THE CONVERSION OF WIND POWER
TO ELECTRICAL POWER

by

James Patrick Needham

Master's Project submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

in

Civil Engineering

APPROVED:

O. J. Blake, Chairman

R. M. Barker

H. L. Wood

December, 1984

Blacksburg, Virginia

ACKNOWLEDGEMENTS

First, the author's wife and his parents, and , should be acknowledged for their patience and encouragement. Second, acknowledgement is due the advisory committee for their review of the paper. In addition, special acknowledgement is due the committee chairman, Professor Oscar J. Blake. Professor Blake helped ease the problem of writing the paper in absentia by clarifying and streamlining school policies, and by reviewing the project several times before its completion. Third, all the people and organizations that supplied information for the project are to be acknowledged.

TABLE OF CONTENTS

Section Page

LIST OF FIGURES

Figure Page

Figure Page

LIST OF GRAPHS

Graph Page

Graph Page

LIST OF TABLES

I. INTRODUCTION

This paper is titled "The Conversion of Wind Power to Electrical Power." Two subject areas are emphasized in the paper. First, an understanding of what wind is, how wind acts, and how to collect, reduce and analyze wind data is developed. And second, the history of windmills is reviewed, windpower systems are classified and described, and six recent windpower systems are reviewed. Although this paper does not get into the real nuts and bolts of windpower systems (for instance the aerodynamics of wind turbine blades or the structrual dynamics of wind turbine towers), it does help to put these subjects in perspective.

Sections II through X are the heart of the paper. These sections are arranged such that the text appears at the front of the section and any figures, graphs or tables appear at the end of the section. The appropriate figure, graph or table is referred to as needed in the text.

Section II contains background information on the atmosphere and on factors affecting the density of air.

Section III describes how the wind is caused by the unequal heating and cooling of the earth. Also a general description of global wind patterns, local wind patterns, low pressure systems and high pressure systems is given.

Section IV gives a brief history of windmills starting with the first windmills over 2000 years ago and leading up to the 1940's. Included in the history are primitive vertical axis windmills, early horizontal axis windmills, post, tower and smock windmills, the famous American water pumping windmill, and the first successful electrical producing windmills.

In Section V the maximum theoretical percentage of power which may be extracted from the wind is derived. The system efficiency is introduced and the basic equation for the power output of a windmill is given.

Section VI explains why the use of windmills is limited to rural areas. Excerpts from the Wind Energy Resource Atlas are given. A procedure for selecting a wind power site is outlined. And the concepts of wind shear, turbulence, boundary layer, and wind gusts are presented in regards to site selection.

In Section VII the methods of gathering wind data are described. This includes the use of switch closure, light chopper and generator anemometers, wind direction sensors which use potentiometers, strip chart recorders and digital data loggers.

Section VIII is an example of wind data reduction and analysis. Wind speed and wind direction data taken at three hour intervals over a one year period is reduced using a computer, graphed, and the important features discussed.

In Section IX four classifications of windmills are described and the advantages and disadvantages of each listed. The four classifications are: (1) low speed, drag-force, (2) low speed, horizontal axis, (3) high speed, horizontal axis, and (4) high speed, vertical axis.

Section X is a review of six windpower systems. The systems reviewed are: (1) Jacobs Model 1023, (2) Enertech 44, (3) ESI-54-S, (4) DOE/NASA MOD-OA-4, and (5) DOE/NASA MOD-2. Included in the review are pictures and schematics of each system. A description of each system's component parts is given. And two graphs are drawn for each system. The first graph plots system output versus windspeed and system efficiency versus windspeed. The second graph plots system output for a year versus windspeed using the wind data analyzed in Section VIII.

II. THE EARTHS ATMOSPHERE & THE DENSITY OF AIR

The earths atmosphere is composed of four layers: the troposphere, the stratosphere, the ionosphere, and the exosphere. We are only concerned with the troposphere which extends from the earths surface up to about 5 miles at the poles and about 10 miles at the equator. The upper limit of the troposphere increases during the summer and decreases during the winter. This upper limit is defined as that point where the temperature of the air stops decreasing with increasing height. The temperature decrease within the troposphere is approximately 3 to 4 degrees Fahrenheit per 1000 feet. The temperature at the top of the troposphere is approximately -50 degrees Fahrenheit above the poles, while it is approximately -100 degrees Fahrenheit above the equator. Most of the air in the atmosphere is contained in the troposphere.[7,13]

Clean, dry air has a molecular composition (by volume) of approximately 78% nitrogen, 21% oxygen, 1% argon and trace amounts of other gases. Also contained in the atmosphere are water vapor, dust, pollen, microbes, and salt from the oceans.[7]

The density of air varies. Factors which should be taken into account when determining the air density are (1) the atmospheric pressure and (2) the air temperature.[32] The atmospheric pressure is closely related to the elevation above sea level while the air temperature is closely related to the time of year. Another factor which only sightly affects the air density is the relative humidity. In the atmospheric pressure range of 1 atmosphere (14.70 psia), air may be treated as an ideal gas.[13] Therefore:

rho = P / (T * R)   where,   Eqn. 1

rho = density of air, (lbm/ft^3)

P = atmospheric pressure, (lbf/ft^2)

T = air temperature, (degrees Rankine = degrees Fahrenheit + 460 degrees)

R = gas constant for a particular gas, in this case air = r/m, (ft*lbf)/(lbm*degrees R)

r = universal gas constant
= 1545 (ft*lbf)/(lbmole*degrees R)

m = molal mass, (lbm/lbmole mixture)

EXAMPLE 1:

For a standard day at sea level, (P)o = 2117 lbf/ft^2,
(T)o = 520 degrees R, (R)o = 53.33 (ft*lbf)/(lbm*degrees R)[13]

Notes: 1. The subscript ( )o shows that these are standard conditions.
2. See Example 2 for the determination of (R)o.

(rho)o = (2117)/(520*53.33) = 0.0763 lbm/ft^3

Example 2 will show that the addition of water vapor to air does not appreciably change the density of the air, as long as the temperature and atmospheric pressure are the same before and after the addition of the water vapor. In effect, the water vapor, or humidity as it may be called, is displacing air to maintain the given pressure. And in fact, the displaced air weighs more than the water vapor which replaces it.

<u>EXAMPLE 2:</u>

A. Dry air at (P)o=2117 lbf/ft^2, (T)o=520 degrees R

Molecular Component	Volume Fraction		Molal Mass		Mass per lbmole mixture	Mass Fraction
	lbmole / lbmole mixture		lbm / lbmole		lbm / lbmole mixture	lbm / lbm mixture
Nitrogen	0.78	*	28.02	=	21.86	0.754
Oxygen	0.21	*	32.00	=	6.72	0.232
Argon	0.01	*	39.9	=	0.40	0.014
	Sum=1.00				m=28.97	Sum=1.000

(R)o = r/m = 1545/28.97 = 53.33 (ft*lbf)/(lbm*degrees R)

(rho)o = 2117/(520*53.33) = 0.0763 lbm/ft^3

B. Saturated air at (P)o=2117 lbf/ft^2, (T)o=520 degrees R:

First determine the partial pressures of the water vapor and air. From psychrometric chart:

(P)w = 36 lbf/ft^2

so, (P)a = 2117-36 = 2081 lbf/ft^2

Next determine the mole fractions (by volume) of water vapor and air.

(x)w = 36/2117 = 0.017

(x)a = 2081/2117 = 0.983

Therefore, the molal mass of the mixture is:

m=(28.97*0.983)+(18.02*0.017)=28.78 lbm/lbmole mixture

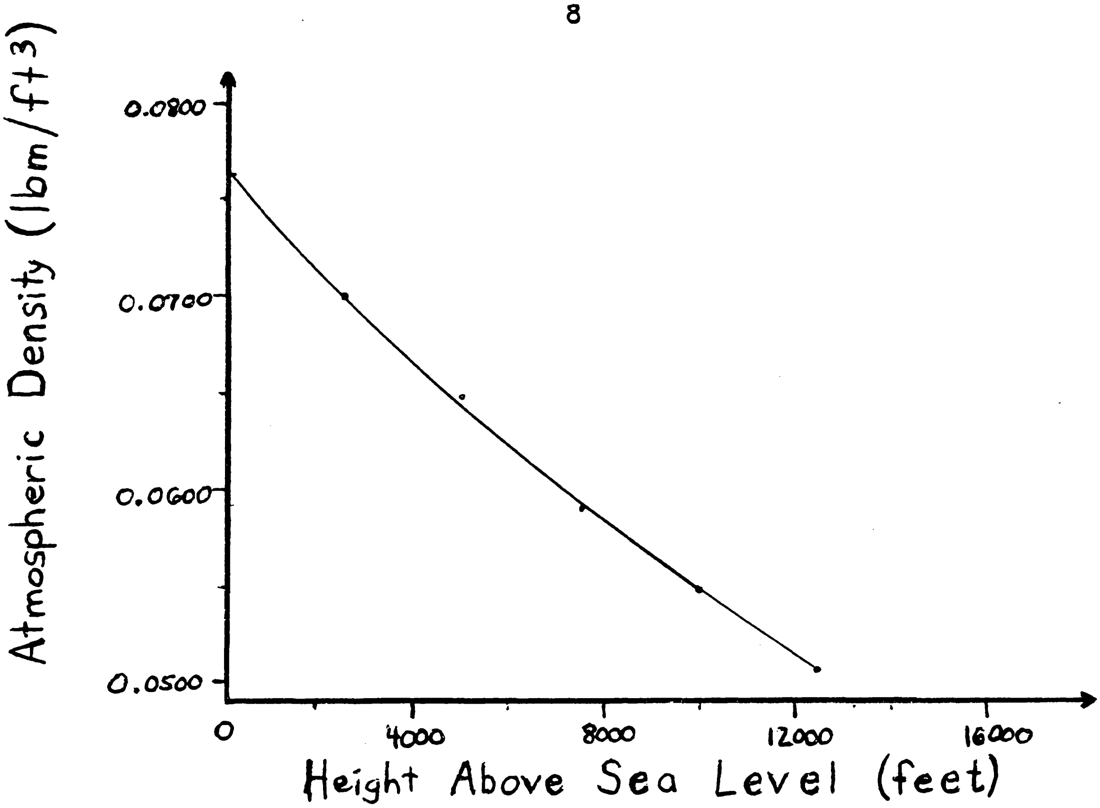
and,

R = 1545/28.78 = 53.68 (ft*lbf)/(lbm*degrees R)

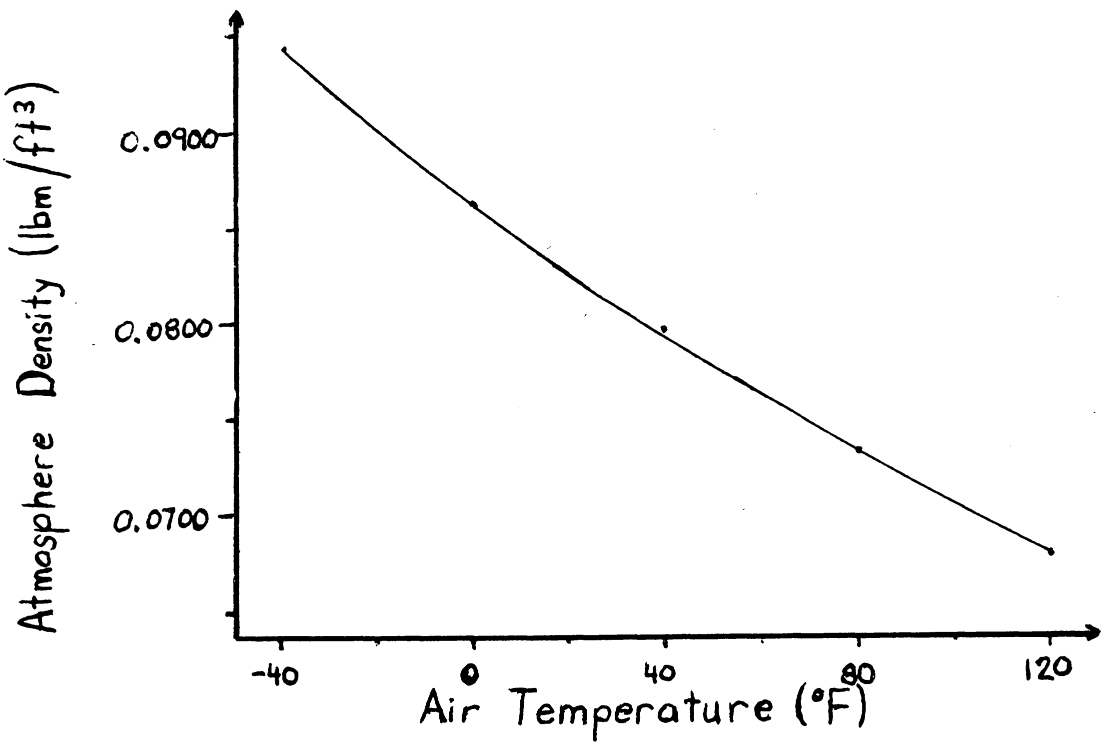
rho = 2117/(520*53.68) = 0.0758 lbm/ft^3

From this example, it can be concluded that the error induced by neglecting the relative humidity when determining the density or air is very small (on the order of 1%).

Graphs 1 and 2 show the approximate variation of atmospheric density with height above sea level and with air temperature, respectively. Note that these are not straight line relationships.



GRAPH 1 - Approximate Variation of Atmospheric Density with Height Above Sea Level for (T)o=60 degrees F.[32]



GRAPH 2 - Approximate Variation of Atmospheric Density with Air Temperature for (P)o=14.70 psia (i.e.,sea level).[32]

III. THE WIND

Wind is the natural movement of the air in the atmosphere. In theory, the wind blows from regions of high atmospheric pressure to regions of low atmospheric pressure. But, in certain instances the wind can blow parallel to isobars. These pressure differentials within the atmosphere are due to the unequal heating and cooling of the earth and its atmosphere. Global wind patterns exist which are largely due to the rotation of the earth. Local wind patterns also exist, for example, land and sea breezes. In most cases, both global and local wind patterns change with the seasons.

The suns radiation heats the earth and its atmosphere. Sunlight is composed of approximately 41% visible light, 9% ultraviolet and shorter wavelength radiation, and 50% infrared and longer wavelength radiation. Most of the ultraviolet and shorter wavelength radiation is absorbed by ozone and other gases. About 33% of the energy is reflected back to space by atmospheric gas, dust and clouds, while the earths surface reflects back about 5%. Water vapor and carbon dioxide absorb some of the remaining insolation, mostly at the infrared and longer wavelengths. The remaining solar radiation is either absorbed by the atmosphere or reaches the earths surface and is absorbed by water, soil, rock, or vegetation. These materials heat up and then re-emit radiation at infrared wavelengths. It is apparent that the atmospheric heating or cooling is dependent on many factors including cloud cover, dust content, humidity, surface reflectivity, surface cover, and time of year.[7] There is also a daily heating and cooling cycle corresponding to night and day. Atmospheric winds are a result of this highly variable, unequal heating and cooling of the earths atmosphere. See Graph 3 and Figure 1.

The global wind pattern is shown in Figure 2. At the equator there is a permanent low pressure center while at the poles there are permanent high pressure centers. Hot air at the equator tends to rise and flow towards the poles, while cold air at the poles stays near the ground and flows toward the equator. The rotation of the earth causes the Coriolis force which curves the path of the global winds. The trade winds are the most consistent winds, and may blow for days or weeks with little change in strength or direction. They hold heavy air moving near the surface, towards the equator. Higher up, the lighter air moving towards the poles sinks at approximately 30 degrees latitude. This air spreads out with some of it forming the trade winds, and the rest changing direction and heading towards the poles to form the prevailing westerlies. The prevailing westerlies of the southern hemisphere are almost as persistant as the trade winds, but the prevailing westerlies of the northern hemisphere are not as persistant due to the large land masses. At about 60 degrees latitude the prevailing westerlies meet the polar easterlies and rise to form jet streams about 6 or 7 miles above the earth. The heat of the prevailing westerlies is lost in the polar region. The air becomes heavy, sinks and becomes part of the polar easterlies literally pushing air out of the poles.

The most violent and varied weather takes place in the mid-latitude, mixing cell between 30 degrees latitude and 60 degrees latitude. This is particularly true in the northern hemisphere. This happens because the warm tropical air and the cold polar air meet in this region.[24]

It should be noted that winds are named by the direction from which they come. For example, the west wind blows from the west to the east. One exception to this is the onshore and offshore winds. Onshore winds blow from off the shore to on the shore, while offshore winds blow from on the shore to off the shore.[24]

A cyclone is a very large mass of low pressure air in which the wind blows inward and the pressure is lowest at the center. Cyclones, more commonly called lows, usually bring "bad" weather. In the northern hemisphere they blow counterclockwise, while in the southern hemisphere they blow clockwise. A anticyclone is a very large mass of high pressure air in which the winds spiral outward and downward. Anticyclones, more commonly called highs, usually bring "good" weather. In the northern hemisphere they blow clockwise, while in the southern hemisphere they blow counterclockwise.[13]

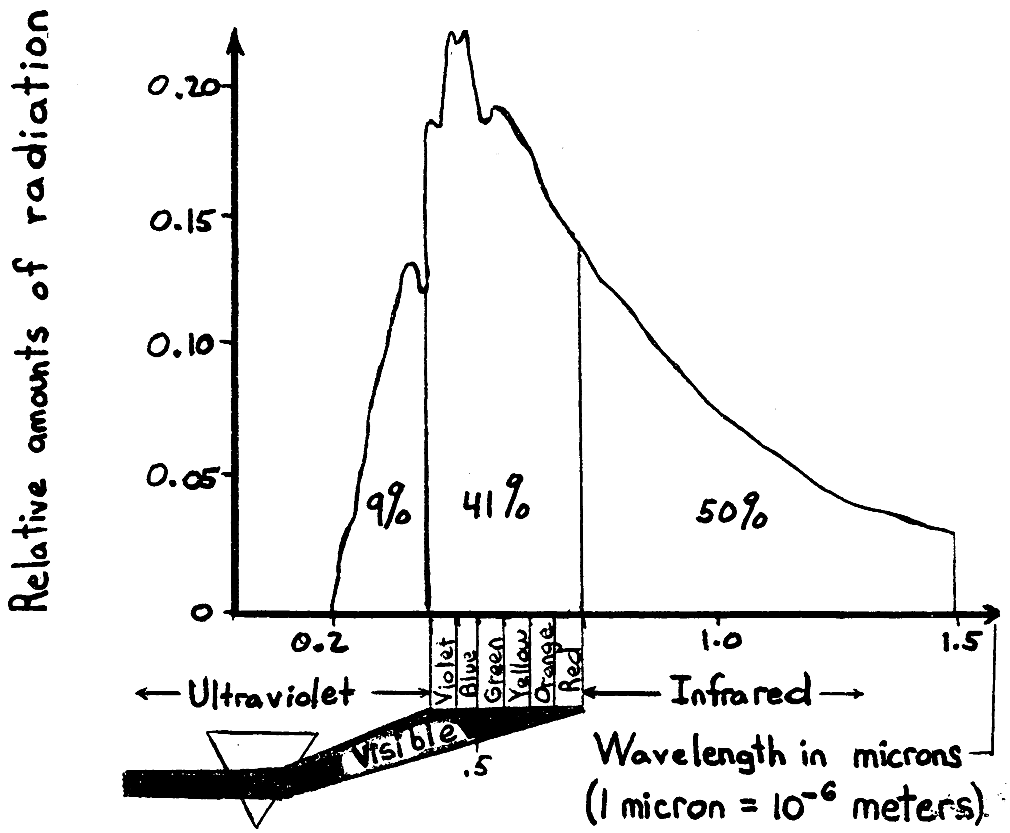
Geostrophic winds do not blow from regions of high atmospheric pressure to regions of low atmospheric pressure. Instead they blow parallel to isobars with a constant speed proportional to the air pressure gradient. These winds result when the Coriolis force and the pressure gradient force cancel each other out exactly. But, they are limited to heights at which the surface friction of the earth is negligible. This is above the so called planetary boundary layer which extends anywhere from 1500 feet to 3000 feet above the earths surface. The surface roughness of the oceans is less than that of land. Therefore, the geostrophic wind is less disturbed by the oceans and the average wind speed tends to be higher over the oceans.[7,21]

Local wind patterns also exist. For example, each major land area has its own wind pattern due to factors which include the lands latitude, size, shape, topography, and distribution of coastal and inland water. Within a land areas wind pattern there are smaller local wind patterns, such as land and sea breezes or mountain and valley breezes. These smaller local wind patterns are also caused by the unequal heating and cooling of the atmosphere.[32]

Land and water, heat and cool at differant rates. This is because the specific heat of water is about two-and-a-half times that of land. In addition, heat is distributed to lower depths of the oceans by turbulent stirring, while only a shallow depth of soil and rock is effected by heating and cooling. For these reasons, the air temperature over land experiences greater extremes during night and day and during summer and winter than does the air over the oceans. These temperature differances can result in land and sea breezes in coastal areas. The breezes are usually onshore during the day, and offshore during the night.[32] See Figure 3. A calm period in duration from several minutes to several hours may occur when the land and sea breezes shift.

