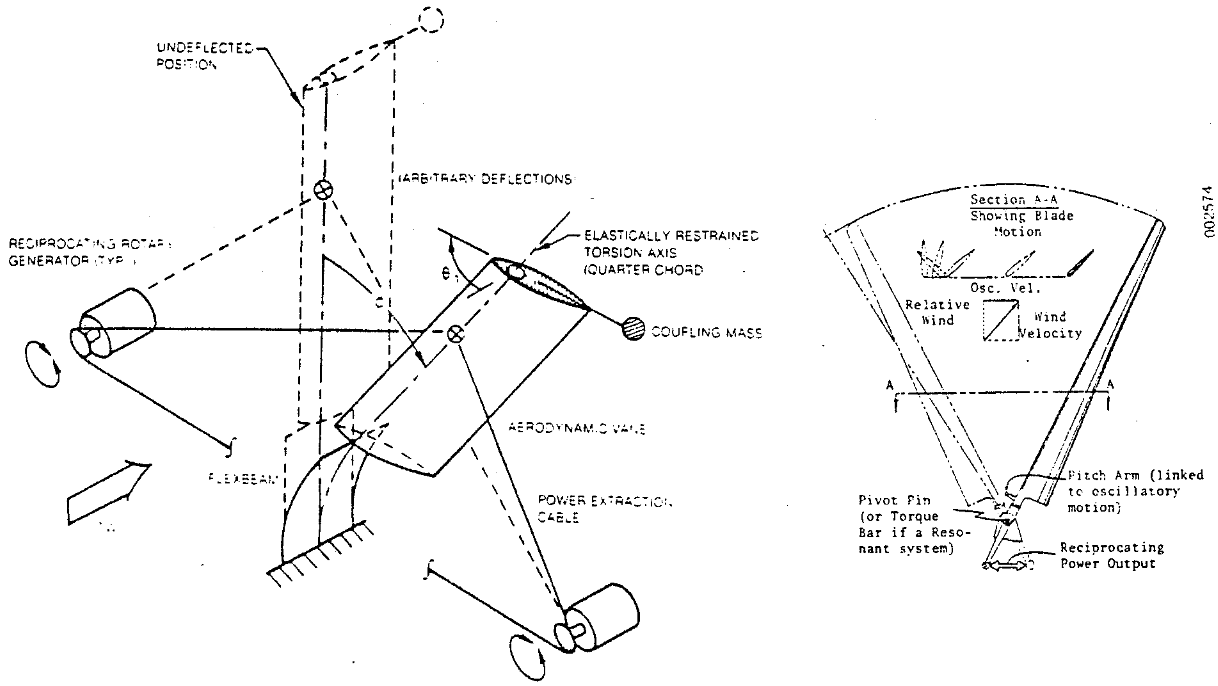

Figure 7-21. An Oscillating Vane WECS

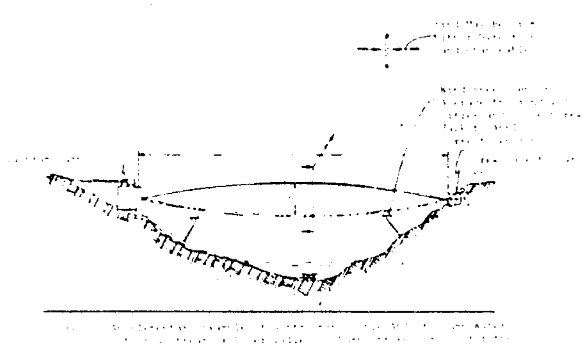

Figure 7-22. Strumming Cable WECS

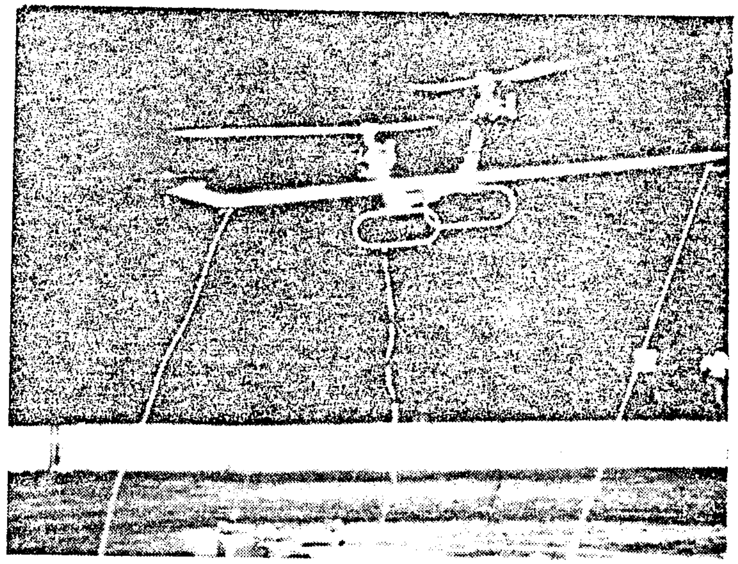

Figure 7-23. Tethered WECS Using Rotors to Provide Lift Force and Power Extraction Mechanism

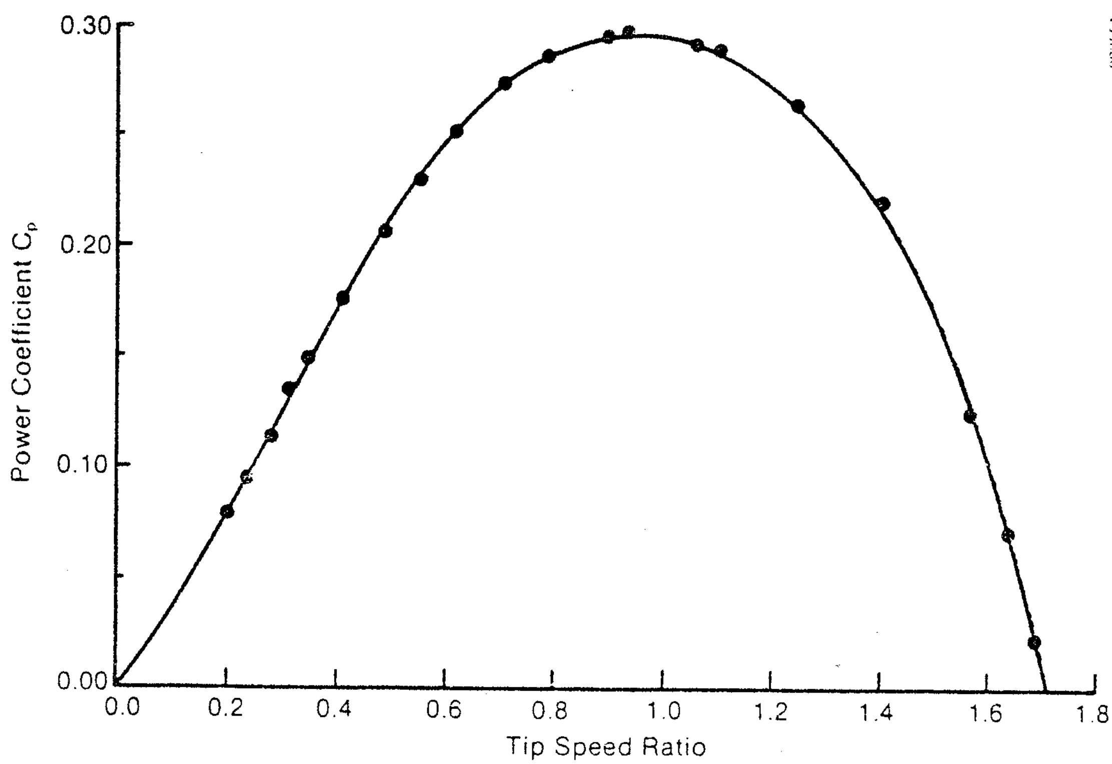

Figure 7-24. Typical Performance of a Split Savonius Rotor

Several ducted augmentor concepts have been investigated. These are static augmentors which redirect the air flow through the conversion system. Concentrator ducts (see Figure 7-26) have little augmentation when a diffuser section is not present. There is also little difference in performance between a diffuser section and a concentrator with a diffuser.

A diffuser creates a low subatmospheric pressure behind a turbine rotor. A consequence of this suction is the capture of significantly more wind through a diffuser-augmented wind turbine than a conventional wind turbine. The resulting increased mass flow increases the output power and has the potential to reduce the busbar cost. One diffuser concept has been under investigation at Grumman Aerospace [Gilbert and Foreman 1979; Lissaman et al. 1979 (May); Proceedings 1979; Tetra Tech, Inc. 1979; Foreman and Gilbert 1979; Proceedings 1980].

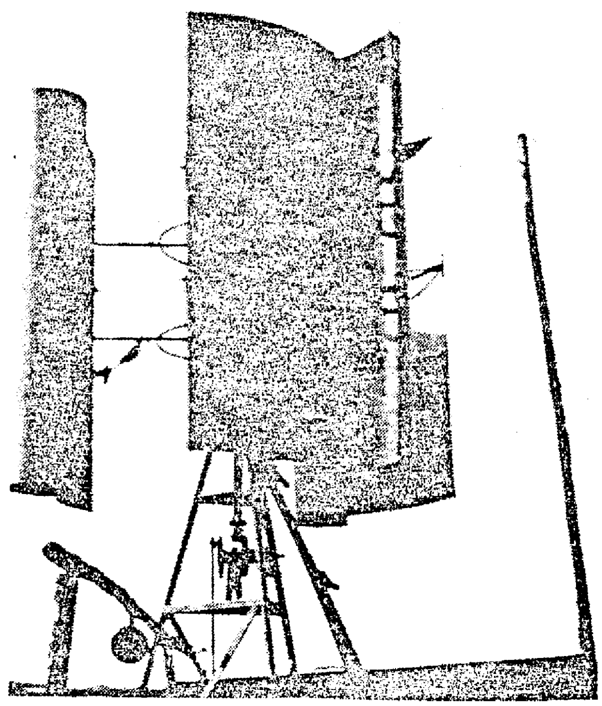

Figure 7-25. WECS Using Both Lift and Drag Elements to Extract Power from Wind

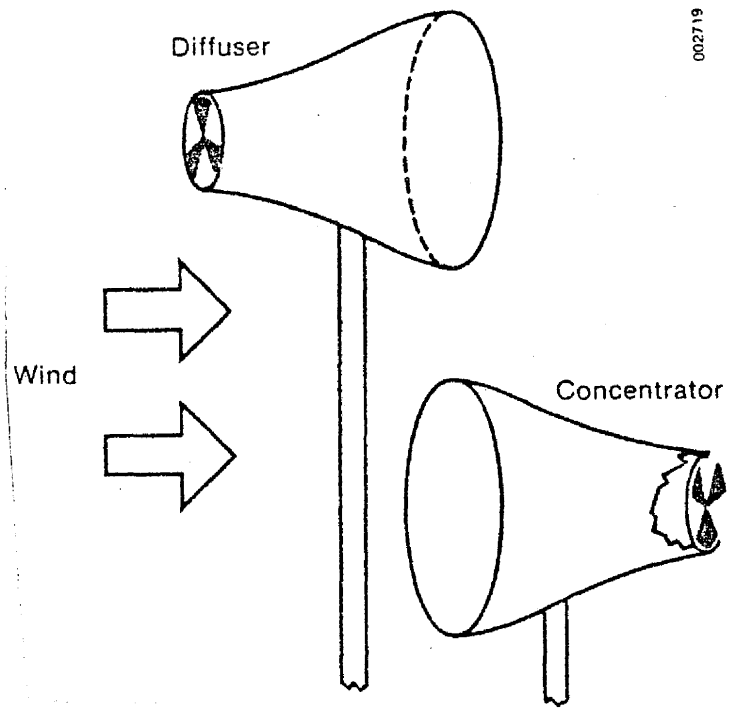

Figure 7-26. Diffusing and Concentrating Ducts

These studies have indicated that a conventional diffuser system would not be cost-effective if the diffuser section was long enough to prevent flow separation (see Figure 7-27). The Grumman Diffuser Augmented Wind Turbine (DAWT) has reduced this problem by shortening the diffuser and by reenergizing the boundary layer (see Figure 7-28). These modifications should improve the cost-effective projections of the DAWT over the prohibitive costs of conventional diffusers.

Another method of creating the diffusion effect is to develop the desired stream tube expansion aerodynamically rather than with a static shroud. This concept has been investigated by the Delft Research Institute and AeroVironment, Inc. [Proceedings 1979; Lissaman et al. 1979 (May); Lissama et al. 1979 (April); Tetra Tech, Inc. 1979; Proceedings 1980; Lissaman et al. 1981; Gyatt et al. 1982] using the Dynamic Inducer (see Figure 7-29). This concept has the same effect as the DAWT with a significant reduction in material requirements. However, the tip vane airfoils create a parasitic drag which reduces the system power output significantly. Vortex augmentation concepts similar to those of the Grumman Aerospace tornado-type WECS (Figure 7-31) (Kornreich et al. 1980; Yen 1980; Ayad 1981) and the Polytechnic Institute of New York (PINY) vortex systems (see Figure 7-32) (Proceedings 1979; Proceedings 1980; Kornreich et al. 1980) are shown in Figure 7-30. This power can then be extracted by a small turbine (see Figure 7-33). Studies have indicated that unconfined vortices may be difficult to control and would probably be dispersed by a rotor placed in them as in the PINY concept. In general, it is material-intensive to generate vortices, whether confined or unconfined.

The best reported power coefficients based on tower frontal area for the symmetrical tornado concept has been about 0.1; and for the vortex augmentor concept, about 0.27 based on turbine disk area. Figure 7-34 shows the required relative sizes of these devices compared with a conventional HAWT. The data used in this figure do not necessarily represent the best that can be obtained but do illustrate just how much these devices must be improved to become as effective as conventional devices.

7.8 THERMAL COLUMNS

The thermal column is best considered not as a wind machine but as a heat engine. It operates on the principle that if a column of air has a different

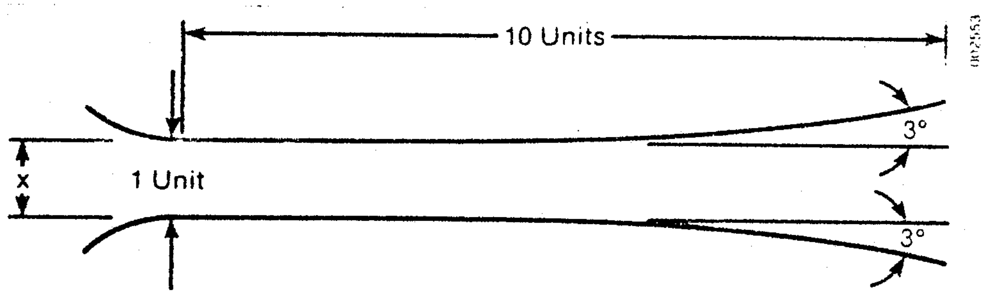

Figure 7-27. Typical Proportions for an Efficient Passive Diffuser

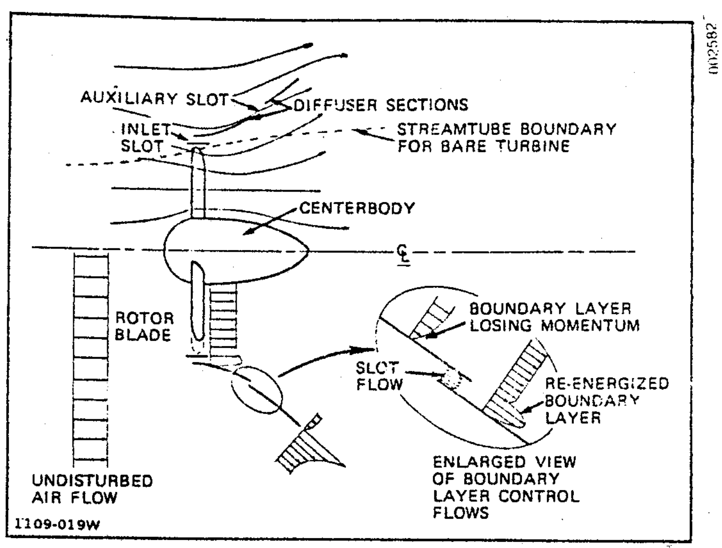

Figure 7-28. Grumman DAWT Using a Reenergized Boundary Layer to Prevent Flow Separation from Diffuser Walls