Mountain and valley breezes are another example of smaller local wind patterns which help make up the overall wind pattern of a major land area. Winds which blow up mountain slopes are called anabatic winds, while winds which blow down mountain slopes are called katabatic winds. Examples of katabatic winds are the Chinook winds of the Pacific Northwest United States, and the Santa Ana winds of Nevada, Arizona and Southern California.[32] See Figure 4.

Global and local wind patterns, and many factors which effect the wind are well known. Overall wind and weather patterns are also well known. For example, winter will be cold and windy while summer will be hot and humid. But, the actual wind and weather can only be accurately predicted a few days in advance, at best. And even though certain events can be predicted within limits, these events can not be pinpointed until they are about to happen or actually are happening. For instance, June to November is known as hurricane season, with most hurricanes occurring during the month of September. But, when and where a hurricane will form, how strong it will be, and what path it will take are unknown until the hurricane actually takes form, grows and moves. This uncertainty concerning the wind and weather has led to the use of probability theory in an attempt to accurately predict what the wind distribution of a particular site will be.



GRAPH 3 - Spectral Distribution of Extraterrestrial Solar Energy and the Dispersion of White Light by a Glass Prism.[27]

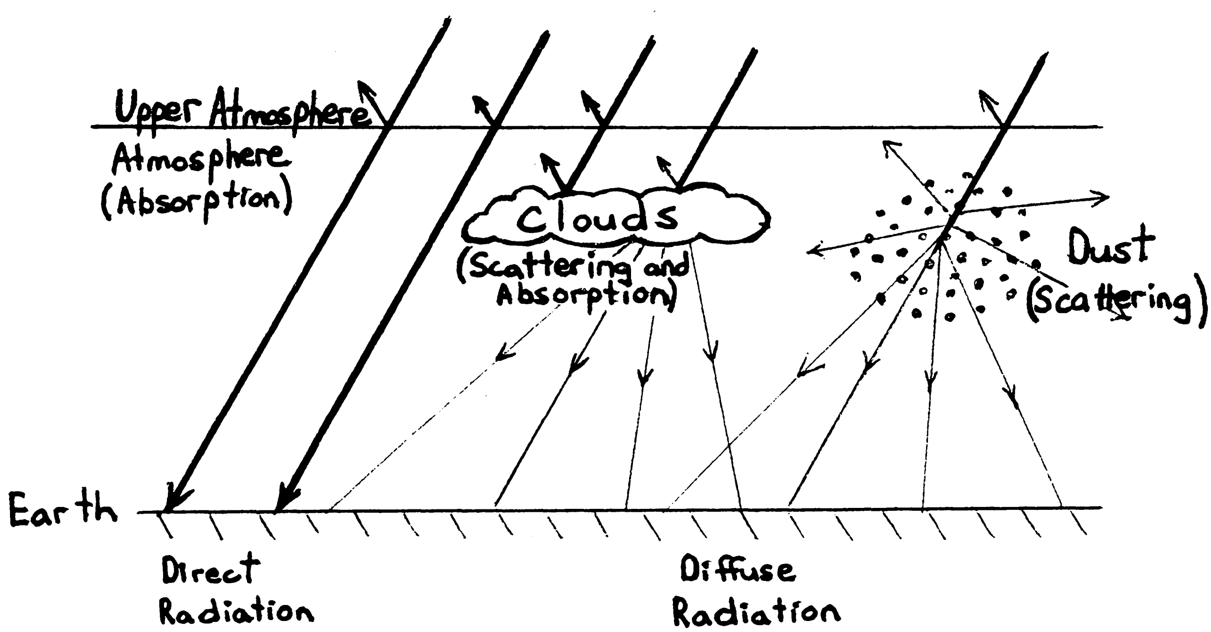


FIGURE 1 - Losses of Solar Radiation as it Penetrates the Atmosphere.[17]

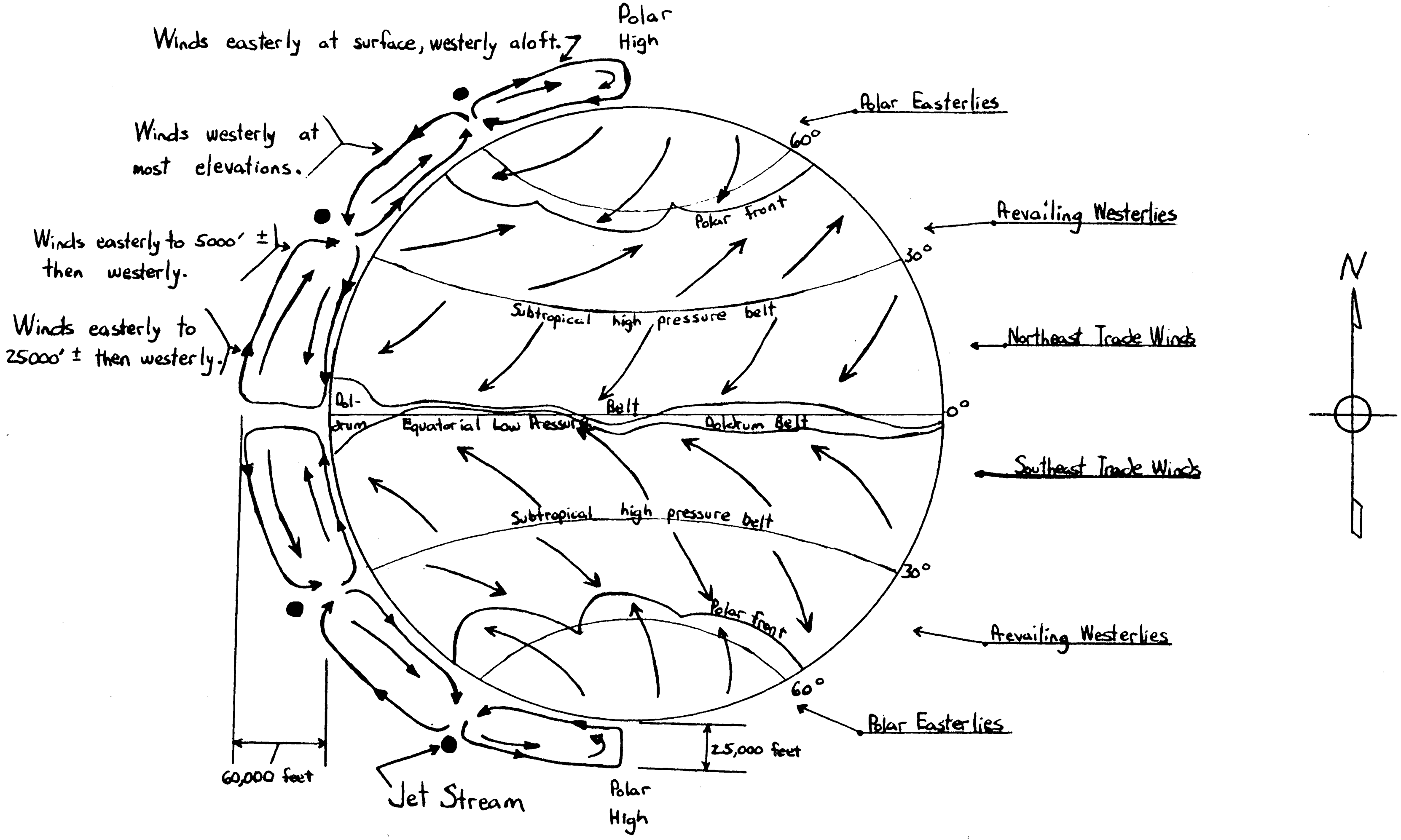


FIGURE 2 - Global Wind Patterns.[24,31]

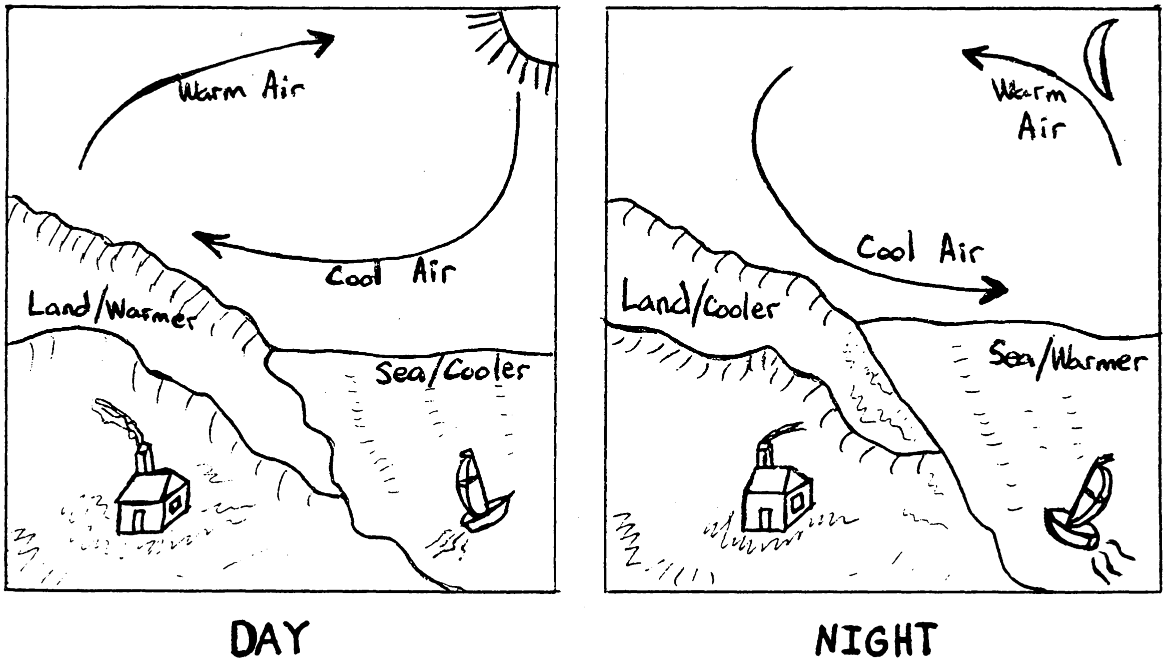


FIGURE 3 - Land and Sea Breezes.[9]

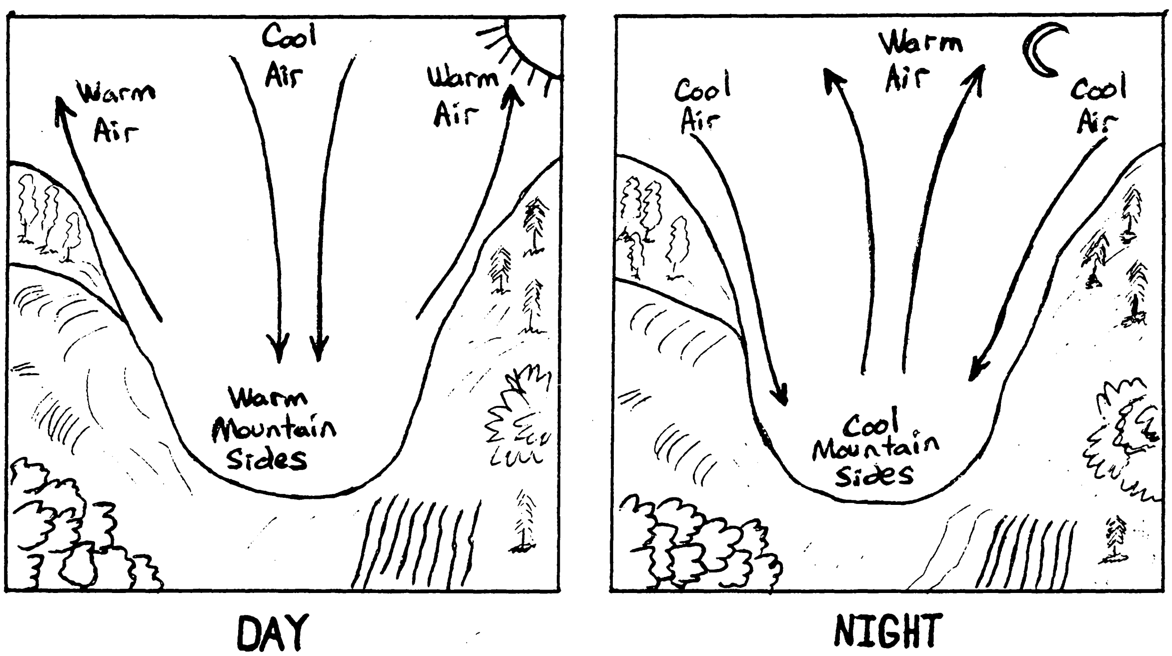


FIGURE 4 - Mountain and Valley Breezes.[9]

IV. THE HISTORY OF WINDMILLS

It is believed that the Chinese, Babylonians or Persians built the first windmills over 2000 years ago. These were vertical axis windmills which probably evolved from the timeless vertical-post horizontal-beam mill pushed or pulled around by men or animals walking in a circular path. One advantage of most vertical axis windmills is that they can respond to wind from any direction.[3] See Figures 5 and 6.

It is reported that the world's oldest windmills are in Afghanistan (called by geographers "The Roof of the World"). These vertical axis windmills are shielded by walls. The wind rushes in slots in the walls to turn the sails like a revolving door. A disadvantage of these primative vertical axis windmills is that they are close to the ground where the wind is the weakest.[35]

The use of these vertical axis windmills subsequently spread throughout the Islamic world. By 700 A.D. they were a common sight in the Near East. These early windmills were used to grind corn, pump water, and control drifting sands.

Later, in the Mediterranean region, the first horizontal axis windmills appeared. From Greece to Portugal the wind's power was tapped by wind wheels made of up to ten wooden booms and rigged with light linen sails. These windmills could not be rotated to face the wind, so they were built facing the prevailing winds. Figure 7 shows a windmill of this type which is still used on one of the Greek islands for grinding grain. [9]

In approximately 1100 A.D. the first windmills appeared in northern Europe. BY 1400 they were a common sight, said to be spurred on by returning Crusaders.[9] All over Europe the windmill became the typical prime mover for grinding grain and corn, pumping water, papermaking, pressing oil from seeds, grinding pigments and chalk, and sawing wood. The Dutch took the lead in improving the design of windmills, although the English would probably dispute this.

Windmills were widely used in Europe until the Industrial Revolution began in the mid-19th century. Each was designed and built not only with its particular site and wind conditions in mind, but with machinery fashioned for a specific work purpose. Most were erected long before the Industrial Revolution. In overall structure, there are three main types of European windmills: post, tower, and smock. These windmills were made sturdier than those of the Mediterranean Region because of the stronger, variable and gusty winds of northern Europe.[24]

Post mills, the earliest, were always made of wood. At first perfectly horizontal windshafts were used but this caused excessive wear on the front wooden bearing block. It was discovered that by angling the shaft the thrust was carried by the rear bearing block which could be made larger.[24] This is shown in Figure 8. Figure 9 shows an authentic reproduction of a post mill in Williamsburg, Virginia. The mainpost is a 2' x 2' made of oak from West Virginia that was a sapling in 1675. It was often necessary to manually turn post mills to face the wind.[35]

The tower mill, often called the Dutch mill, was developed in the 15th century. It had a fixed tower and a rotatable cap. This was a significant step because the tower could be built to practically any height. A subsequent invention, the fantail, was also made so that the sails would automatically turn to face the wind. The fantail is set at 90 degrees to the main sails and through a set of gears, with a ratio of several thousand to one, keeps the windmill facing into the wind.[24] Figure 10 shows a tower mill in England that has a brick tower and a rotatable cap. This particular tower mill was built by the once famous firm of millwrights, Whitmore and Binyon.