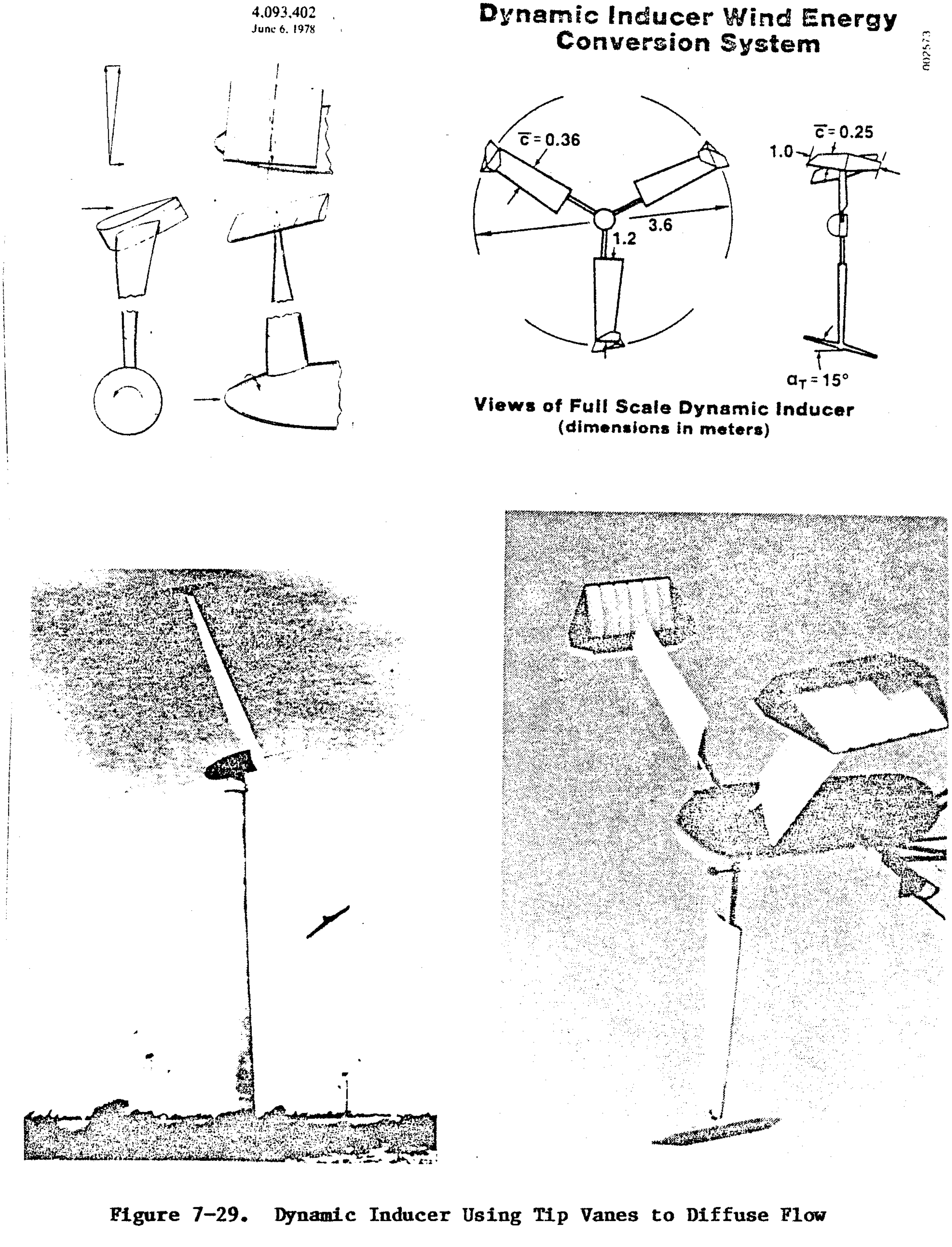

Figure 7-29. Dynamic Inducer Using Tip Vanes to Diffuse Flow

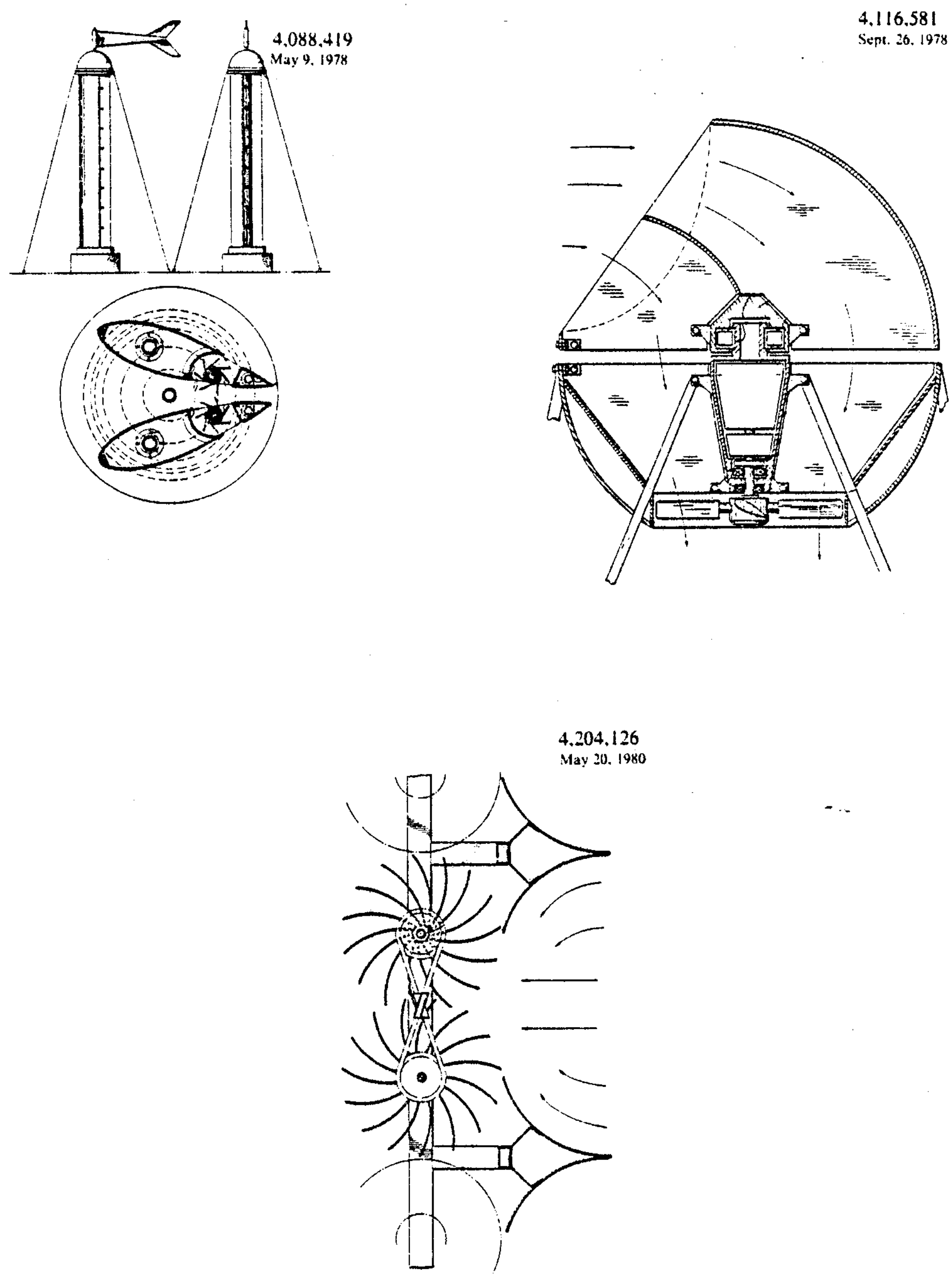

Figure 7-30. Examples of Proposed Energy Concentrators

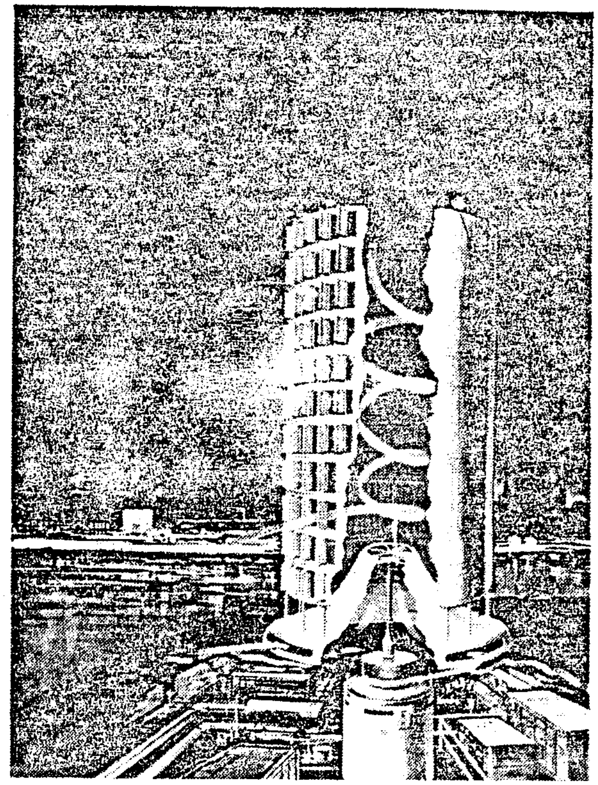

Figure 7-31. Grumman Tornado-Type WECS

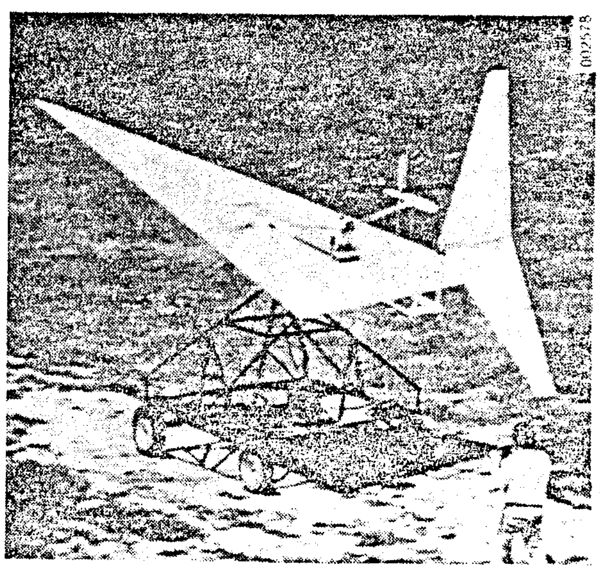

Figure 7-32. Vortex Augmentor Concept

Figure 7-33. Turbine from Scale Model of Grumman Tornado-Type WECS

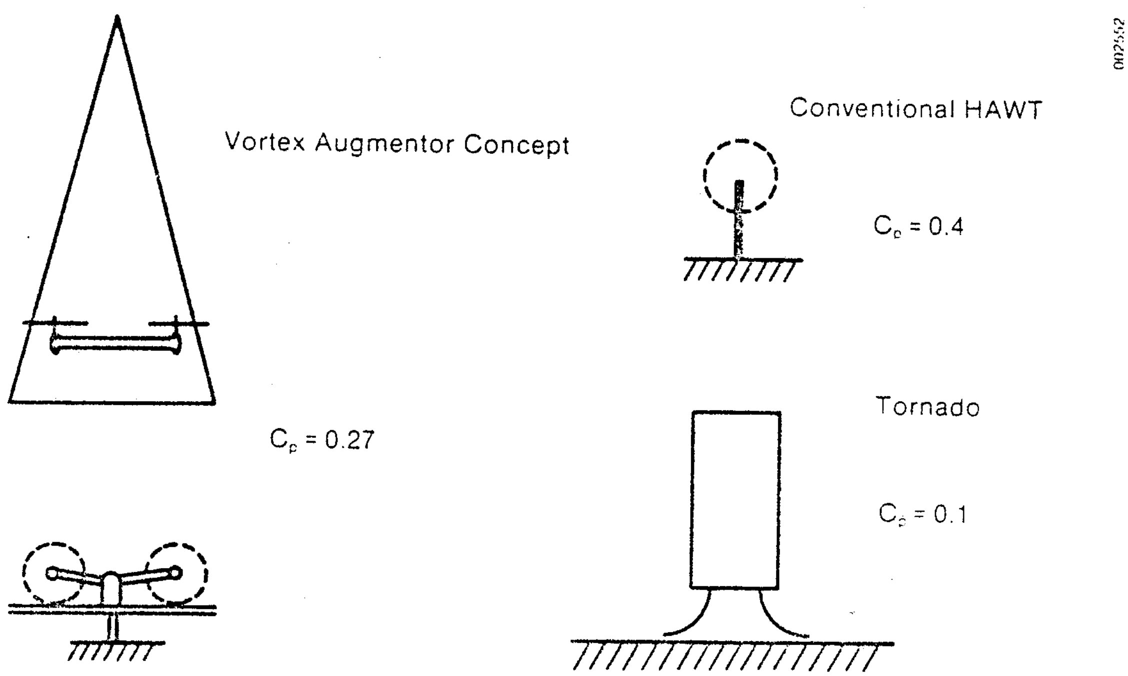

Figure 7-34. Relative Sizes of WECS Based on Power Output

density than the surrounding atmosphere, a flow will occur, and energy can be extracted from this flow. The density of the column can be changed, either by heating or by cooling the column. In the atmosphere, temperature normally decreases with height, and the rate of change of temperatures with height is called the lapse rate. If the altitude of a mass of dry air is changed and no heat is added or subtracted, the change in pressure will cause a change in temperature of the air mass. If the atmospheric temperature lapse rate is such that the change in temperature with altitude of a given mass of air is the same as the atmospheric lapse rate, the atmosphere has a dry adiabatic lapse rate and is neutrally stable. The dry adiabatic lapse rate is the maximum stable lapse rate. In a neutrally stable atmosphere, the temperature of a mass of air that is heated will continue to rise and will always remain hotter than the surrounding air unless heat is lost through conduction, radiation, or convection; and if it is cooled, the temperature will continue to fall and stay cooler than the surroundings unless heat is gained through conduction, absorption, or other means. In a neutral atmosphere, the ideal efficiency of converting heat energy to mechanical energy is a heated column of air is about 1% per 1000 ft. If the atmospheric temperature gradient is stable, then the column temperature will not rise until it is heated above some threshold temperature and then only 1% per 1000 ft of the additional heat will be converted. If the atmosphere is unstable, then no heat need be added to cause the flow. In the neutral atmosphere low-grade heat can be used, and hence the heated column appears to be an attractive method for extracting high-grade energy from low-grade heat.

The cooled column is similar in function to the heated column but uses the evaporation of water droplets to extract heat from the air for cooling. As the temperature rises in a descending column of air, the relative humidity decreases and allows the column to evaporate more moisture; therefore the relative cooling process can be continued for the full length of the column. As the column temperature descends, the absolute temperature rises but the evaporation of the water causes the rise in temperature to be slower than in the dry air. As with the heated column, the ideal conversion efficiency of the heat extracted is 1% per 1000 ft. The power output is also dependent on ambient relative humidity and air temperature and is affected by atmospheric stability. The amount of water consumed would be about 100 lb/kWh for a column 10,000 ft high and about 1000 lb/kWh for a column 1000 ft high. Hence the cooled-column energy converter would need to be placed in a hot, dry area adjacent to an abundant source of water.

The cooled column does not necessarily need physical boundaries as long as its cross-sectional area is sufficiently large so that the effects of missing the edges are insignificant. The cooled flow could be directed down a sloping valley or down a mountainside.