The smock mill was a variation of the tower mill. The differance being in construction material. It usually had a stone base with a wood frame upper section covered in weather boarding. Figure 11 shows King's Mill, a smock mill in England which has been restored and opened to the public. It features a stone base, a wooden tower and a rotatable cap.[3]

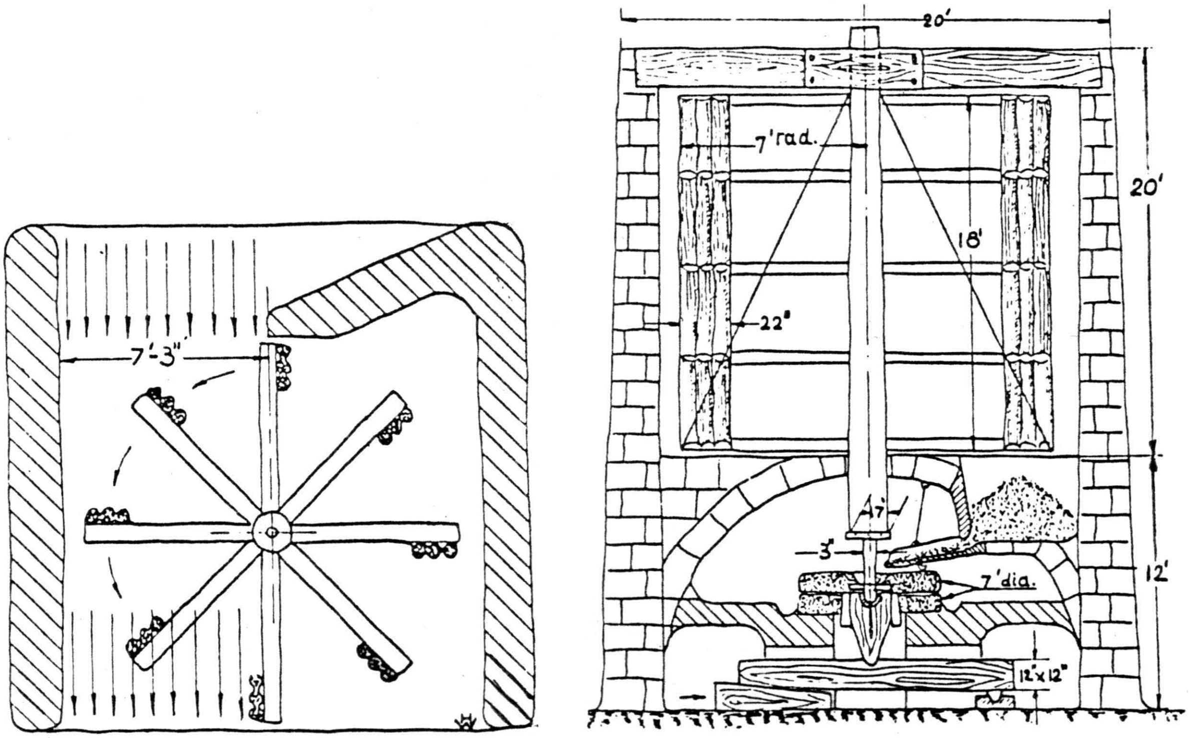
As the windmill structure developed, the sails also developed. The earliest sails used in Europe, common sails, were wooden frames covered with cloth. Rotational speed of the sails was controlled by the area of cloth exposed and by a brake. The major disadvantages were that the miller had to stop the windmill to adjust the sails and that the cloth was hard to work with in wet and/or cold weather. Also, if a strong wind came up and the miller was unable to brake, the runaway sails could vibrate the windmill to pieces. In 1772, the spring sail was invented. This consisted of a series of shutters, connected by a bar and arranged like a venetian blind. The shutters were opened or closed by a spring to control sail speed. But the mill still had to be stopped to adjust the shutters. This problem was solved in 1807 with the invention of patent self-reefing sails. These were similar to spring sails but the shutters were controlled automatically by a suspended weight. A problem with all sails was that they often broke.[24]

Many of the European type windmills were built along the United State Atlantic Coast in the 1600's. But as inland travel and development expanded, watermills replaced these windmills.[24]

In the 1860's, the American windmill boom started. Factory-built water-pumping windmills were produced by the tens-of-thousands. The expanding railroad system needed water tanks filled, and sodbusters needed household water as well as water for their livestock. These windmills were of all metal construction, with multi-vaned wind wheels of 12 to 16 foot diameters. Most used a tail blade to keep the blades pointed into the wind. Two main types of governors were used. The first had movable blades which acted like shutters and were controlled by a centrifugal governor. The second had fixed blades with the tail blade fixed so that as the wind pressure increased the blades would be turned out of the wind. The windshaft was connected to a set of gears and a cam. The cam drove a connecting rod up and down which in turn operated a pump at the base of the tower. These were slow-speed machines, but in a 15 mph wind a 12 foot diameter wind wheel could produce about 1/6 horsepower and could pump 35 gallons of water per minute to a height of 25 feet. The moderate rotational speeds simplified design so that today there is little room for improvement in this type of windmill. These machines were so durable, that with minimal maintenance they would literally last a lifetime. The American water pumping windmill, as seen in Figure 12, is still produced and used worldwide.[24]

In the early 1900's, wind powered, electical, d.c generators started to appear. To produce electricity, fast turning propellers were required. This resulted in the use of 2 and 3 bladed windmills. Two of the more highly thought of generators of this time were the Jacobs and the Wincharger.[18] Marcellus Jacobs combined a 15 foot, wooden propeller and a smooth-working flyball governor with a massive 440 pound battery charging generator. His 32 volt generator was rated at 2500 watts and 110 volt generator at

3000 watts. Figure 13 shows a Jacobs 3 kW wind generator in which rated output occurred in a 27 mph wind. He also sold a 50 foot tower which could be installed by 2 men in two days. The Wincharger, shown in Figure 14, is a 12 volt electrical battery charging generator with a 6 foot diameter, two bladed, wood propeller. Rated output was 200 Watts in a 20 mph wind. As the Rural Electrification Administration (REA) brought power to rural areas in the 1950's, fuel fired generating plants replaced windpower. At the peak, 6 million small windmills, both electrical generating and water pumping, were operating in the United States. But, today only a small fraction of this number are operating.[24]



PLAN

CROSS SECTION

FIGURE 5 - Drawing Showing How Persians Built Windmills in Seistan.[35]

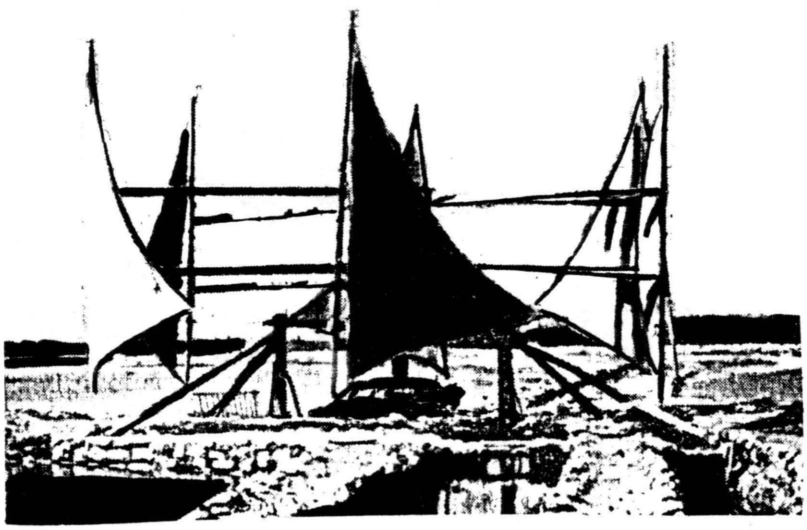


FIGURE 6 - Primative Vertical Axis Windmill.[3]

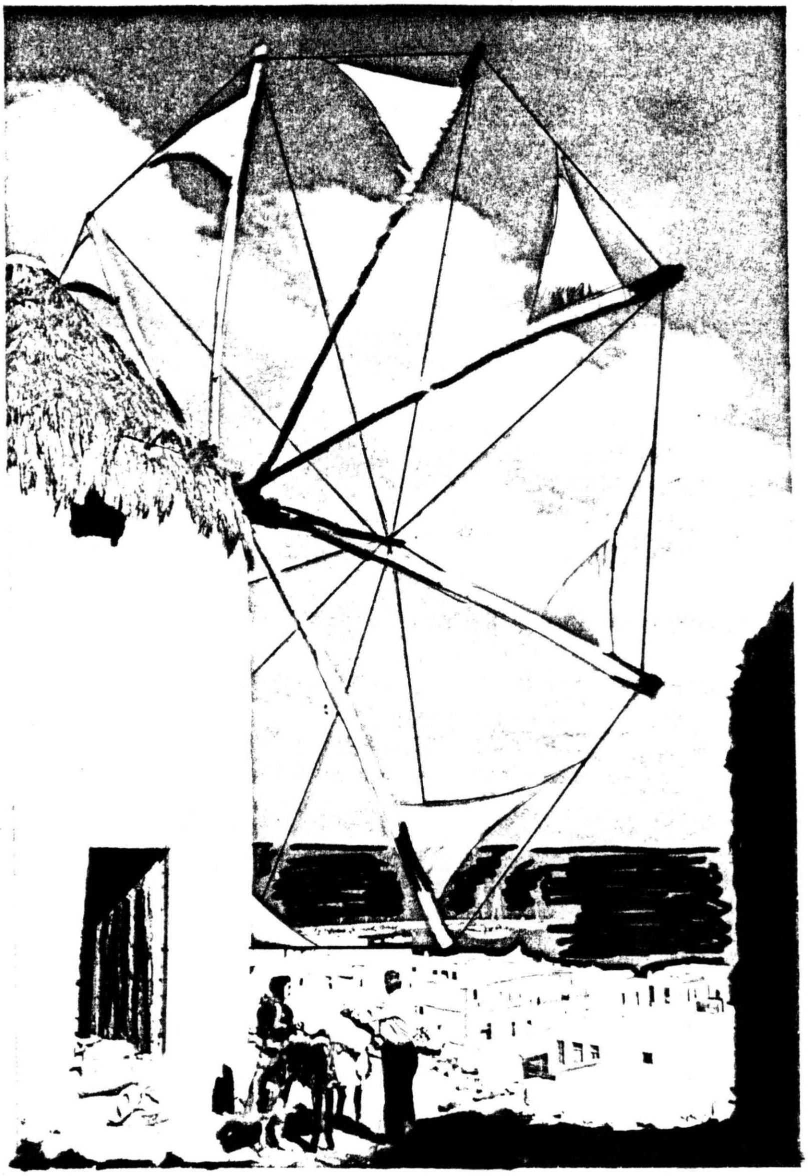


FIGURE 7 - Horizontal Axis Windmill Typical of Early Windmills in the Mediterranean Region. [9]

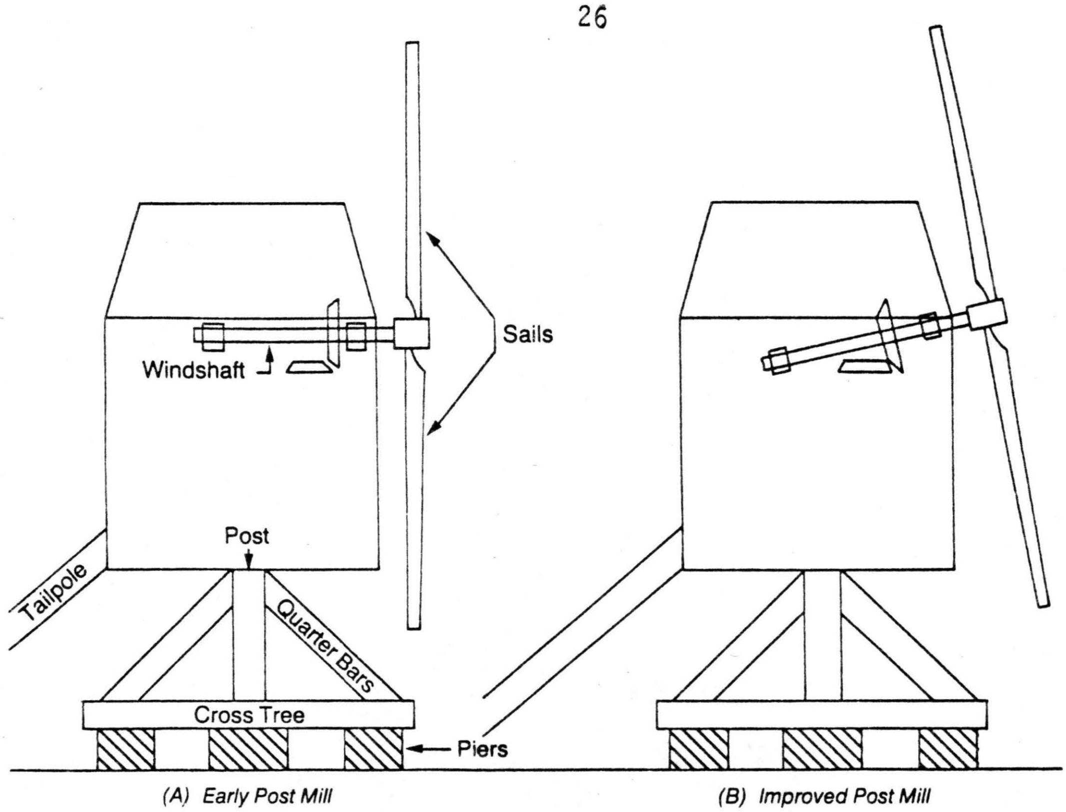


FIGURE 8 - Basic Layout of a Post Mill.[24]

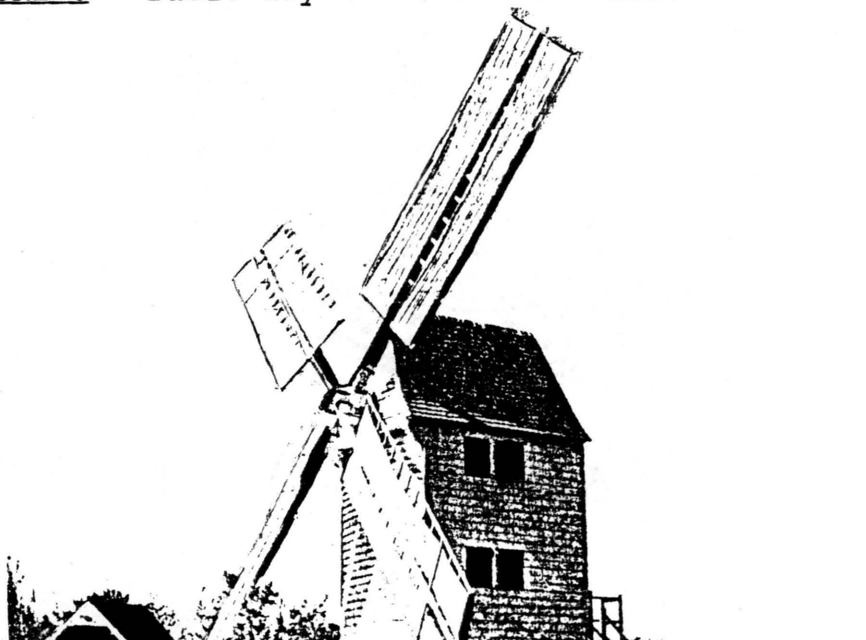


FIGURE 9 - The Reconstructed Robertson Post Mill at Williamsburg, Virginia.[35]

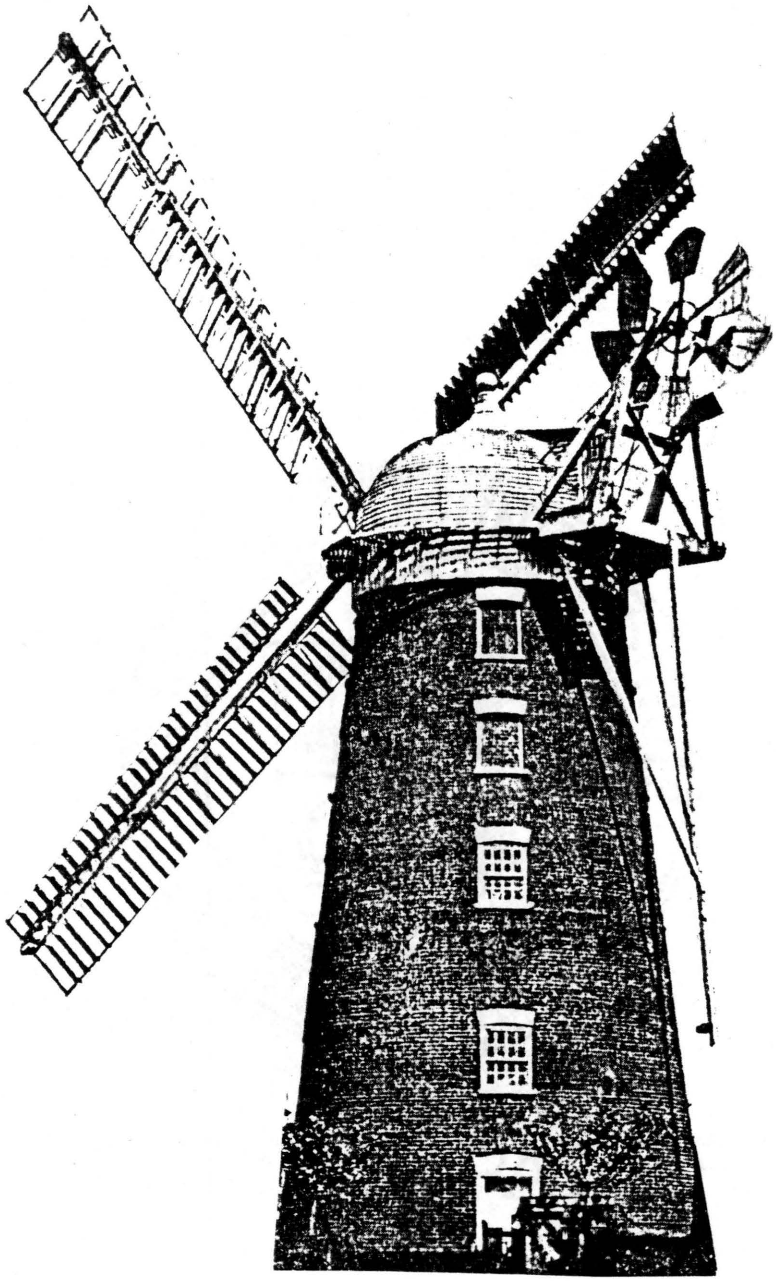


FIGURE 10 - Tower Mill in England. [38]

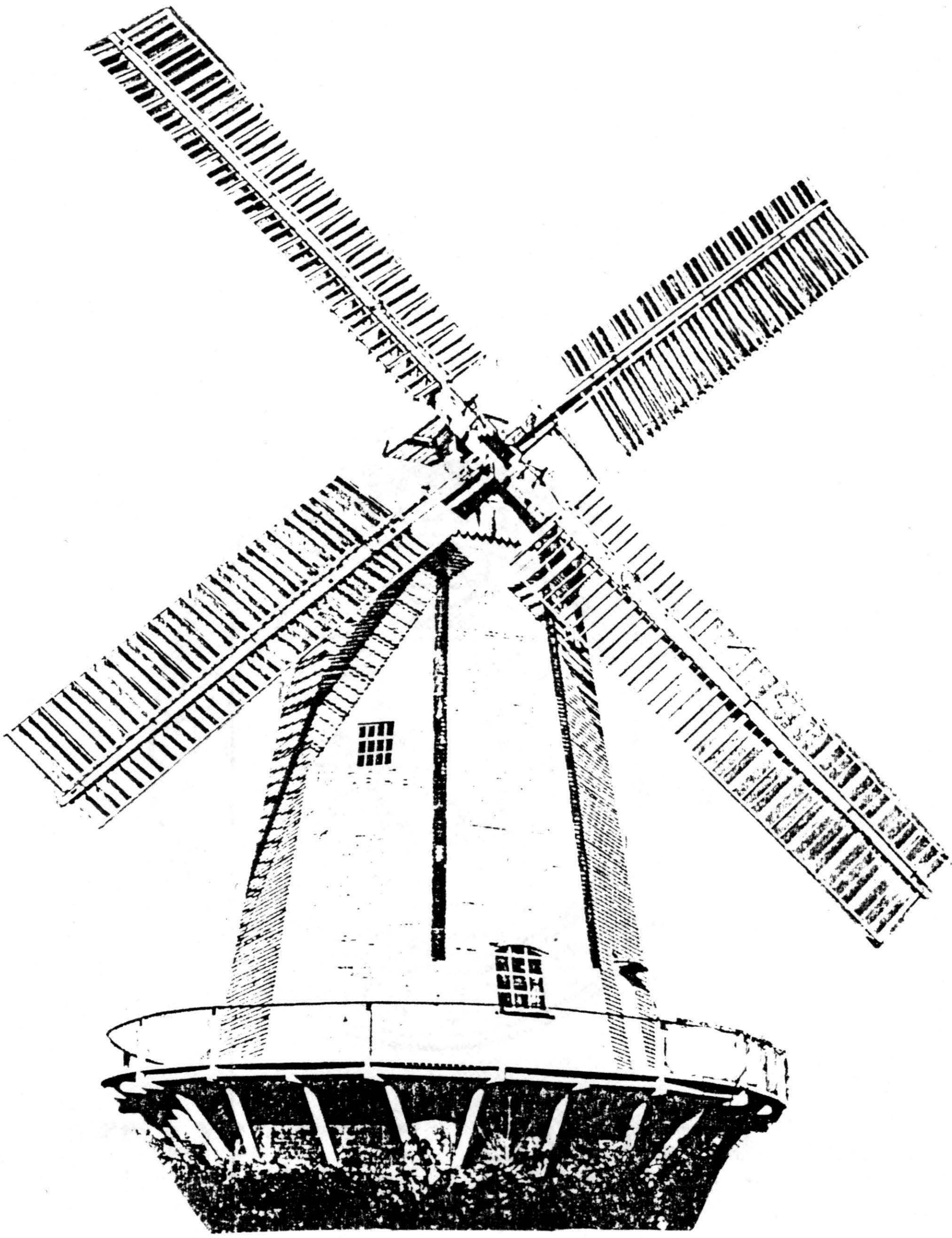


FIGURE 11 - Smock Mill in England.[3]