The humid air system of the South Dakota School of Mines and Technology (Oliver et al. 1982), shown in Figure 7-35 is an example of a thermal column and a heat engine that is driven by the wind--it extracts energy from the humidity in the air. The low static pressure in a contracted vortex is used to condense water vapor and extract the latent heat of condensation. Power is then extracted, and the static pressure is increased as the vortex expands. The vortex expansion is accompanied by a spray of cool water. The change from

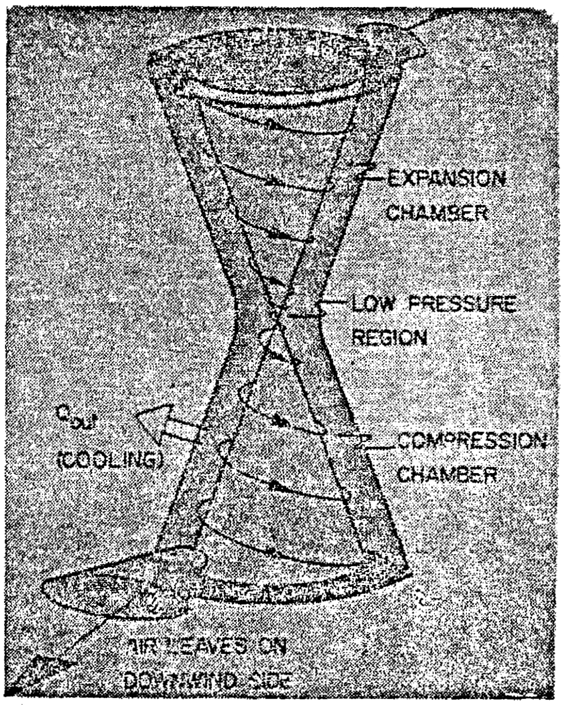

Figure 7-35. Device for Extracting Energy from Humid Air (South Dakota School of Mines)

inlet to outlet humidity causes a small pressure difference across the turbine and, along with the pressure drop associated with the air flow, accounts for the power extracted. The humid air concept therefore requires a source of cold water in a region where the air is hot and humid.

Both the heated and the cooled column are fascinating devices, but there are enormous technical problems to overcome before these devices become practical.

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APPENDIX A

THE LANCHESTER-BETZ LIMIT

In Section 2.0 the power available in the wind was expressed as the volume flow rate through an ideal actuator disk multiplied by the change in total (dynamic) pressure (i.e. change in kinetic energy per unit volume).

$$P = (A_D\ V_D)\ \left(V^2 - V_1^2\right)/2\ . \tag{A-1}$$

An analysis of Equation A-1 shows a trade-off between the volume flow rate and the change in total pressure; increasing the magnitude of one will decrease the other. Thus the ideal maximum power coefficient, the ratio of wind power extracted to wind power available, is given by the combination of volume flow rate and total pressure change that maximizes the product of the two for a given upstream wind velocity V.

To determine the ideal power coefficient, i.e. the Lanchester-Betz limit V_D, the wind velocity through the actuator disk must be determined. This can be achieved by using the laws of conservation of mass, momentum, and energy. The analysis is known as the classical actuator disk or axial momentum theory.

Upstream of the actuator disk, the total pressure in the air flow is equal to the sum of the free stream static and dynamic pressures; i.e.,

$$P_{total} = P_{static} + \rho\ V_0^2/2\ . \tag{A-2}$$

By conservation of mass there can be no discontinuity of velocity in the air flowing through the disk, and therefore the drag on the disk is proportional to the change in static pressure across the disk. However, at some distance downstream of the actuator, the static pressure is constrained to return to its free stream value. Hence from the Bernoulli equation (i.e., conservation of energy), the change in static pressure is equal to the difference in dynamic pressures upwind and downwind of the disk.

The power output of an actuator disk is also equal to the product of the drag force on the disk and the wind velocity through the disk. Thus from $P = (A_D V_D) \times \rho(V^2 - V_1^2)/2$ and the Bernoulli equation, the drag on the actuator can be expressed as

$$D = \rho\ A_D\ (V_D^2 - V_1^2)/2\ . \tag{A-3}$$

To satisfy the law of conservation of momentum, the drag force must also equal the product of the mass flow rate and the overall change in velocity from that of freestream to that of the actuator's wake, or

$$D = \rho\ A_D V_D\ (V_0 - V_1)\ . \tag{A-4}$$

Equating Equations A-4 and A-5 shows that the wind velocity through the actuator disk must be the average of the freestream (upwind) velocities, or

$$V_D = \frac{V + V_1}{2} \; . \tag{A-5}$$

Thus Equation A-6 can be substituted in Equation A-1 to give

$$P = \frac{\rho A_D}{2} \; \frac{V_0 + V_1}{2} \; \left(V_0{}^2 - V_1{}^2\right) \; . \tag{A-6}$$

The Lanchester-Betz limit can be found by differentiating Equation A-7 with respect to V_2:

$$\frac{\partial P}{\partial V_1} = \frac{\rho A_D}{2} \, 1/2 \; \left(V_0{}^2 - V_1{}^2\right) - 2V_1 \; \left(\frac{V_0 + V_1}{2}\right) \; . \tag{A-7}$$

Setting Equation A-8 equal to zero to find the maximum power yields

$$\left(V_0{}^2 - V_1{}^2\right) = 2V_1 \; \left(V_0 + V_1\right) \; , \tag{A-8}$$

or

$$V_1 = 1/3 \; V_0 \; . \tag{A-9}$$

Thus the maximum power is

$$P_{max} = \frac{\rho A_D V_0{}^3}{2} \left(\frac{1 + 1/3}{2}\right) \left(1 - 1/9\right) = \frac{\rho A_D V_0{}^3}{2} \left(16/27\right) \; . \tag{A-10}$$

From this result it follows that the Lanchester-Betz limit or ideal power coefficient based on classical actuator disk theory is

$$C_{P_{max}} = \frac{P_{max}}{\rho A_D V_0{}^3/2} = 16/27 = 0.593 \; . \tag{A-11}$$

Note that at maximum power, the wind velocity through the actuator disk is $V_D = 2/3 \; V_0$. Hence at maximum efficiency, the disk extracts 8/9 of the energy available in a stream tube that originally was 2/3 of the cross-sectional area of the disk.

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APPENDIX B

LANCHESTER-BETZ LIMIT APPLIED TO TWO ACTUATOR DISKS IN SERIES

The actuator disk theory can be used to determine the ideal gain in power output that can be achieved by adding a second actuator disk in a series or tandem configuration with the one previously analyzed. This configuration is shown in Figure B-1.

Assuming streamline flow and sufficient distance between disks, actuator disk theory gives the total power output as:

$$P = \frac{\rho}{2} A \left[(V_0^2 - V_1^2) \left(\frac{V_0 + V_1}{2}\right) + (V_1^2 - V_2^2) \left(\frac{V_1 + V_2}{2}\right) \right] . \qquad \text{(B-1)}$$

Differentiating Equation B-1 with respect to velocity, V_1, and setting the derivative equal to zero yields the maximum power for a given V_0 and V_2.

Solving for V_1 provides the result:

$$\frac{V_0 + V_2}{2} = V_1 \quad . \qquad \text{(B-2)}$$

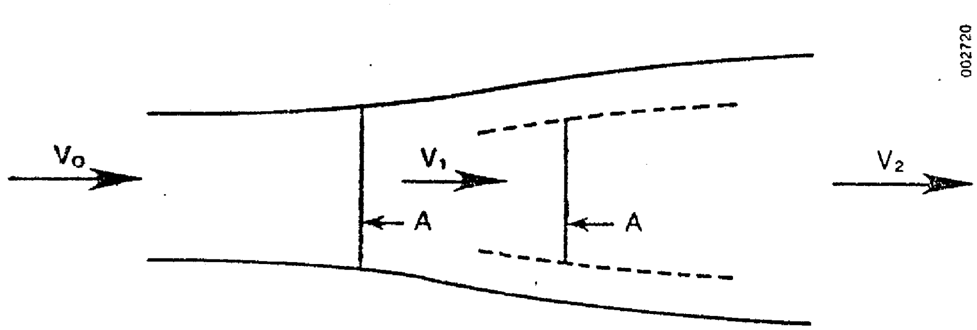

Figure B-1. The Series or Tandem Configuration for Actuator Disks

Substituting V_1 for Equation B-1 and differentiating with respect to V_2 we obtain $V_2 = 0.2\ V_0$ and $V_1 = 0.6\ V_0$, and

$$P_{max} = 0.64 \frac{\rho}{2} A\ V_0^3 \tag{B-3}$$

or

$$C_{P_{max}} = 0.64. \tag{B-4}$$

Thus adding a second actuator disk in series only increases the maximum or ideal power coefficient from 0.593 to 0.64.

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APPENDIX C

DRAG DEVICES AND LIFT DEVICES

Normally power coefficients are based upon the actuator disk area or, in other words, the area in which the active elements operate. Since the amount of material in the actuator disk is more closely related to the area of the active elements than to the area in which they operate, it is instructive to use a power coefficient based on the active area of the elements when comparing different types of active elements.

C.1 DRAG DEVICES

The aerodynamic drag is the force on an object that tends to move it downwind. This force can be used to extract power from the wind. The drag force is proportional to the density of the air and to the square of the relative wind speed. The power output is equal to the product of the drag force and the speed downwind of the object.

Aerodynamic drag, is

$$D = \frac{\rho}{2} (V_0 - U)^2 A C_D$$

where the power output = D × U and

$$P = \frac{\rho}{2} (V_0 - U)^2 U A C_D \quad .$$

The power will obviously be zero when either U = 0 or U = V; hence, there must be some speed U at which the power output will be a maximum. If we differentiate the power with respect to U, we find that the power will be a maximum when U = V/3. Substituting V/3 for U in the equation for power:

$$P = \frac{\rho}{2} \left(V_0 - \frac{V_0}{3}\right)^2 \frac{V_0}{3} A_D C$$

$$= \frac{2}{27} \rho V_0{}^3 A C_D \ .$$

In any practical wind machine, the drag object will not spend more than one half the time moving downwind; therefore the average power will be one half of the maximum.

The maximum drag coefficient based on front area might reach a value of 2. The average power output will then be

$$P_{AV} = \frac{2}{27} \rho V_0{}^3 A \ .$$

If we put the power in coefficient form by dividing it by the power flowing through a stream tube with the same frontal area as the object, we get

$$C_{P_W} = \frac{P}{\frac{\rho}{2} V_0{}^3 A} = \frac{4}{27} \; .$$

The power extracted from the wind by an ideal drag element is

$$P = \frac{\rho}{2} (V_0 - U)^2 \; VAC_D \; .$$

Hence, the ratio of its ideal power output to the power extracted

$$= \frac{\frac{\rho}{2} (V_0 - U)^2 \; UAC_D}{\frac{\rho}{2} (V_0 - U)^2 \; VAC_D} = \frac{U}{V_0} \; .$$

Since P is maximized when $U = V_0/3$, 2/3 of the power extracted from the wind by an ideal drag device is dissipated.

C.2 LIFT DEVICES

Lift is defined as the force normal to the relative wind. If the object upon which the force acts is allowed to move, and if some component of its velocity is in the direction of the lift force, it will produce power. The power produced by an isolated lifting device moving across the wind is

$$P = \frac{\rho}{2} V^3 A \left\{1 + \left(\frac{U}{V}\right)^2\right\}^{1/2} \left(\frac{U}{V}\right) \quad \left(C_L - \frac{U}{V} \; C_D\right) \; ,$$

since

$$P = \left(L - \frac{U}{V} D\right) \frac{V_R}{V} U$$

and

$$L = \frac{\rho}{2} V^2 A C_L \; ,$$

$$D = \frac{\rho}{2} V^2 A C_D$$

$$\frac{V_R}{V} = \left(1 + \left(\frac{U}{V}\right)^2\right)^{1/2} .$$

Typically $U >> V$; therefore,

$$\left\{1 + \left(\frac{U}{V}\right)^2\right\}^{1/2} \simeq \frac{U}{V} \; .$$

Hence,

$$P = \frac{\rho}{2} V^3 A \left(\frac{U}{V}\right)^2 \left(C_L - C_D \frac{U}{V}\right)$$

and

$$C_{P_W} = \frac{P}{\frac{\rho}{2} V^3 A} = \left(\frac{U}{V}\right)^2 \left(C_L - C_D \frac{U}{V}\right) .$$

It is easy to show that

$$\left(\frac{U}{V}\right)_{optimum} = \frac{2}{3} \frac{C_L}{C_D} ,$$

and at optimum $\left(\frac{U}{V}\right)$,

$$C_{P_W} = \frac{4}{27} \frac{C_L{}^3}{C_D{}^2} .$$

We can write C_D as a function of C_L and C_{D_0}, where C_{D_0} is the section drag coefficient at zero lift.

In general,

$$C_D = C_{D_0} + KC_L^n .$$

If we use the general expression, we can show that the maximum power coefficient that can be obtained from the isolated lifting device is

$$C_{PW} = \frac{4}{27} \frac{\left(\frac{3}{K}\right)^{3/n}}{4n^2} (2n - 3)^{(2 - 3/n)} C_{D_0}^{(3/n - 2)} .$$

For an isolated wing with an aspect ratio of 10, typical values might be

$K = 1/30$

$n = 2$

$C_{D_0} = 0.01$

$C_{PW} = \frac{4}{27} [534]$.

Hence, a moderately good lifting device has the potential for extracting 500 times the power that can be extracted by a drag device with the same characteristic area. (That is, the projected area of the lifting blades could be about 1/500 times the area of the drag surfaces for the same lower output.) Practical lift devices do not have power coefficients that approach this level (possibly one half as much), but even their power extracting capacity vastly exceeds that of a drag device.

APPENDIX D

AUGMENTORS

If we use the classical actuator disk theory for the wind machine we obtain the following results:

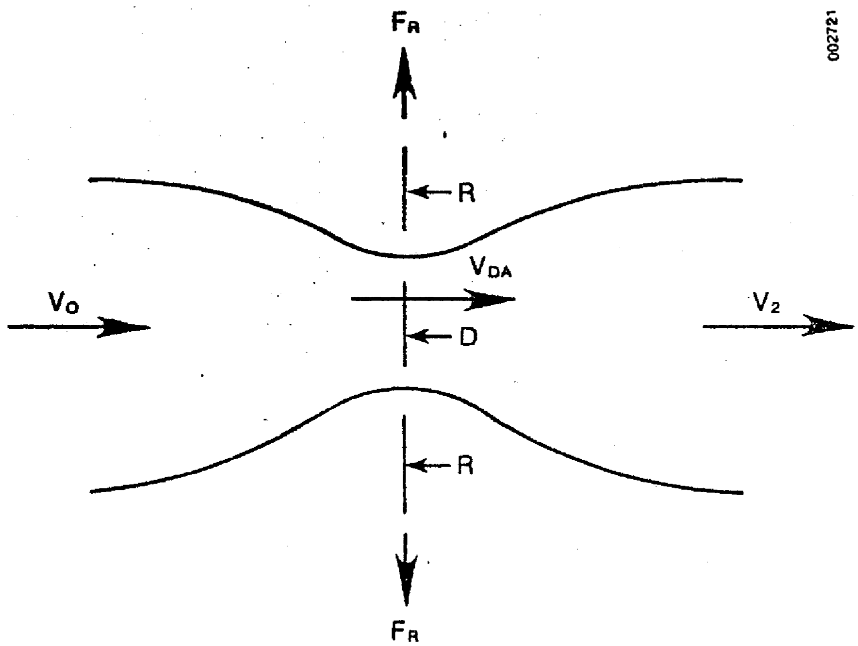

Figure D-1.