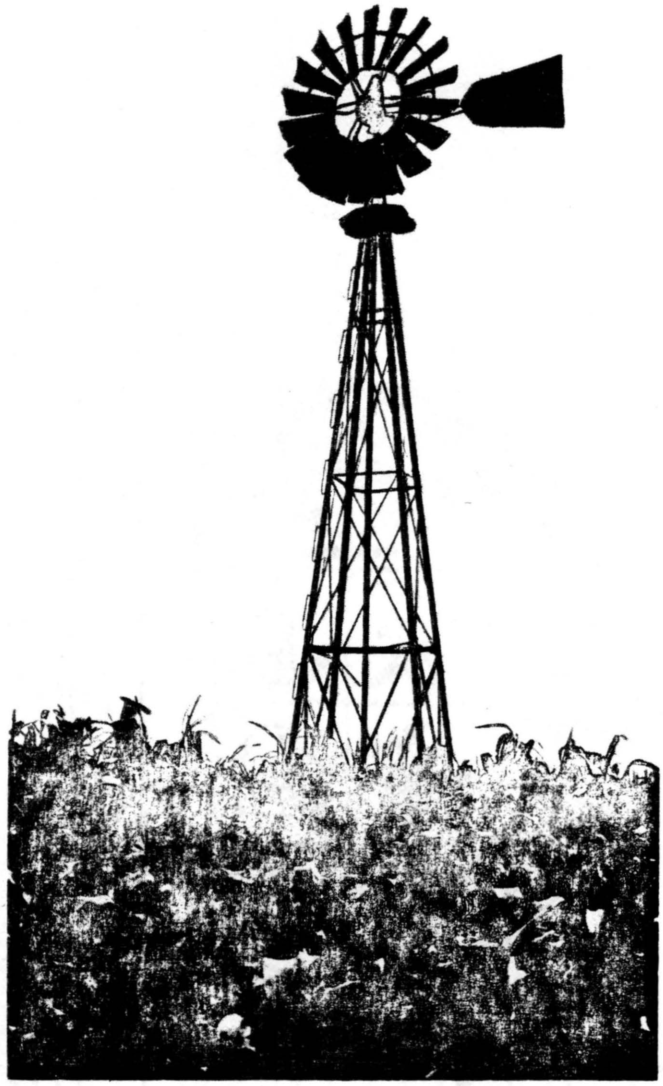


FIGURE 12 - American Water Pumping Windmill.[14]

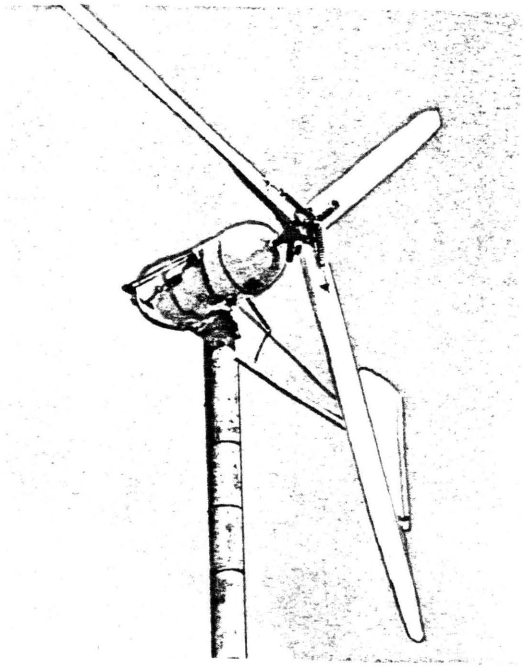


FIGURE 13 - One of the Early Jacobs 3 kW Wind Generators.[32]

FIGURE 14 - Windcharger Wind Generator.[24]

V. THE THEORY OF WINDPOWER

A. Betz of the Institute of Gottingen, Germany developed the following theory in approximately 1930.[15] The theory derives the maximum power that theoretically can be extracted from a stream of free flowing air. Figure 15 shows an idealized stream of free flowing air which passes through a rotor.

ASSUMPTIONS:

1. The rotor is ideal in that it has no hub.
2. There are an infinite number of rotor blades.
3. The rotor blades have no drag resistance.
4. There is uniform flow at each section.
5. Steady flow conditions.
6. The velocity of the air at all points is axial, i.e., no swirl.
7. Air density is a constant, i.e., air is incompressible.
8. Blade tip losses are neglected.

NOMENCLATURE:

rho=air density

m'=mass flow rate

V1=velocity of undisturbed stream of free flowing air

A1=area of undisturbed stream of free flowing air

V2=velocity of stream of free flowing air at rotor

A2=area of stream of free flowing air at rotor

V3=minimum velocity of stream of free flowing air at some point beyond the rotor

A3=area of stream of free flowing air at the point of minimum velocity beyond the rotor

(P)available=power available in undisturbed stream of free flowing air

P=power extracted from stream of free flowing air by rotor

(P)max=maximum theoretical power which can be extracted from the stream of free flowing air

(P)out=the actual power output of a wind power system

F=force on rotor due to stream of free flowing air

(T)=change in kinetic energy of stream of free flowing air between points of maximum and minimum velocity

[(C)p]max=maximum power coefficient = Betz Coefficient

(n)e=system efficiency

DERIVATION:

Constant mass flow rate at all points = m'

m' = rho*V1*A1 = rho*V2*A2 = rho*V3*A3 Eqn 2

POWER AVAILABLE [(P)available] IN THE AIR STREAM.

The power available in the stream of free flowing air is from momentum theory:

(P)available = [rho*A2*(V1^3)]/2 Eqn 3

MAXIMUM AMOUNT OF POWER WHICH CAN BE EXTRACTED FROM THE AIR STREAM BY A HORIZONTAL AXIS WINDMILL.

From Momentum Theory (Euler's Theorem):

F = Force on rotor = m'*(V1-V3) Eqn 4

P = Power extracted = F*V2 = m'*V2*(V1-V3) Eqn 5

Change in kinetic energy (T) from section 1 to section 3:

(T) = m'*[(V1^2)-(V3^2)]/2 Eqn 6

Equate P and (T):

m'*V2*(V1-V3) = m'*[(V1^2)-(V3^2)]/2 Eqn 7

so, V2 = (V1+V3)/2 Eqn 8

This shows that the axial flow velocity at the rotor is the average of the initial and final velocities.

And,

F=rho*A2*[(V1^2)-(V3^2)]/2 Eqn 9

P=rho*A2*{(V1^3)+[(V1^2)*V3]-[V1*(V3^2)]-(V3^3)}/4 Eqn10

For a given V1, the fluctuation of P with V3 can be studied.

(dP/dV3)=0 for (P)max Eqn 11

(dP/dV3)=rho*A2*[(V1^2)-(2*V1*V3)-(3*V3^2)]/4 Eqn 12

Solving gives, V3=V1/3 Eqn 13

So, (P)max = [rho*A2*(V1^3)/2]*[16/27] Eqn 14

Therefore,

[(C)p]max = maximum power coefficient

[(C)p]max = (P)max/(P)available Eqn 15

[(C)p]max = 16/27 = 0.593 or 59.3%

This is also called the Betz Coefficient.

Figure 16 shows the idealized optimum operating conditions for a horizontal axis windmill.

If [A2>(3*A1/2)], then [V2<(2*V1/3)]. This results in a low volumetric flow rate, a large pressure drop, and less than optimum performance. This occurs when there is too much blade area.[9]

If [A2<(3*A1/2)], then [V2>(2*V1/3)]. This results in a high volumetric flow rate, a small pressure drop, and less than optimum performance. This occurs when there is too little blade area.[9]

To optimize performance the flow rate and the pressure drop must be optimized. Accomplishment of this is dependent on the overall system design. The system efficiency, [(n)e], is defined as:

(n)e=(useable power produced)/(wind power available) Eqn 16

Existing wind power systems have system efficiencies of anyway from 0.10 to 0.50, with 0.20 to 0.30 being the norm. Factors which affect the system efficiency include the rotor and generator efficiencies, friction losses in the bearings, gears, and other rotating machinery, losses in transmission wires, power used on site, and the limitations caused by the cutin, cutout and rated wind speeds.[9,32] When system efficiency is included, the equation for power output is:

(P)out = [(n)e*rho*A*(V1^3)]/2 Eqn 17

From this equation it can be seen that the power output is linearly related to the system efficiency, air density, and area swept, while being related to the cube of the wind velocity. This means that doubling the system efficiency, air density or area swept only doubles the power output. But, doubling the wind speed increases the power output eight fold. Therefore, choosing a site with a high annual average wind speed is the easiest way to increase the power output of a wind power system.

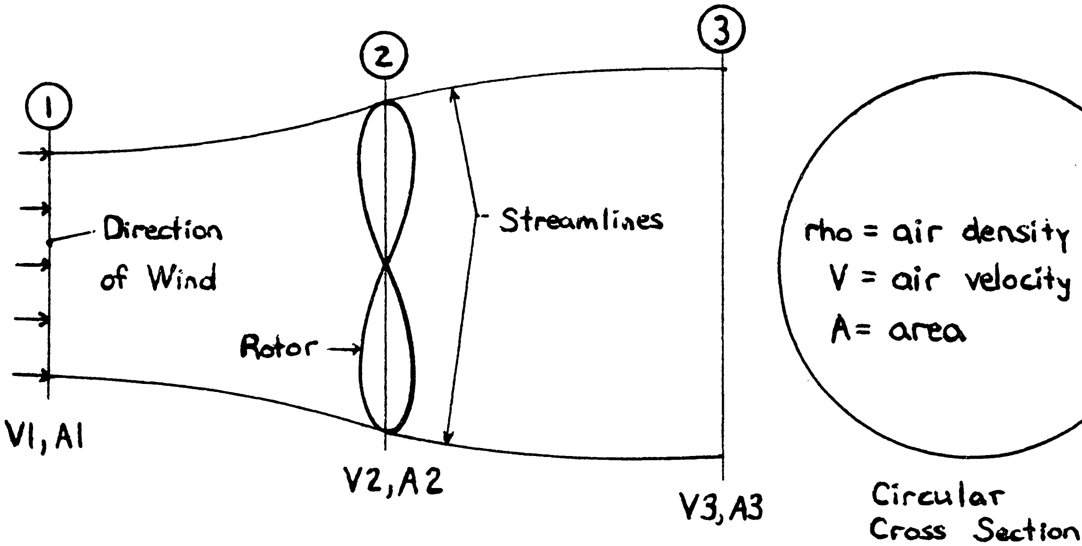


FIGURE 15 - Idealized Stream of Free Flowing Air.

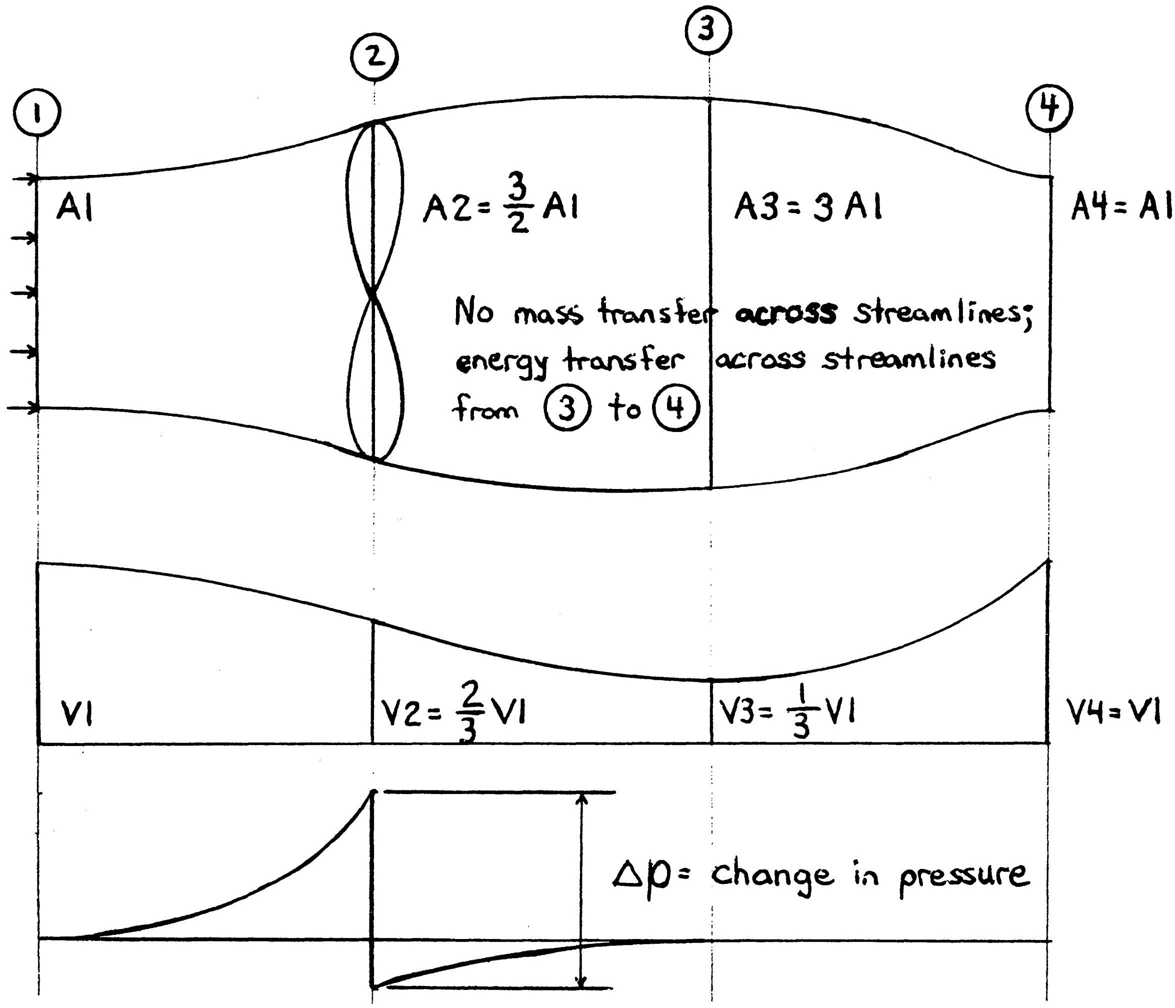


FIGURE 16 - Idealized Optimum Operating Conditions.[9]

VI. SITE SELECTION

Care must be taken in choosing a site because it can be the deciding economical factor in a wind power system. In comparison to internal combustion engines and large power stations, wind power systems have very, very small power outputs per square foot of land used. This fact alone limits windmills used for commercial electricity production to rural areas. In most cases, the use of windmills in urban areas by homeowners or small businesses is not possible either. This is due to several factors, including safety and zoning laws. In general, windmills are limited to rural areas.[25]

Choosing a site for a wind power system has been widely studied.[23,42] To start, it is probably best to look at a map, such as in Figure 17, of the continental United States which shows the annual average wind power at a particular height. This map gives a rough idea of the regions with good wind power potential. Note that the Mid-Atlantic coast to the North Atlantic coast, and the mountains of North Carolina to the mountains of Vermont are regions which show promise for wind power sites. But, the low lying, inland regions of Virginia and North Carolina show little promise for wind power sites.

The U.S Department of Energy has published 12 volumes of the Wind Energy Resource Atlas.[42] Volume 5, The East

Central Region, covers the states of Delaware, Kentucky, Maryland, North Carolina, Tennessee, Virginia, and West Virginia. In the atlas are maps of each state showing the approximate wind power potentials. Also, there is processed wind data for about 20 sites in each state. Graphs are given for each site which show the Interannual Wind Power and Speed, Monthly Average Wind Power and Speed, Diurnal Wind Speed by Season, Directional Frequency and Average Wind Speed, Annual Average Wind Speed Frequency, Annual Average Wind Speed Duration, and Annual Average Wind Power Duration. The wind power potential of each site can be compared by using these graphs. As an example of the value of these graphs, information on 3 locations in North Carolina has been taken from Volume 5 and placed in Figure 18. It is apparent from the information shown that Cape Hatteras has the most abundant wind resources of the 3 locations, while Charlotte has the least. Several other important points should be noted: (1) the average wind speed varies with the time of day, the month, the year, and the direction from which the wind blows, and (2) caution must be used when using wind data because it can be unrepresentative of the actual wind conditions at a site due to the location of the wind sensors. Use of the atlas in the preliminary stages of site selection will show how regions compare to one another in regards to wind power potential, and will give a good idea of whether or not a region is worthy of consideration for wind power sites.

Topographic maps should be consulted once the process of site selection is narrowed down to certain regions within a state. Topographic maps used in conjunction with other maps such as road maps, land use maps and meteorological charts will show specific areas within a region which may be good wind power sites. The following features are indicative of high mean wind speeds: gaps, passes and gorges in areas of frequent strong pressure gradients, long valleys extending down from mountain ranges, high elevation plains and plateaus, plains and valleys with persistent strong downslope winds associated with strong pressure gradients, exposed ridges and mountain summits in areas of strong upper-air winds, and exposed coastal sites in areas of either strong upper-air winds or strong thermal and pressure gradients. Features which are indicative of low mean wind speeds include valleys perpendicular to the prevailing winds aloft, sheltered basins, short and/or narrow valleys, and areas of high surface roughness such as forested hilly terrain.[42]

Before going out in the field and surveying possible sites, several factors other than available wind power must be considered. These factors include ease of site access, distance to existing power lines, land price or land rights, adequate room for expansion, zoning laws, aesthetics, possible interference with air traffic and proximity to bird sanctuaries. These factors should help in rating the areas in terms of value as wind power sites.

At this point it would be advantagous to go the the most highly rated areas. The purpose of the trip is to get a first hand look at the areas under consideration and to decide which sites are best suited for windmills.[24] It has been suggested that the trip include a meteorologist. An extensive and informative account of the site investigation undertaken for the Smith-Putnam wind turbine (1940's) is contained in Putnam's Power From the Wind, second edition.[23] Among the techniques used by Putnam and others to identify high wind sites is the deformation of vegetation. This technique can be particularly useful in forested country. Good exposure to the wind may also be a sign of a high wind site. Tall obstructions should be avoided as they tend to block the wind. Low hills with gentle slopes can be good sites because air streams are often compressed while passing over a hill.[24]As shown in Figure 19, this is an advantage because the mean wind speed increases and the wind shear is reduced. Low wind turbulence areas are desirable. One type of turbulence, eddy currents, is illustrated in Figure 20. Eddy currents can interfere with normal wind flow and subsequent power output. Small eddy currents will occur even at good sites, but large eddy currents will develop in winds passing over sites with rough terrain. Excessive turbulence can also cause premature failure of wind power systems. As can be seen in Figure 21, raising the rotor above the turbulence is one way of avoiding turbulence. In this case the rotor should be about three times as high as the house.[24] The prevailing winds must also be considered during the survey, as they will be a controlling factor in the site selection. Caution must be taken when evaluating mountain summits and ridges because the winds in these areas can be complex and highly variable.[43] In coastal areas, the winds diminish with distance inland.