From conservation of energy, the power extracted from the wind will be

$$P = \frac{\rho V_D}{2} A_D \left(V_0^2 - V_1^2\right) .$$

The power must also equal the force on the disk D times the velocity through the disk V_D:

$$P = DV_D .$$

Hence

$$D = \rho A \frac{(V_0^2 - V_1^2)}{2} .$$

To conserve momentum,

$$D = \rho V_D A (V_0 - V_1) .$$

Hence

$$\rho V_D A (V_0 - V_1) = \rho A \frac{(V_0^2 - V_1^2)}{2} .$$

If

$$V_0 \neq V_1 \ ,$$

$$V_D = \frac{V_0 + V_1}{2} \ .$$

Hence, achieving an increase in mass flow through an actuator disk operating at zero power does not indicate that output power augmentation can be achieved.

A necessary characteristic of an augmentor can be determined by applying the law of conservation of energy. The power output of the disk is

$$P = TV_D \ ;$$

and the power extracted from the wind is

$$P = RV \ .$$

Since the power output of the disk must be less than the power extracted from the wind, the resultant streamwise force on the wind produced by the power augmentation requires that the resultant force on the wind be greater than the force on the disk. However an augmentor must have some device that produces a streamwise force on the wind as well as the actuator disk. The generalized device is then the contraction diffusion augmentor.

D.1 CONTRACTION DIFFUSION AUGMENTOR

An actuator disk with an area A acts on an augmented flow velocity V_{DA}. In general there will be a force on the disk T and axial forces on the augmentor R. There will also be a radial force F_R on the augmentor.

The equations for power and force then become:

$$P = \rho V_{DA} A \frac{\left(V_0^2 - V_1^2\right)}{2} = TV_{DA} \ .$$

Hence

$$T = \rho\frac{A}{2} \left(V_0^2 - V_1^2\right) \quad \text{as with the classical actuator disk.}$$

For conservation of momentum,

$$(T + R) = \rho V_{DA} A \left(V_0 - V_1\right) \ .$$

Let

$$V_{DA} = \frac{a(V_0 + V_1)}{2} ;$$

then

$$(T + R) = \rho Aa \frac{(V_0 + V_1)}{2} (V_0 - V_1) ,$$

$$= \rho Aa \frac{(V_0^2 - V_1^2)}{2} ,$$

$$= aT ;$$

hence,

$$R = (a - 1)T .$$

This result shows that the augmentor must carry an axial load equal to the ratio of the increase in the area of the stream tube intercepted to the original area, multiplied by the axial force on the actuator disk.

Since axial force can only be produced by physical elements with some radial extent, the augmentor must increase the diameter of the rotor. This result has interesting implications for the tip vane augmentor. If the effective disk loading of the tip vanes is the same as that of the actuator disk, the diameter of the augmented rotor plus tip vanes must be equal to that of the unaugmented rotor that extracts the same power from the wind.

D.2 VORTEX AUGMENTATION

A second style of augmentor uses high velocity and low static pressure in the core of a vortex to augment the flow through an actuator disk. In one general type of vortex augmentor, the actuator disk is submerged in a vortex and power augmentation is potentially achieved by acting upon the high speeds near the vortex core. Since the vortex is a delicate phenemenon that can burst if subjected to an adverse pressure like that existing across an actuator disk, an analysis is quite difficult. However while a number of experiments have been performed, there is no known evidence of an actuator disk submerged in a vortex core producing a lower coefficient greater than can be achieved by an augmented disk.

In another general type of vortex augmentor the low pressure in the vortex core can be used to pump flow through an actuator disk. The following analysis examines the vortex pump augmentor to determine the important parameters. The limitations have not been considered due to the vortex's burst phenomenon.

D.3 VORTEX FLOW

In general, a vortex of strength Γ will exit from a cylinder of radius R_e into a flow. In the outer part of the vortex, the flow will be irrotational and in this region, the tangential velocity will be equal to $\Gamma/2\pi r$, where r is the local radius. This outer flow will surround a rotational core in which the tangential velocity is $r\omega$, where ω is a constant.

The flow properties of the irrotational vortex will be

$$p_s + \frac{\rho}{2}\left[V_A^2 + \left(\frac{\Gamma}{2\pi r}\right)^2\right] = p + \frac{\rho}{2} V^2 \quad .$$

At the edge of the core,

$$p_{sc_o} = p + \frac{\rho}{2}\left[V^2 - V_A{}^2 - \left(\frac{\Gamma}{2\pi r_c}\right)^2\right] \; ;$$

and inside the rotational core,

$$p_{sc} = p_{sc_o} - \frac{\rho}{2}\,\omega^2\left(r_c{}^2 - r^2\right) \; .$$

The total pressure in the core is

$$p_T = p_{sc} + \frac{\rho}{2}\left[(r\omega)^2 + V_{Ac}{}^2\right]$$

where V_{Ac} is the local axial velocity in the core.

The maximum power that could have been extracted from the flow is equal to the total pressure deficit multiplied by the volume flow rate:

$$P = \int_{r=o}^{r=r_c}\left(\left(p_o + \frac{\rho}{2} V^2\right) - \left\{p_{sc} + \frac{\rho}{2}\left[(r\omega)^2 + (V_{Ac}^2)\right]\right\}\right) 2\pi r\, V_{Ac} dr$$

$$= \frac{\rho}{2}\int_{r=o}^{r=r_c}\left[\left(\frac{\Gamma}{2\pi r_c}\right)^2 + V_A{}^2 + r_c{}^2\omega^2 - 2r^2\omega^2 - V_{Ac}{}^2\right] 2\pi r\, V_{Ac} dr \; .$$

Differentiating power with respect to V_{Ac} to find optimum distribution of V_{Ac} gives

$$V_{Ac\ opt}^2 = \frac{1}{3}\left[\left(\frac{\Gamma}{2\pi r_c}\right)^2 + V_A{}^2 + r_c{}^2\omega^2 - 2r^2\omega^2\right] \; .$$

The integrated power then becomes

$$P = \frac{\pi\rho}{15\sqrt{3}\,\omega^2}\{[(\frac{\Gamma}{2\pi r_c})^2 + V_A^2 + r_c^2\omega^2]^{5/2} - [(\frac{\Gamma}{2\pi r_c})^2 + V_A^2 - r_c^2\omega^2]\} .$$

The concept of power coefficient based upon exit area C_{PE} is useful for characterizing the limiting power that could have been extracted from a vortex that exits from a tube:

$$C_{PE} = \frac{P}{\frac{\rho}{2} V^3 \pi r_e^2}$$

$$= \frac{2}{15\sqrt{3}} (C_\Gamma)^3 \frac{r_e}{r_c} \frac{1}{C_\omega{}^2} \{1 + (\frac{V_A}{V})^2 (\frac{r_c}{r})^2 \frac{1}{C_\Gamma^2} + C_\omega^2]^{5/2}$$

$$- [1 + (\frac{V_A}{V})^2 (\frac{r_c}{r_e})^2 \frac{1}{C_\Gamma^2} - C_\omega{}^2]^{5/2}\} .$$

where

$$C_\Gamma = \frac{\Gamma}{2\pi R_e V_o}$$

$$C_\omega = \frac{2\pi r_c{}^2\omega}{\Gamma} .$$

For $0 < C_\omega < 1$,

$$C_{PE} \simeq \frac{2}{3\sqrt{3}} C_\Gamma^3 \frac{r_e}{r_c} [(\frac{V_A}{V_o})^2 (\frac{r_c}{r_e})^2 \frac{1}{C_\Gamma^2} + 1]^{3/2} .$$

For most applications, $(\frac{V_A}{V_o})^2(\frac{r_c}{r_e})^2 \frac{1}{C_P{}^2} \leqslant 1$.