Wind power surveyors and enterprisers should have an understanding of the boundry layer concept.[22] The concept was officially introduced by Ludwig Prandtl, a German aerodynamicist, in 1904. As shown in Figure 22, the concept idealizes the flow of a fluid (air) past a boundary (the earth) as being divided into two regions. One, the boundary layer, in which the viscosity of the fluid is important, and the other, outside of the boundary layer, in which the viscosity of the fluid may be neglected. This idealization simplifies the visualization of a fluid's velocity varing from zero at the boundary to a constant value at a point some distance away. The following equation is widely used to determine the wind velocity at differant heights within the boundary layer:[32]

V1/V2 = (H1/H2)**n   where,   Eqn 18

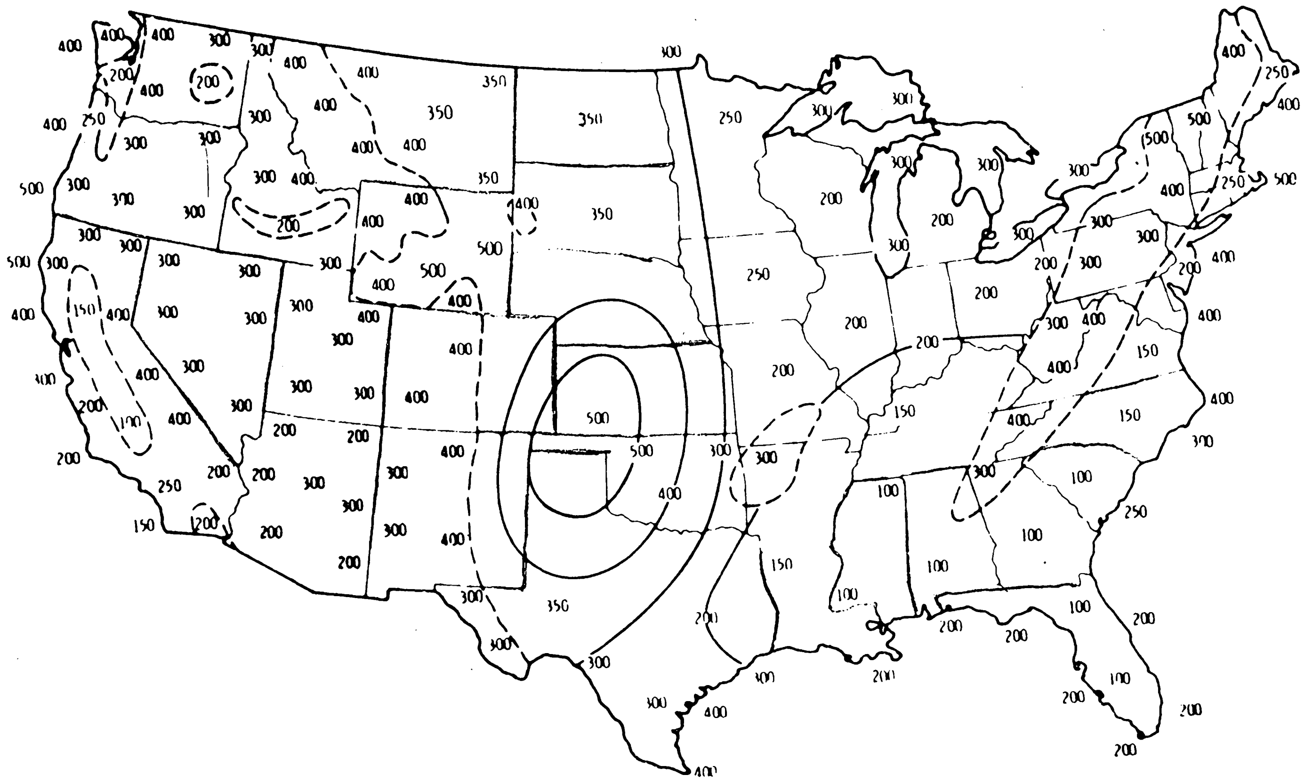
V1 and V2 are wind speeds at heights H1 and H2, respectively, and

n - the surface friction coefficient - is a dimensionless exponent whose value may depend on wind speed, atmospheric stability, and surface roughness.

In many cases, n=1/7 has been used as a rule of thumb. This happens to be the same equation and exponent used in fluid mechanics and heat transfer for turbulent flow past a flat plat.[5] In an attempt to account for the various terrain roughnesses, tables of surface friction coefficients have been developed. Table 1 is such a table. In general, the rougher the terrain is, the greater the boundary layer thickness will be.[32] One problem caused by boundary layers is wind shear. In large wind turbines, the wind velocity at the top of the rotor can be much greater than that at the bottom of the rotor. Figure 23 shows that sites with low surface friction coefficients exhibit less wind shear than sites with high surface friction coefficients. This wind shear results in a cyclic shearing force on the windmill blades. Wind shear can be especially troublesome at sites experiencing land and sea breezes, as the wind may be blowing in one direction at the bottom of the rotor while it is blowing in the other direction at the top of the rotor.

Wind gusts are also a type of turbulence. In general, the rougher the ground, the gustier the wind. Short gusts have little effect on power output. But, wind gusts must be taken into account in the structural design of windmill blades and towers. Figure 24 shows graphically what a wind gust looks like. Table 2 gives information on predicting the number of gusts that can be expected at a site during a year. As an example of the use of this table assume n=0.3 and the mean wind speed=14 mph. We can then expect 207 gusts to speeds of 60 mph during the year while the wind is blowing 30 mph.[32]

It should also be pointed out that the wind does not have to blow horizontal. For example, at Grandpa's Knob, site of the Smith-Putnam wind turbine, the mean flow through the rotor area from 50 feet to 237 feet above the ground is 5 degrees above horizontal.[23]



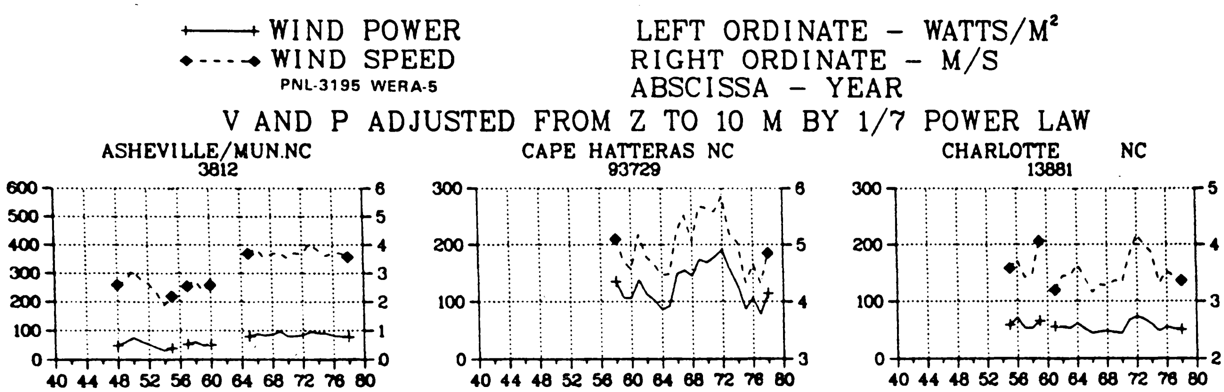
<u>FIGURE 17</u> - Annual Average Wind Power at 50 Meters Above Higher Elevations (In Watts Per Square Meter).[44]

Cape Hatteras is on the easternmost island of the Outer Banks off the coast of North Carolina. Wind measurements are taken at the Weather Office in Buxton, within about 1 kilometer (0.6 mi) of the shoreline. The wind power estimates should be representative of most of the coastal islands, with the instruments mounted on a ground mast at 9.8 m (32 ft). However, obstruction from trees growing around the anemometer may have affected data recorded from approximately 1972 to 1978 (see Section 6.3.1).

Charlotte is located in the southern Piedmont. The wind power estimates should be representative of the surrounding area.

Asheville is located in the French Broad River valley, which cuts through the Great Smoky and Blue Ridge Mountain ranges, and is oriented northwest-southeast near the Tennessee border and becomes more north-south at the southern end of the valley. Ridge crests and mountain summits rise about 1,200 m (4,000 ft) above the valley floor within about 25 km (15 mi) on either side of the valley. The wind-measuring instruments are located at the airport about 20 km (12 mi) south of the city of Asheville, and their exposure is excellent.

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s: At Anemometer Height	At 10 m	At 50 m	Annual Average Wind Power, watts/m²: At Anemometer Height	At 10 m	At 50 m
Asheville, North Carolina	Asheville Municipal Airport	35.43	82.53	659	09/64-12/78	6.1	3.5	3.8	4.7	69	86	171
Cape Hatteras, North Carolina	Cape Hatteras WBO	35.26	75.54	8	01/65-12/78	9.8	5.1	5.1	6.4	136	137	273
Charlotte, North Carolina	Charlotte Douglas Municipal Airport	35.23	80.93	226	11/60-12/78	6.1	3.3	3.5	4.5	44	54	108

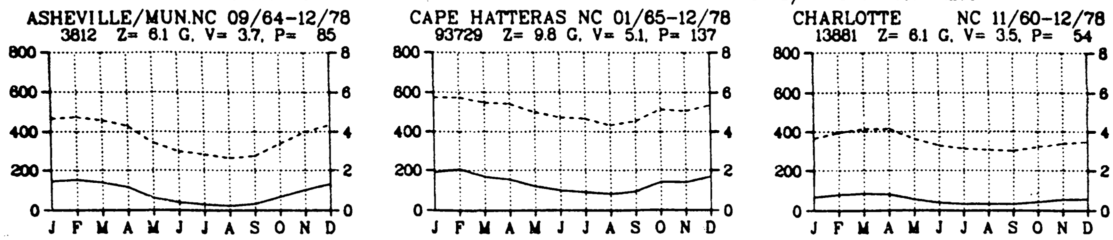


Interannual Wind Power and Speed

FIGURE 18 - Excerpts from the Wind Energy Resource Atlas.[42]

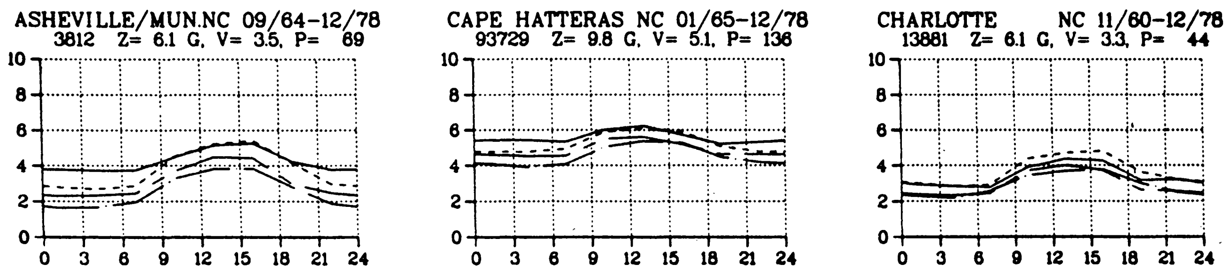
—— WIND POWER   LEFT ORDINATE - WATTS/M²
------- WIND SPEED   RIGHT ORDINATE - M/S
PNL-3195 WERA-5   ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW



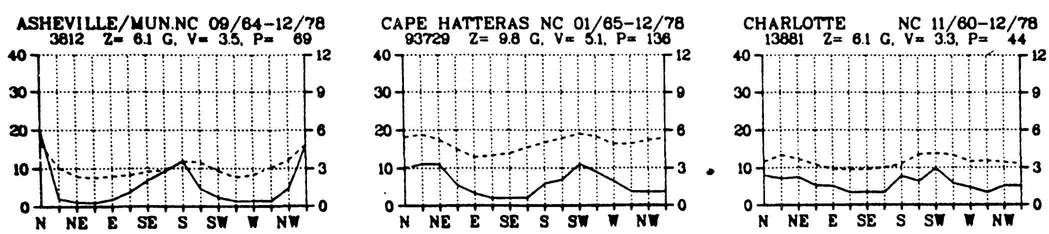
Monthly Average Wind Power and Speed

—— WINTER   ◆----◆ SPRING   ORDINATE - M/S
⊕— —⊕ SUMMER   ⊞---⊞ AUTUMN   ABSCISSA - HOUR
PNL-3195 WERA-5



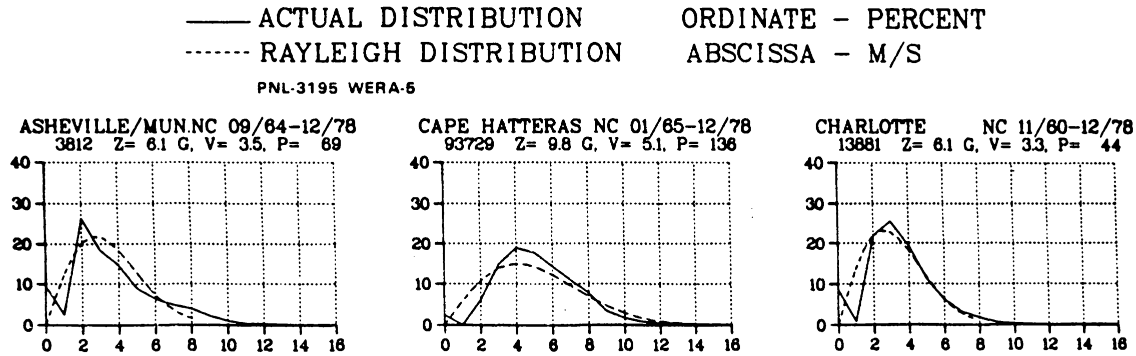
Diurnal Wind Speed by Season

—— PERCENT FREQUENCY   LEFT ORDINATE - PERCENT
------- WIND SPEED   RIGHT ORDINATE - M/S
PNL-3195 WERA-5   ABSCISSA - WIND DIRECTION

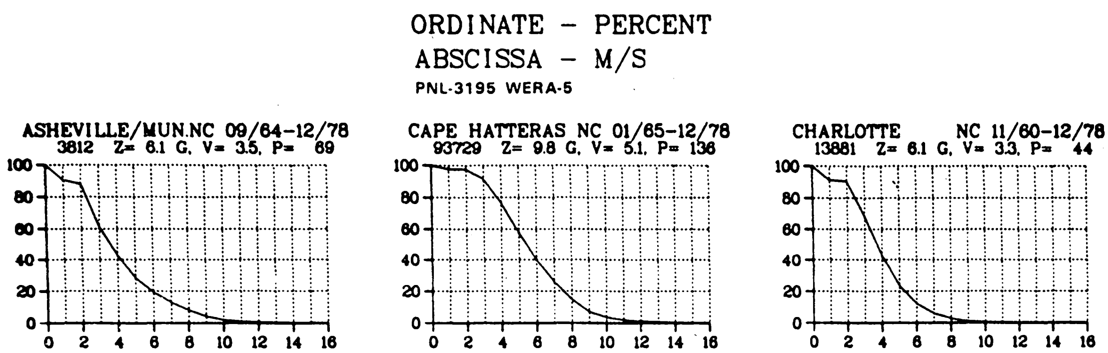


Directional Frequency and Average Wind Speed

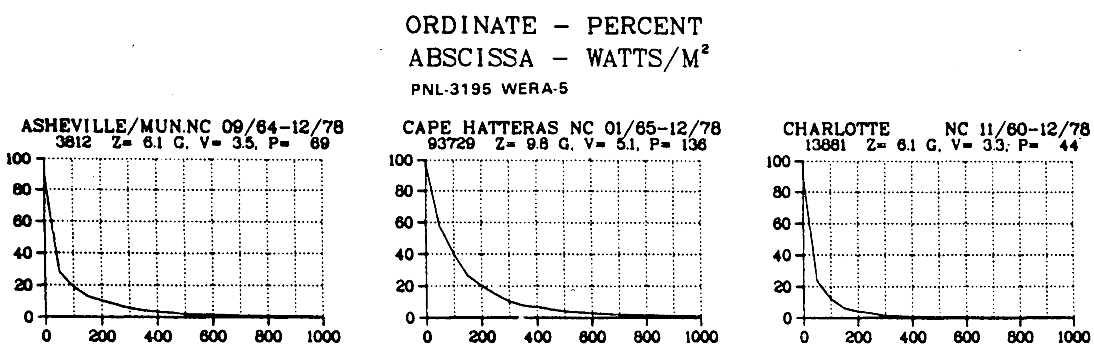
FIGURE 18, con't.-Excerpts from the Wind Energy Resource Atlas.[42]



Annual Average Wind Speed Frequency



Annual Average Wind Speed Duration



Annual Average Wind Power Duration

FIGURE 18, con't.-Excerpts from the Wind Energy Resource Atlas.[42]

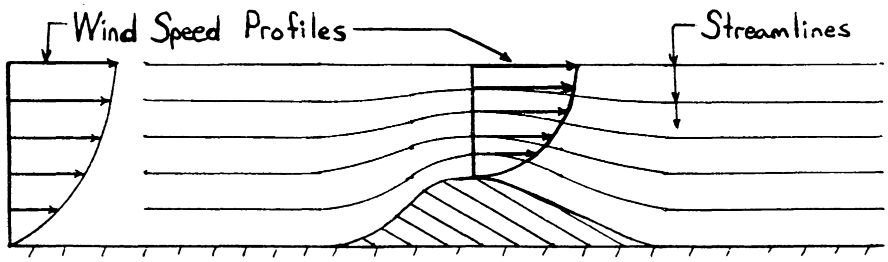
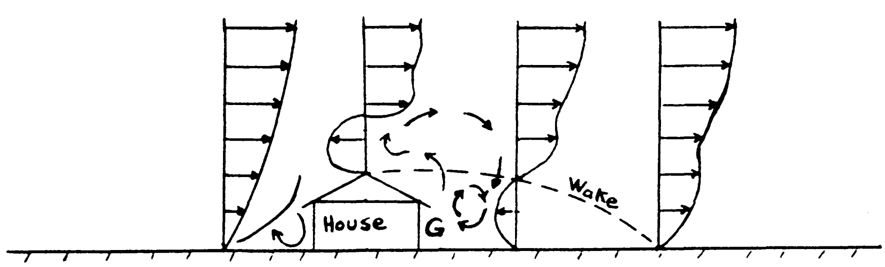


FIGURE 19 - Air Streamlines Compressed by a Low Hill With Gentle Slope.[24]

Small eddy current caused by slow wind over smooth terrain

Large eddy current caused by high wind over rough terrain

FIGURE 20 - Eddy Currents.[24]



Approaching Wind Profile

Reverse Flow Due to Obstruction

Redeveloping Wind Profile

FIGURE 21 - Avoid Excess Turbulence by Raising the Rotor Above the Turbulence.[24]

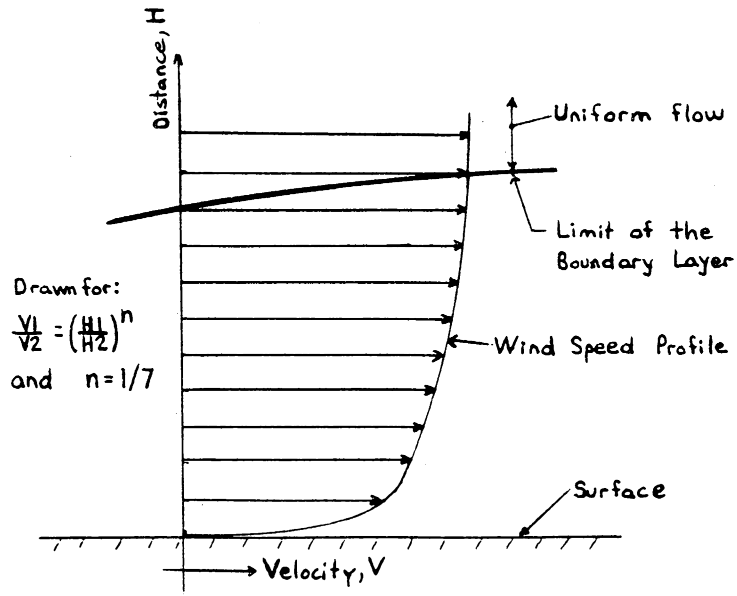
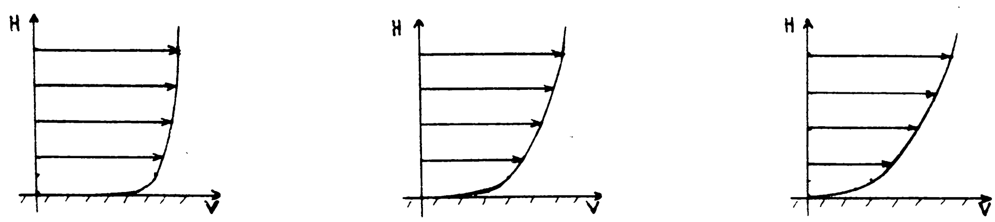


FIGURE 22 - The Boundary Layer Concept.[5]



n=0.10 n=0.25 n=0.40

FIGURE 23 - Comparison of Wind Speed Profiles for Differant Surface Friction Coefficients.

TABLE 1 - Surface Friction Coefficients[32]

Terrain Description	n
Smooth, hard ground; lake or ocean	0.10
Short grass or untilled ground	0.14
Level country with foot grass, occasional tree	0.16
Tall row crops, hedges, and a few buildings	0.20
Many trees and occasional buildings	0.22-0.24
Wooded country: small towns and suburbs	0.28-0.40
Urban areas, with tall buildings	0.40

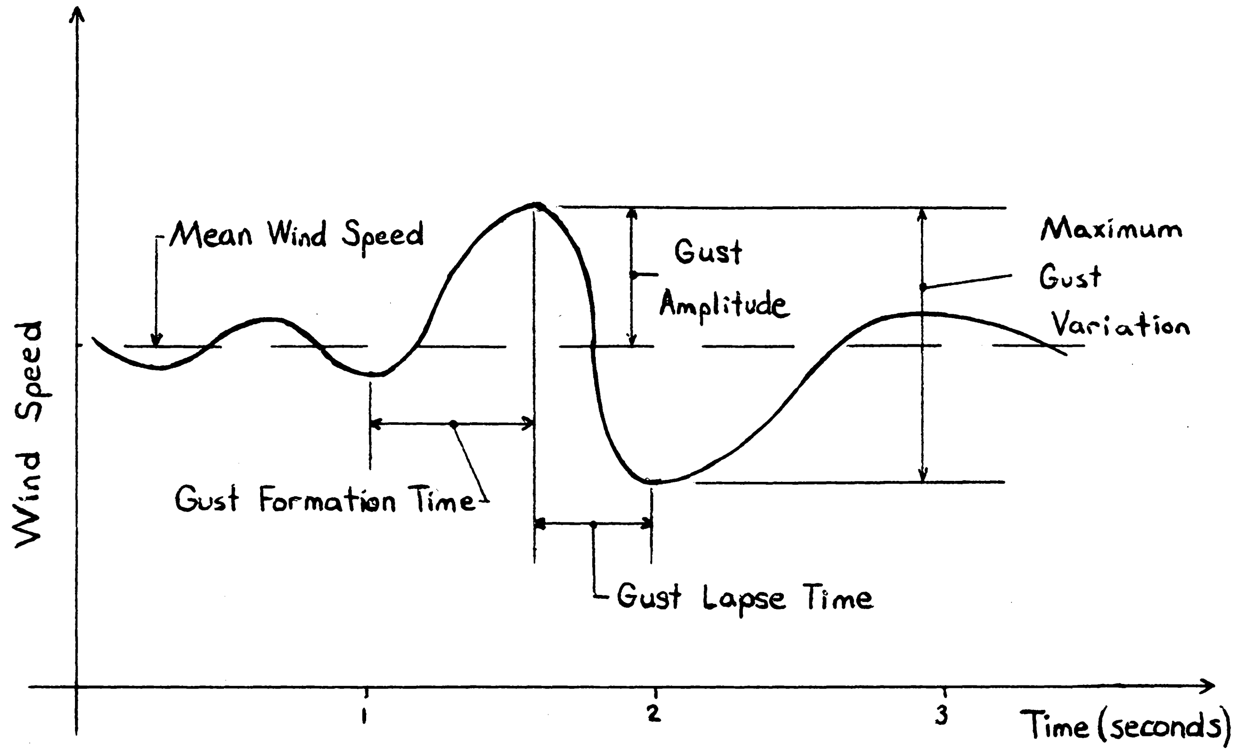


FIGURE 24 - Graphical Description of a Typical Wind Gust.[9]

TABLE 2 - Number of Wind Gusts Per Year to Twice the Departure Speed.[32]

Departure Speed (mph)	Surface Friction Coefficient/Mean Wind Speed (mph)							
	n=0.20				n=0.30			
	10	12	14	16	10	12	14	16
10	25	22	18	15	2269	2004	1701	1430
20	5	8	11	12	430	780	1022	1140
30	0	1	2	4	13	77	207	369
40	0	0	0	1	0	2	17	57
50	0	0	0	0	0	0	1	5

VII. GATHERING WIND DATA

Once it has been decided which sites are best suited for windmills, the process of gathering wind and weather data should begin. The best way to get wind data for a site is to install wind speed sensors, wind direction sensors, and recording instruments at the site. It is perferable that data be gathered at the site continuously for at least a one year period. Gathering data for shorter periods of time will reduce the accuracy of the data. A one year record may depart from the five year average by as much as 25 percent, while a one month record may depart from the 5 year average for that month by as much as 75 percent.[23] In view of these facts, the gathered data should be correlated with data from nearby meteorological recording stations (within 50 miles and 2000 feet elevation) to obtain a correction factor. Recording stations which may supply data for comparison are operated by several organizations, including the U.S. National Climatic Data Center (NCDC), NASA, NOAA, U.S. Forest Service, airports, universities, utility companies, and military installations.[42] Care must be taken when determining a correction factor because a direct comparison between the two sets of data may not be possible. For instance, airports are often located at low wind sites, and airport anemometers are typically 13 feet above the ground. Therefore, a direct comparison of wind data from an airport and a windmill site may not be made. But, the airport wind data will contain valuable information on such things as the monthly, seasonal and yearly wind patterns.[32]

The wind data gathering instruments installed at a site should consist of at least one anemometer (wind speed sensor), one or more wind direction sensors, and a recording device. A meteorological instrument tower is also required. The height of the tower will depend on the anticipated windmill height. If only one anemometer and one wind direction sensor is used, they should be mounted at the anticipated windmill hub height. Any additional anemometers and wind direction sensors should be mounted at heights different from the hub height so that information on the wind shear can be obtained. These additional sensors should be mounted on struts at least 10 tower diameters in length and pointing into the prevailing wind at a 45 degree angle. It is also suggested that lightning arrestors be used and indicating safety lights affixed to all towers. Security measures such as fences and pad locks are advisable because vandals seem to be drawn to installations such as this.[32]

The most common anemometer is the rotating cup anemometer. Other anemometers used are the impeller, pressure-plate, pressure-tube and Gill. Basically there are three configurations used in anemometers: (1) switch closure or wind run, (2) light chopper, and (3) generator.

The switch closure and light chopper have low starting thresholds, while the generator provides long term maintenance-free operation. The switch closure employs a magnet and a reed switch. It measures the miles of wind passing the instrument per unit time. Miles of wind divided by time gives the average wind speed in miles per hour. This information can be automatically recorded on strip chart recorders or digital data loggers. The switch closure can be used as a odometer for long term wind speed averages, or as a speedometer for instantaneous wind speed readings. A low power source is required. The light chopper employs a slotted, circular disk, a light emitting diode (LED), a phototransistor, and a drive shaft. As the drive shaft responds to the wind, the phototransistor is alternately exposed and masked to the LED by the slotted disk. In response to the light, the phototransistor generates electrical pulses which are proportional to the wind speed. The output signal is amplified, shaped and conditioned by a signal conditioner and power supply. The output signal can be conditioned to take many forms depending on the signal processor used. In a generator type anemometer, a AC or a DC generator is coupled to the wind speed shaft. The internal drag of the generator causes the starting wind speed threshold to be relatively high. As in the light chopper, the output signal can be conditioned to take many forms. The output signal required will be determined by the signal processor used, whether it be indicating dials, a strip chart recorder, etc. The generator type anemometers are relatively inexpensive, have long service lives, and do not require an independent power source. A couple of other factors concerning anemometers should also be considered. One, when there is a short term decrease in wind speed, there is a tendency for anemometers to overspeed and indicate higher than actual wind speeds. The distance constant is a measure of this tendency. A low distance constant indicates good anemometer response. And two, a heated anemometer may be required to avoid ice build up in the cups and subsequent loss of data.

Most wind direction sensors use a potentiometer to create an output signal. For years a 360 degree potentiometer has been standard. But when the wind is from the north, slight variations in the wind move the potentiometer wiper back and forth from maximum output to minimum output. This output signal presents problems for recording instruments and data analysis equipment. More recently, 2 potentiometers with wipers joined together have been used to provide a continuous, uninterrupted 540 degree output. In addition to measuring wind direction; amplitude and frequency variations in wind direction can be measured. But, as the wind vane responds to a change in wind direction, there is a tendency for the vane to overshoot. The dynamic response of wind vanes is primarily determined by their damping ratio. A vane with a damping ratio of 0.6 damps out quickly, while a vane with a damping ratio of 0.2 damps out slowly. The output signals of wind direction sensors can be made compatible for operation with dial indicators, strip chart recorders, data loggers, etc. A power source is required for operation of wind direction sensors using potentiometers.

Manually taking recordings at certain time intervals is one method of recording the wind data. But this method is probably not practical for gathering data at a proposed wind power site because the site is likely to be remote and unmanned. This method is also limited in the amount of data which can be recorded. Strip chart recorders and digital data loggers are two good ways of automatically recording wind data at potential wind power sites. Strip charts give a continuous record of wind speed and direction. Typically the chart moves at a rate of 1 inch/hour and must be replaced every month or so. The major disadvantage of strip charts is that the data is in graphical form and may take many man hours to interpret and reduce. Digital data loggers record the information in a form which may be used directly by a computer. Therefore, when compared to strip charts, in an equal amount of time significantly more wind data can be reduced and analyzed by digital data loggers.[4,6,23,24,31,32]

It might be noted that the fastest mile of wind recorded in the shortest period of time, in the free atmosphere near the earth's surface, was 231 mph (SE) in April of 1934 at Mt. Washington, New Hampshire.[39]

Other details about a site which should be known include the number and duration of calm periods (a calm period being described as a time the wind speed is less than 10 mph), surface roughness, altitude, temperature trends, gale, tornado and thunderstorm chances, amounts of ice, sleet, hail, snow and freezing rain, soil conditions, seismic stability, and occurences of blowing dust, sand or other objects.[32]

VIII. WIND DATA REDUCTION AND ANALYSIS

After gathering wind data at a perspective wind power site, it must be reduced and analyzed. Basically, the data will consist of wind speed and wind direction readings taken at set time intervals. The time intervals may range from a matter of seconds to several hours, depending on the recording instruments used.

An example will be used to illustrate the reduction and analysis of wind data. The data used was obtained from the National Climatic Data Center (NCDC). It was recorded at the Cape Hatteras, North Carolina weather bureau office during the year 1982. The data consists of wind speed and wind direction readings taken at 3 hour intervals. The wind speed is rounded to the nearest whole knot (1.15 mph=1 knot) and the wind direction is rounded to the nearest 10 degrees. Appendix A contains information on NCDC, samples of the data used in the example (Local Climatological Data), and a letter from NCDC concerning the type, location and exposure of the wind instruments.

Reduction of this wind data consisted of: (1) manually entering the data into sequential access files which were then stored on a floppy disc, (2) writing several computer programs (BASIC) to summarize the data, and (3) graphing the summarized data. There were 5840 data points which had to be entered. A total of 24 sequential access files were used; two for each month, one for wind speed and one for wind direction. It took six to eight hours to input the data. After this, several computer programs were written. These programs are listed in Appendix B. The programs are basically all the same. First, the data was read into arrays, then the data was searched in a step-wise fashion, and last, the desired results were printed out. The programs were written and tested for one month data periods, and then expanded to cover the entire year. As a final step in data reduction, Graphs 4 through 22 were drawn using the summarized data from the computer programs.

The wind power plotted in these graphs is the total power in the wind. That is, the power has not been reduced by the Betz coefficient (0.593).

Graph 4 is a plot of the mean monthly wind speeds. The mean monthly wind speeds for January, February, March, and April are higher than the annual mean wind speed. The annual mean wind speed of 11.2 mph is slightly below the normal annual mean wind speed of 11.4 mph. Graph 5 is a plot of the average monthly wind power. The mean monthly wind power for the months of January, February, April, and October is higher than the annual mean wind power. The cubic nature of wind speed in relation to wind power can be seen in the sharp peaks and valleys of the wind power plot. This point is easily seen in the month of October where the mean monthly wind speed is equal to the mean annual wind speed, but the mean monthly wind power is much greater than the mean annual wind power. This increase in wind power is due to a strong storm with high winds which occurred during the month.

Estimating the mean annual wind power at a site by using the mean annual wind speed may be conservative. Once again, this is due to the cubic relation of wind speed to wind power. For instance, if the mean annual wind speed of 11.2 mph is used to directly estimate the mean annual wind power, a value of only 7.2 (watts/ft^2) is obtained. This is far below the estimate of 12.1 (watts/ft^2) obtained by determining the wind power at 3 hour intervals and then averaging them over the entire year.

The air density must also be considered when determining the wind power. In this analysis, average air density values for each month were used. More accuracy can be obtained by determining and using the air density at each 3 hour interval.

Graph 6 shows the diurnal variation of wind speed with season. Graph 7 shows the diurnal variation of wind power with season. There is a definite trend during all four seasons for both the wind speed and the wind power to begin building at about 7 A.M., peak at about 1 P.M., decrease until about 8 P.M., and then level off.

When the monthly and diurnal variations of wind power are known, they can be correlated with the load to determine how well they match. For example, Graph 5 shows that the winds of the cold months are powerful, while the winds of the warm months are weak. Therefore, the heating load of winter is well matched. But, the air conditioning load of summer occurs when there is little wind power. This a problem if wind power is to be coupled with the utility industry because summer is a heavy load period for the utilities. As a matter of fact, VEPCO set a new generating mark late in August, 1983 at almost 10,000 MW,[37] but at the time the winds were light and variable. The diurnal wind power variation of Graph 7 can be used as another example for correlating the available wind power to the load. In this case, the diurnal wind power variation correlates well with the daily load experienced by utilities.

Graphs 8 and 9 show the direction frequency of the wind. The prevailing wind directions are north-northeast, and southwest. Two graphs are used to show the same information because the first graph is easy to read, while the second graph or wind rose is easy to visualize.

Graphs 10 and 11 show the average wind speed coming from each direction. The strongest winds are from the north-northeast, with the next strongest coming from the south. The southwest to northwest winds are fairly strong, while the east winds are the weakest.

Graphs 12 and 13 are drawn by combining the information of Graphs 8 through 11. In these two graphs, the miles of wind are obtained by multiplying the wind speed by the time it blows. For example, 10 miles of wind is equal to a 5 mph wind blowing for 2 hours. It can be noted from these two graphs that most the wind comes from the north-northeast, and from the southwest.

Graphs 14 and 15 show the average wind power of each direction. On the average, the north-northeast and the south winds are the most powerful. Once again the cubic nature of wind speed in relation to wind power can be seen by comparing the wind roses in Graphs 11 and 15.

Graphs 16 and 17 show the percentage of total wind energy coming from each direction. Most of the energy comes from the north to north-northeast, and from the south to west-southwest directions. These graphs are very similar to Graphs 12 and 13.

Graph 18 shows the percent of time the wind blows at each speed. The Rayleigh Distribution for a mean wind speed of 11.2 mph is also plotted. The agreement between the actual data and the Rayleigh Distribution is good.

The Rayleigh Distribution is a distribution function which can provide a reasonable description of wind characteristics in some locations. It provides an approximation of the annual average wind speed frequency when the only data available is the annual average wind speed. The error is usually less than ten percent, but should not be used for sites with less than a 10 mph annual average wind speed. Other distribution functions which have been used before are: (1) Bivariate, (2) Weibull and (3) Square Root Normal. The equation for the Rayleigh Distribution is given below:[23,32]

H = (PI/2) * (V/$\overline{V}$^2) * [e^(-k)] * 8760 Eqn 19

where,

H=the number of hours per year the wind blows at speed V,

V=wind speed,

$\overline{V}$=annual mean wind speed,

k = (PI/4) * [(V/$\overline{V}$)^2]

Graph 19 shows the annual total energy density (Kwhr/ft^2) contributed at each wind speed. The area under the curve is the annual total energy density. Note that most of the energy is contained in wind speeds higher than the mean wind speed, and that little energy is contributed by wind blowing at speeds three times that of the mean wind speed. Again the Rayleigh Distribution has been plotted and shows good agreement with the actual data.

Graph 20 shows the percentage of time during the year that the wind attained a specific wind speed. Using this graph, it can be seen that 36% of the time the wind speed was greater than 10 knots. But only 11% of the time was the wind speed greater than 15 knots.

Graph 21 shows the percentage of time during the year that the wind power reached a specific level. Using this graph, it can be seen that 36% of the time the wind power was greater than 7.7 (Watts/ft^2). But only 11% of the time was the wind power greater than 26 (Watts/ft^2).