Therefore,

$$C_{PE} = \frac{2}{3\sqrt{3}} C_\Gamma{}^3 \frac{r_e}{r_c} .$$

The average deficit of total pressure in the vortex cone $\overline{\Delta p_T}$ is given by the following expression:

$$\frac{\overline{\Delta p_T}}{\frac{\rho}{2} V_o{}^2} = \frac{2}{3} (\frac{\Gamma}{2\pi r_c V_0})^2 + (\frac{V_A}{V_0})^2 = C_T$$

for

$$\frac{V_A}{V_0} << \frac{\Gamma}{2\pi r_c V_0}$$

$$C_T = \frac{2}{3} (\frac{r_e}{r_c})^2 C_\Gamma{}^2 ,$$

or

$$\frac{r_e}{r_c} = \frac{3}{2} C_T \frac{1}{C_\Gamma}$$

and

$$C_{PE} \simeq \frac{\sqrt{2}}{3} C_\Gamma^2 \sqrt{C_T} \ .$$

This result suggests that circulation is the most important parameter that influences the amount of power extracted by a vortex augmentor. It should be noted that for a two-dimensional lifting body, the circulation coefficient is related to the lift coefficient by the expression

$$2\pi C_\Gamma = C_L \ .$$

Since

$$L = \rho V \Gamma \ ,$$

$$C_L = \frac{L}{\rho \frac{V^2}{2} C} = \frac{\rho V \Gamma}{\rho \frac{V^2}{2} C} = \frac{2\Gamma}{VC} = \frac{\Gamma}{VR} \ .$$

The vortex augmentor problem has been examined by Loth (1978) and his calculations suggest some limits to the amount of augmentation that can be achieved.

D.4 IDEAL ACTUATOR DISK MOVING INTO WIND

A third style of augmentor moves the actuator disk into the wind to increase the mass flow through the disk. Moving the actuator disk into the wind will obviously increase the wind speed seen by the actuator; however moving the disk upwind will require a power input, and this must be subtracted from the gross power to give the net power output. The following analysis examines the ideal frictionless actuator disk moving into the wind.

Gross power output of disk = $(Po - P_1) V_D A$

$$V_D A = \frac{(V + U) + (U + V_1)}{2} A$$

$$= A \frac{(2U + V + V_1)}{2} \ ;$$

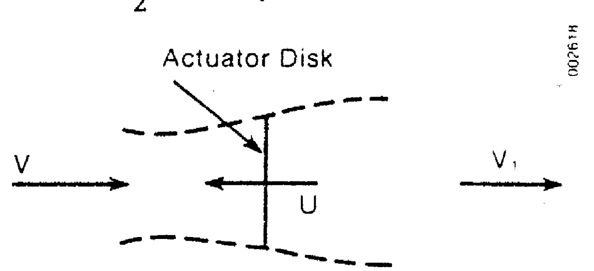

Figure D-2.

$$(Po - P_1) = \frac{\rho}{2}\left[(V + U)^2 - (U + V_1)^2\right]$$

$$= \frac{\rho}{2}(2U + V + V_1)(V - V_1) ;$$

$$\text{Gross power output} = \frac{\rho}{4} A (2U + V + V_1)^2 (V - V_1) .$$

$$\text{Power input} = (Po - P_1) A U$$

$$= \frac{\rho}{2} A (2U + V + V_1)(V - V_1) U .$$

$$\text{Net power} = \frac{\rho}{4} A (2U + V + V_1)(V - V_1)(V + V_1) .$$

To relate to power in original wind stream,

$$C_P = \frac{\text{net power}}{\frac{\rho}{2} V^3 A} = \frac{\left(2\frac{U}{V} + 1 + \frac{V_1}{V}\right)\left(1 - \frac{V_1}{V}\right)\left(1 + \frac{V_1}{V}\right)}{2} .$$

The maximum value of the power coefficient for the ideal machine can vary from $\frac{16}{27}$ at $\frac{U}{V} = 0$ to $\left(\frac{U}{V} + 0.5\right)$ at large values of $\frac{U}{V}$. In practice, there will be some inefficiencies that severely limit the amount of power augmentation that can be obtained.

D.5 DUCTED DISKS

A fourth type of augmentor that is often proposed is the ducted disk augmentor. In this type of augmentor some of the power is extracted from the actuator disk to drive a second actuator disk that is arranged to increase the mass flow through the first disk. The following analysis examines the ideal ducted disk augmentor.

Power = change in total pressure x volume flow rate.

For disk $_{1-2}$, Power=$(P_{T1} - P_{T2}) V_{D1}A_{D1}$.

For disk $_{3-4}$, Power=$(P_{T3} - P_{T4}) V_{D2}A_{D2}$.

Total power = $(P_{T4} - P_{T2}) V_{D1}A_{D1} + (P_{T3} - P_{T4}) V_{D2}A_{D2}$.

By continuity, $V_{D1}A_{D1} = V_{D2}A_{D2}$.

According to Bernoulli,

$$P_T = P_{T1}$$

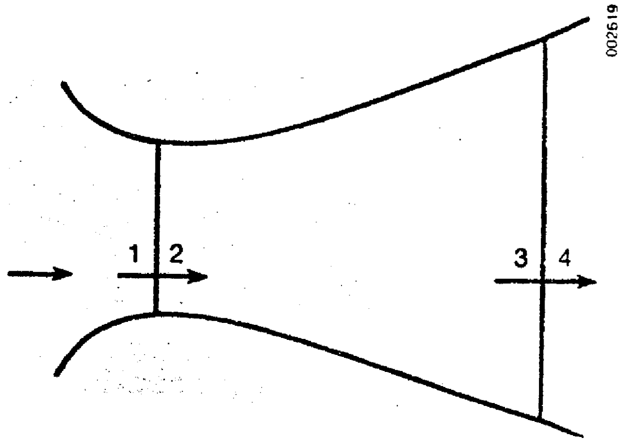

Figure D-3.

$$P_{T2} = P_{T3}, \quad P_{T4} = P_{T5} \ .$$

$$\text{Total power} = (V_{D1}A_{D1}) \ (P_T - P_{T2} + P_{T2} - P_{T5}) = V_{D1}A_{D1} \ (P_T - P_{T5}) \ .$$

Therefore, the presence of the second disk does not affect the power output of the ideal system. As with the single disk, the power is equal to the change in total pressure multiplied in the volume flow rate. The volume flow rate is controlled by the total pressure change and the duct properties.

Reduction of Streamwise Force on a WECS

It is often considered desirable to try to reduce the streamwise force that exists on a WECS. One method that is often proposed is to use some of the power output to drive a thruster arranged to reduce the net streamwise load on the WECS.

Consider two actuator disks, with one disk arranged to extract power from the wind while the other uses some of the power output of the first actuator disk to produce a thrust:

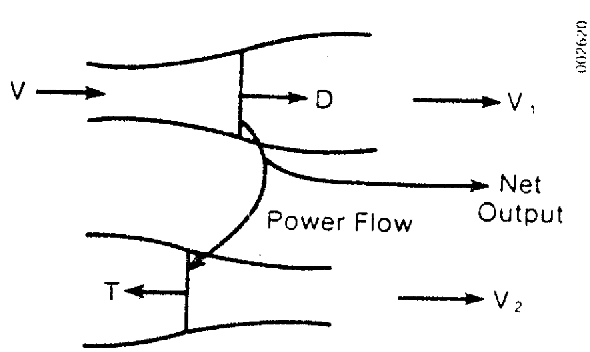

Figure D-4.

$$\text{Net Streamwise Force} = D - T\,.$$

$$\text{Net Power} = D\,\frac{(V_1 + V)}{2} - T\,\frac{(V_2 + V)}{2}\,.$$

$$\frac{\text{Net Power}}{\text{Net Streamwise Force}} = D\,\frac{(V_1 + V) - (V_2 + V)T}{2(D-T)}$$

$$= \frac{(D - T)(V_1 + V) - (V_2 - V_1)T}{2(D-T)}$$

$$= \frac{V + V_1}{2} - \frac{T}{(D-T)}\,\frac{(V_2 - V_1)}{2}\,.$$

Since $V_2 > V_1$ for D Positive, the ratio of $\frac{\text{Net Power}}{\text{Net Drag}}$ will be a maximum when $T = 0$; hence it is not possible to reduce the drag of a WECS by using a thruster. While the analysis was performed for a simple actuator disk, it is equally valid when augmentors are used.

This result is also obvious from the law of conservation of energy because if the streamwise force could be sufficiently reduced it would be possible to obtain sufficient power from the actuator to drive it in still air and create perpetual motion.

D.6 REFERENCE

Loth, J. L., July-Aug. 1978, "Wind Power Limitations Associated with Vortices," J. Energy, Vol. 2, No. 4, pp. 216-222.