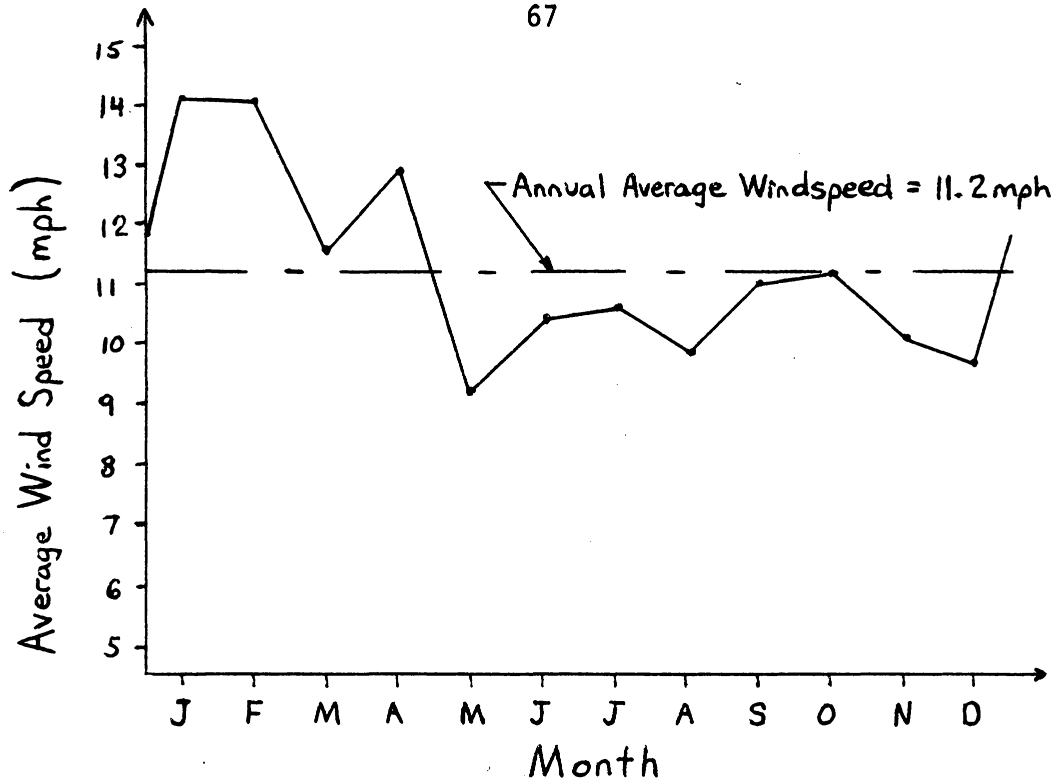
Graph 22 is drawn by using the data of Graph 19. The graph shows cumulatively the percent of energy contributed by the wind up to a certain speed. For example, 55% of the wind energy is contributed by winds with speeds of 15 knots or less. It can also be seen that about 85% of the wind energy is contributed by winds with speeds between 7 and 24 knots.

Figure 18 has graphical data for the Cape Hatteras, NC weather bureau office. The graphs in Figure 18 are based on 14 years of data (1965-1978). Comparing Graphs 4, 5, 6, 8, 10, 18, 20, and 21, which are based on 1 year of data, with those of Figure 18, shows that the two sets of graphs are in good agreement, in most cases. The only graphs which do not compare well are the average monthly wind speed, and the average monthly wind power graphs.

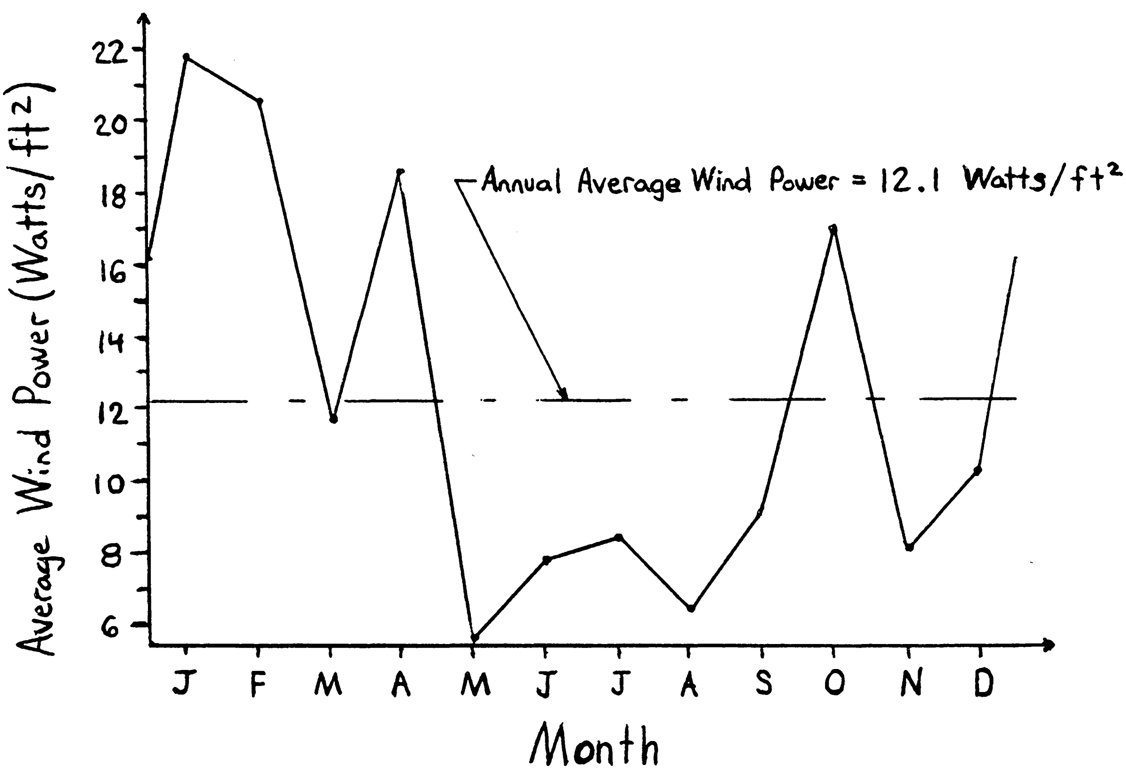
The fastest wind speed recorded at this site during 1982 was 44 mph from the north-northeast. The fastest wind speed recorded at this site since 1971 was 48 mph from the north-northeast. A 110 mph west wind was recorded in 1944 at another site in the same locality.

The anemometer at the Cape Hatteras site is reportedly 30 to 32 feet above ground level. But, the exposure is questionable and would have to be inspected in person before the data could be used with confidence.

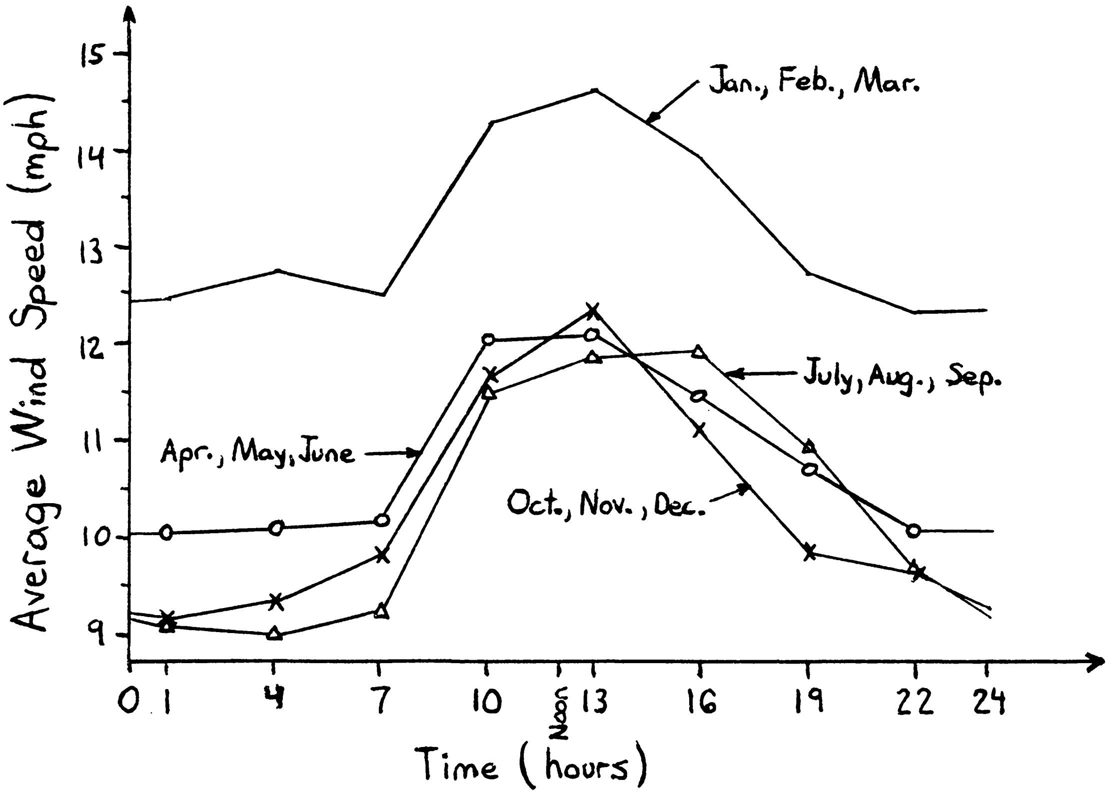
The conclusions which can be drawn from this example are: (1) Before beginning to gather wind data at a perspective wind power site, data reduction and analysis should be carried out on data obtained from at least one meteorological recording station in the locality being considered. The data should cover at least a five year period. (2) The results of the analysis should yield valuable information on the energy densities of the wind in the locality, the prevailing wind power directions, and the diurnal, monthly, seasonal and yearly wind patterns. (3) The recording station from which the data is obtained should be inspected in person to determine the height, and more importantly, the exposure of the wind instruments. (4) Once the wind data for the perspective site is gathered, it should be reduced in a similar fashion. The cutin, cutout and rated wind speeds of various wind power systems may then be used to compare the estimated yearly energy output of each system.



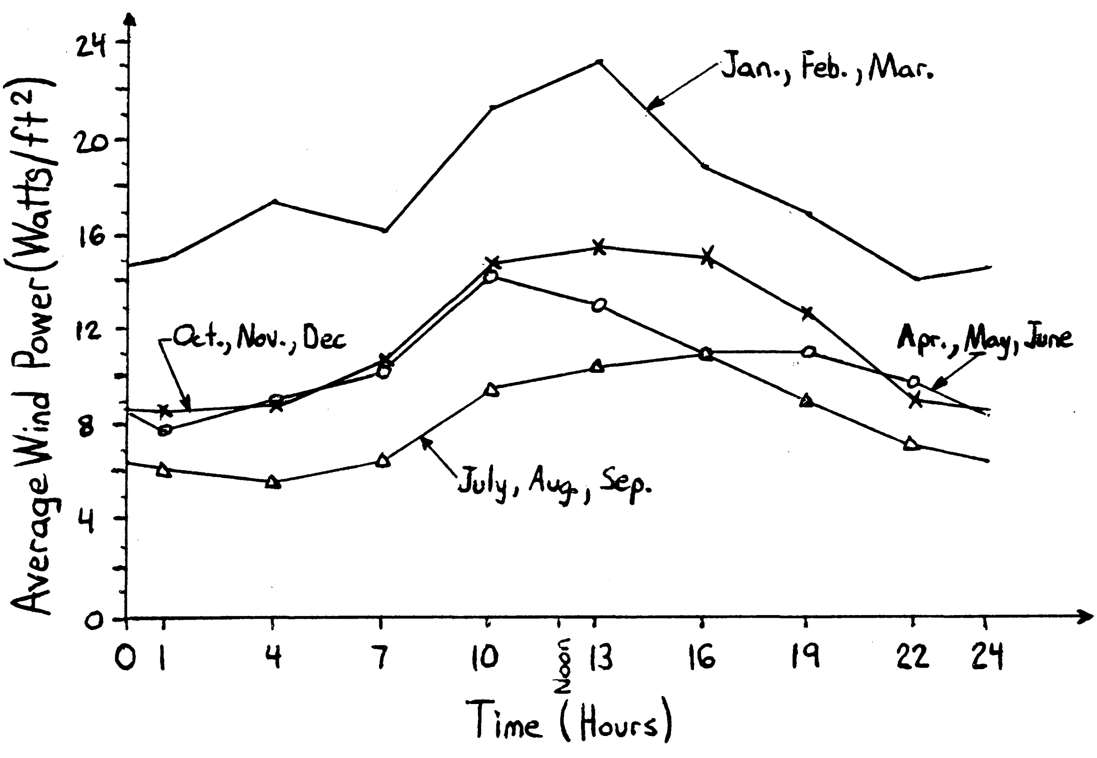
GRAPH 4 - Average Monthly Wind Speed (Cape Hatteras, NC-1982)



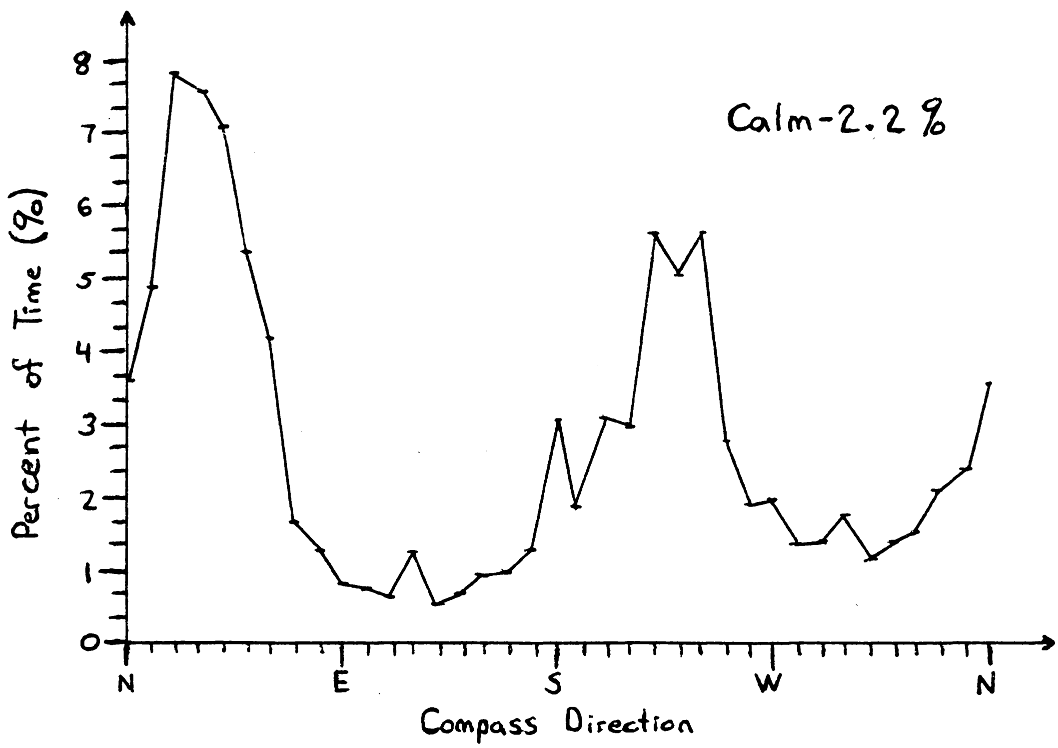
GRAPH 5 - Average Monthly Wind Power (Cape Hatteras, NC-1982)



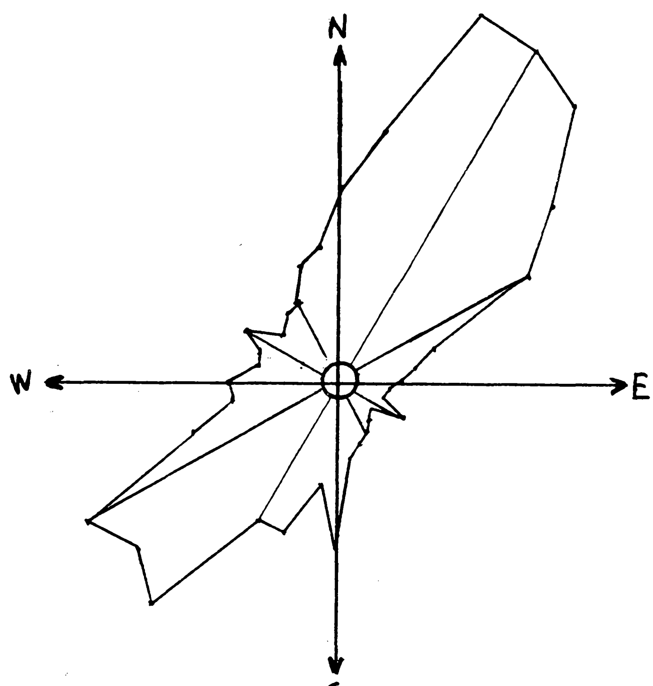
GRAPH 6-Diurnal Wind Speed By Season (Cape Hatteras, NC-1982)



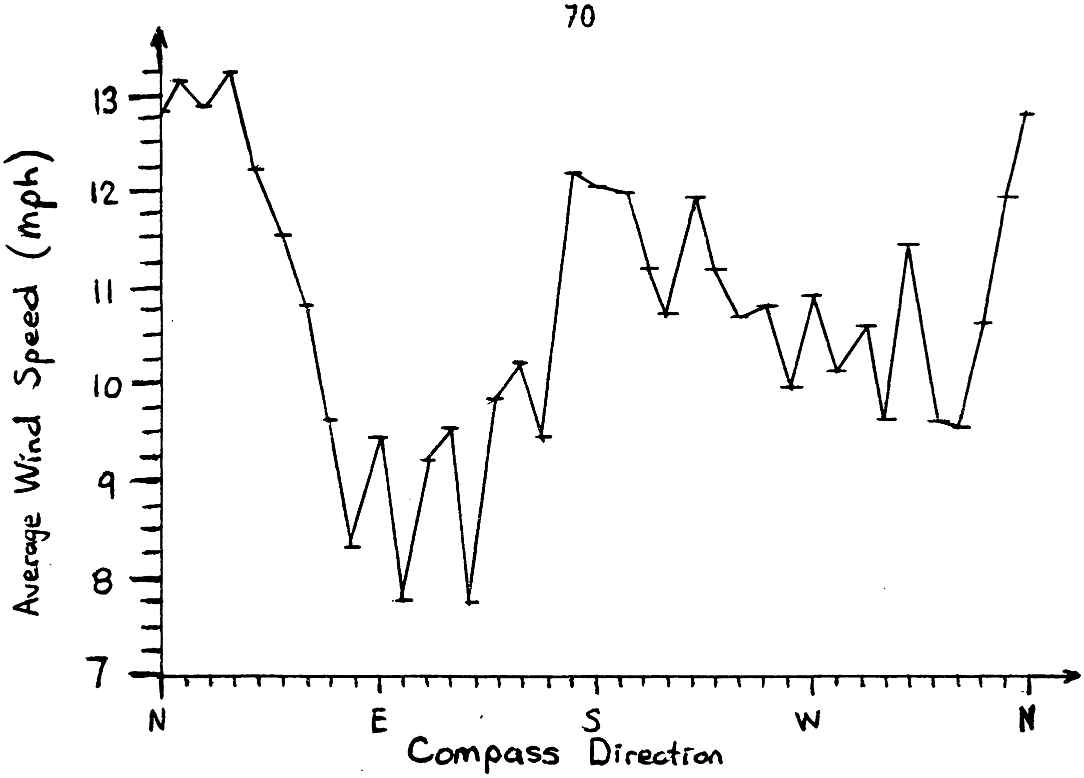
GRAPH 7-Diurnal Wind Power By Season (Cape Hatteras, NC-1982)



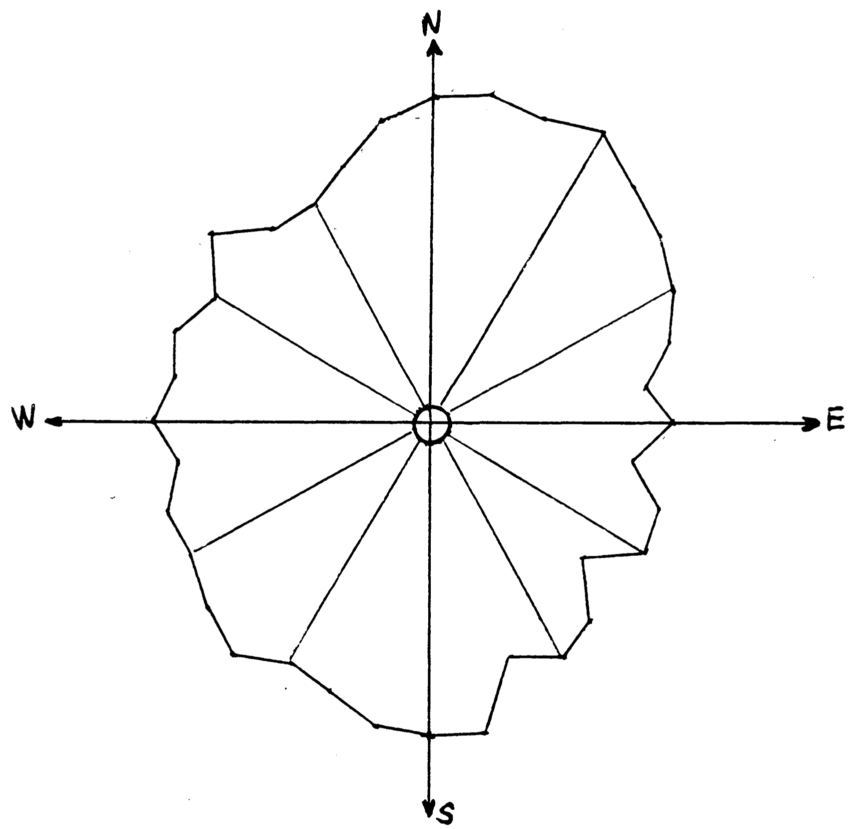
GRAPH 8-Direction Frequency of Wind (Cape Hatteras, NC-1982)



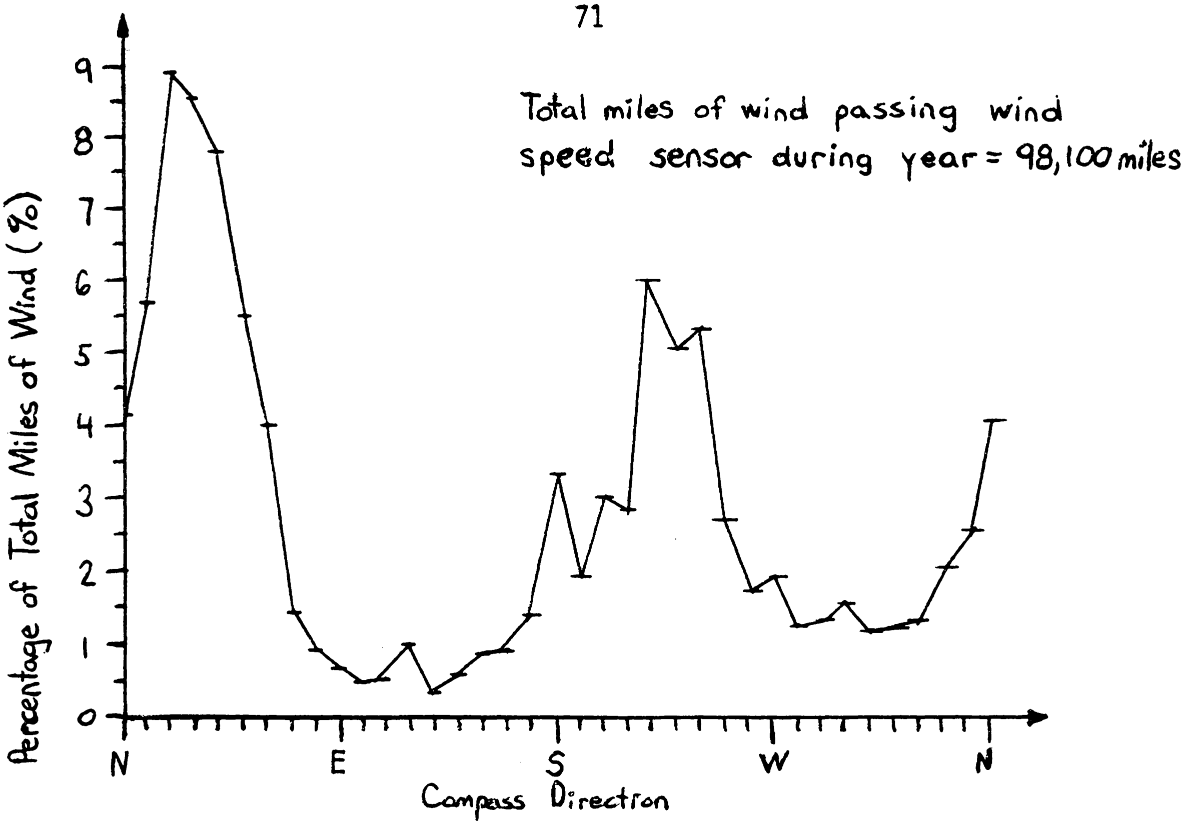
GRAPH 9 - Wind Rose Showing Same Information as Graph 8



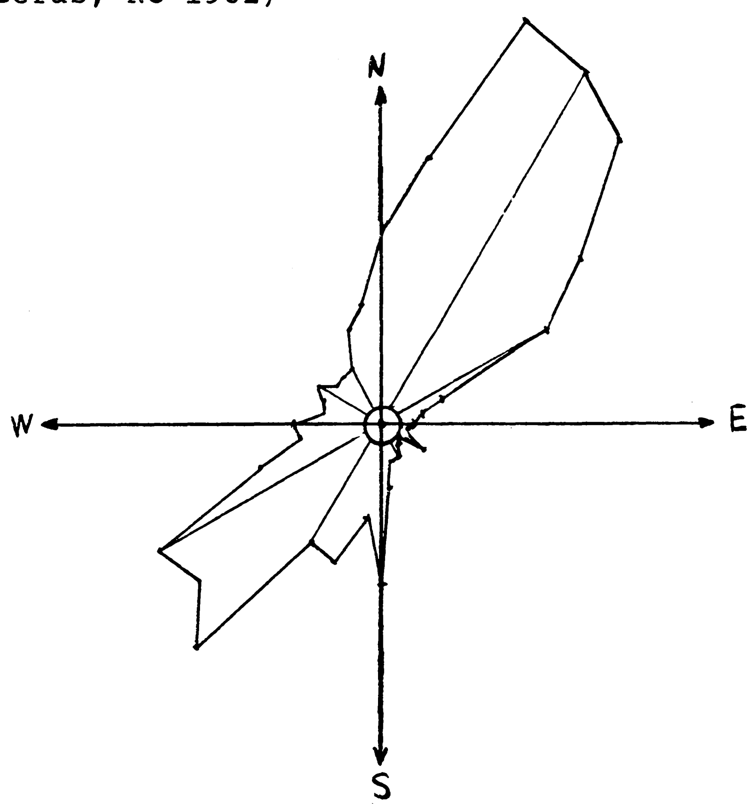
GRAPH 10 - Average Wind Speed versus Wind Direction
(Cape Hatteras, NC-1982)



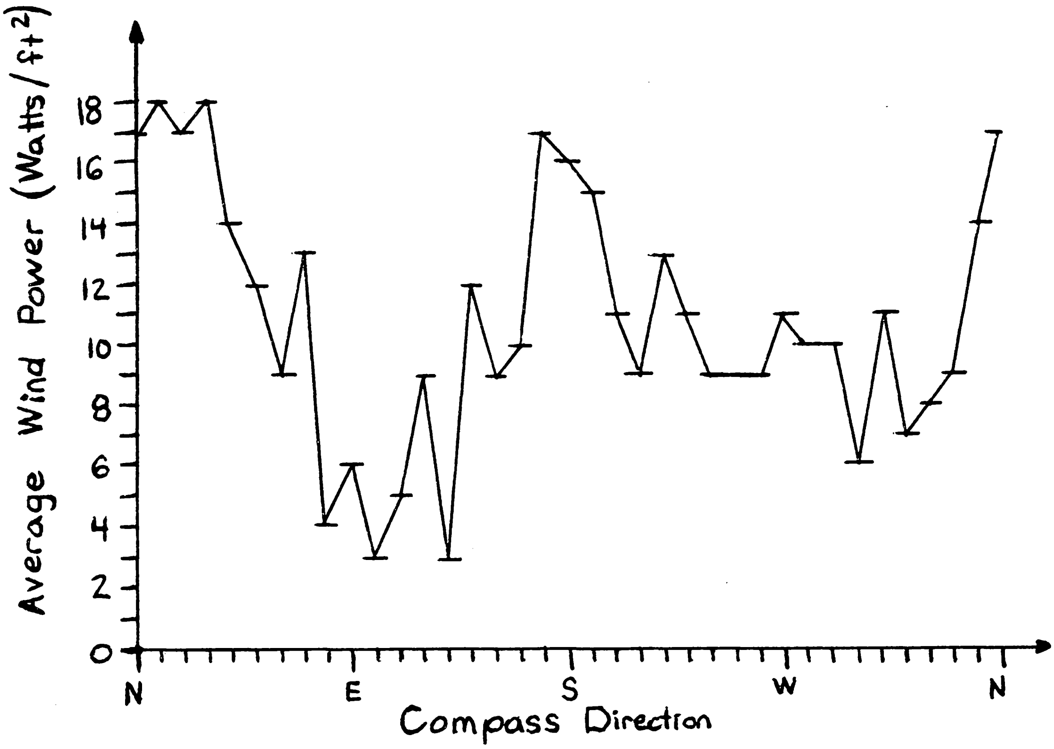
GRAPH 11 - Wind Rose Showing Same Information as Graph 10



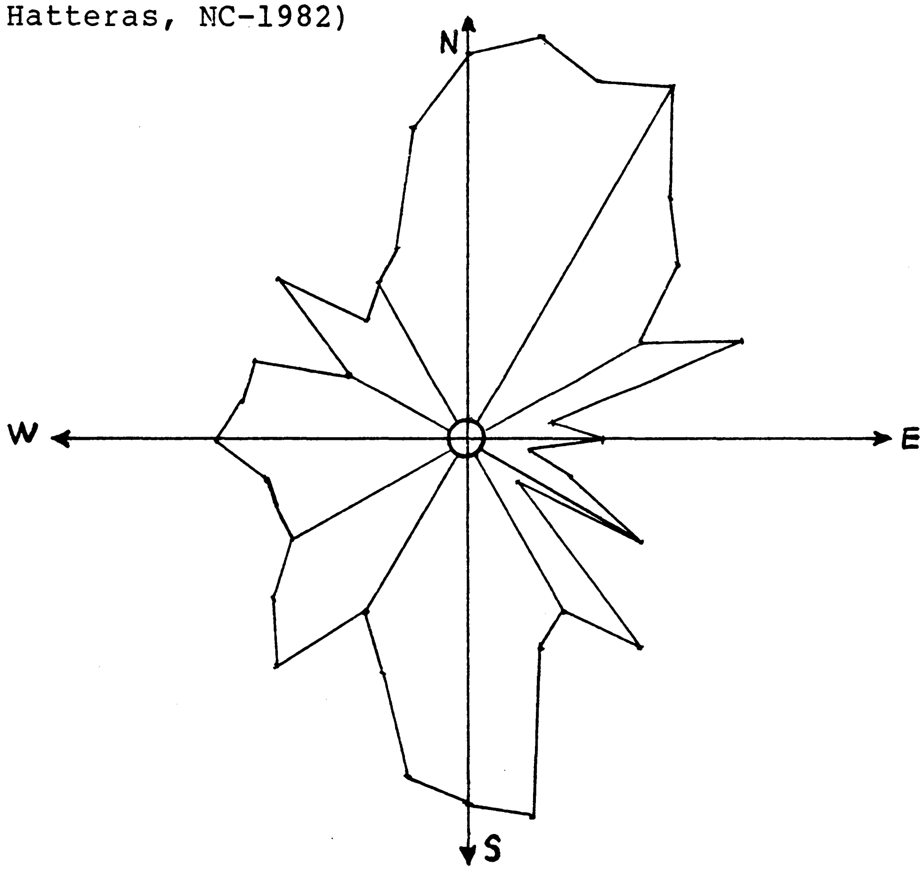
GRAPH 12 - Percentage of Total Miles of Wind by Direction (Cape Hatteras, NC-1982)



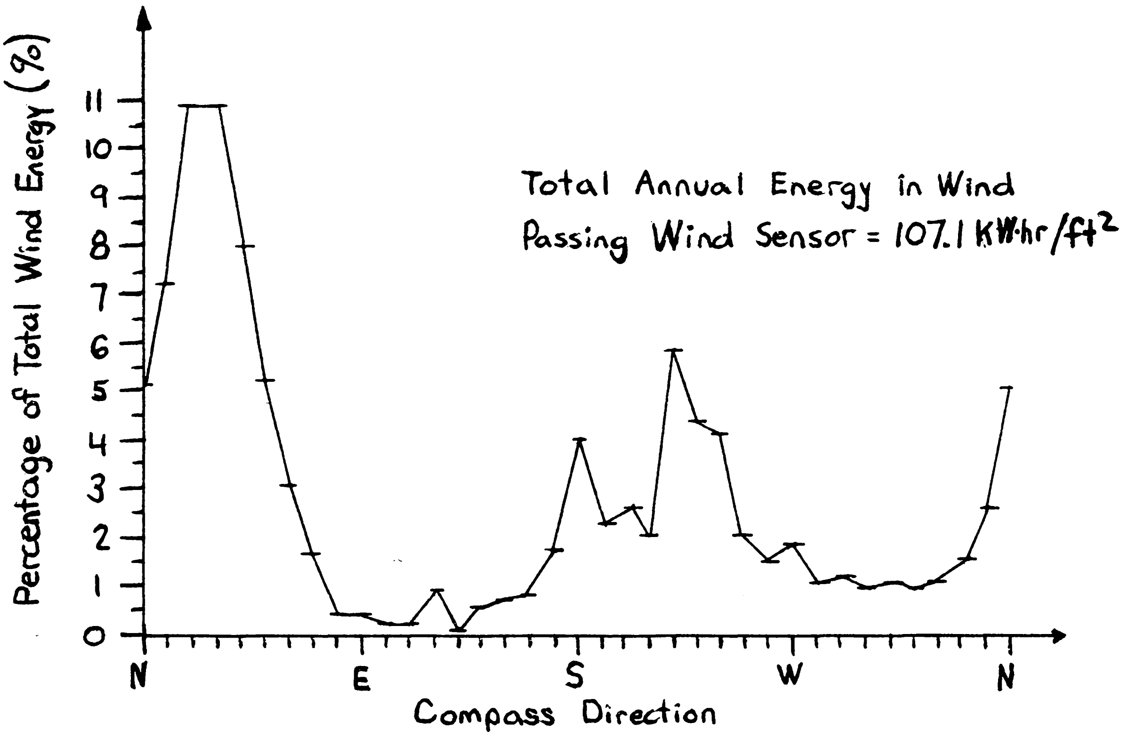
GRAPH 13 - Wind Rose Showing Same Information as Graph 12



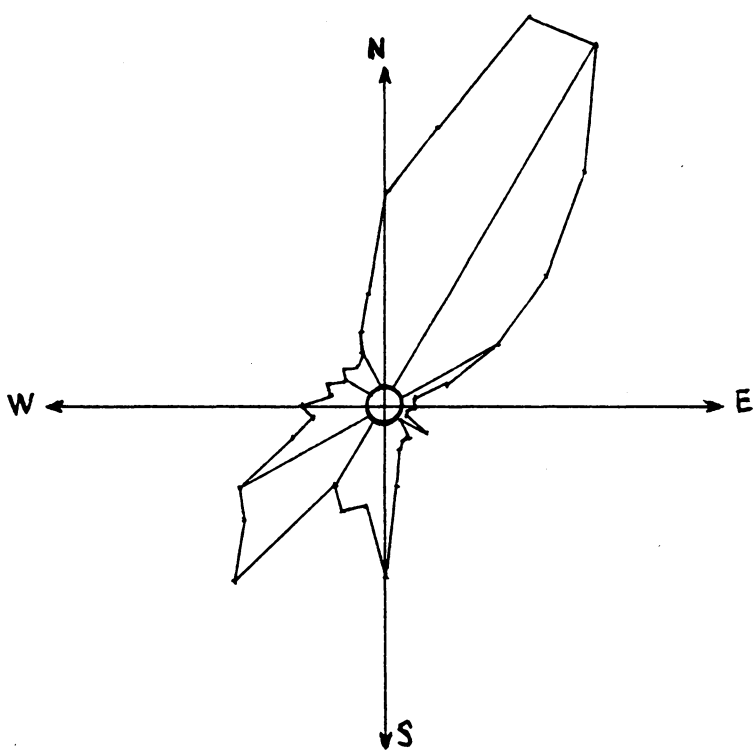
GRAPH 14 - Average Wind Power versus Wind Direction (Cape Hatteras, NC-1982)



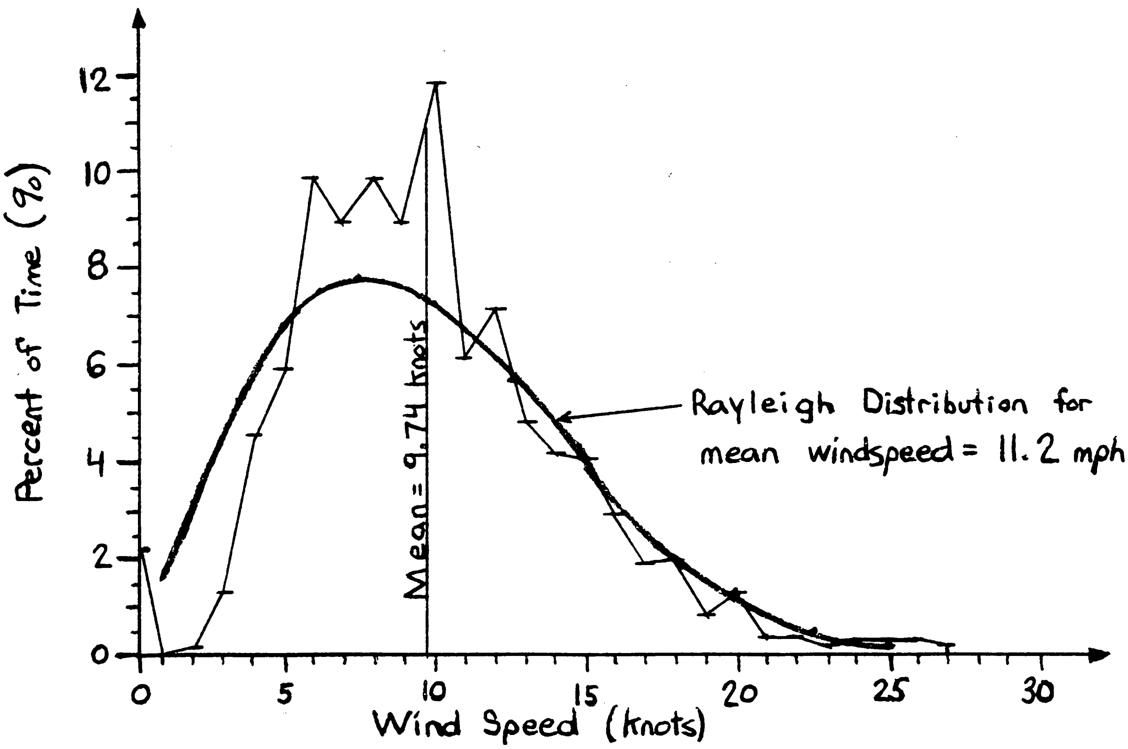
GRAPH 15 - Wind Rose Showing Same Information as Graph 14



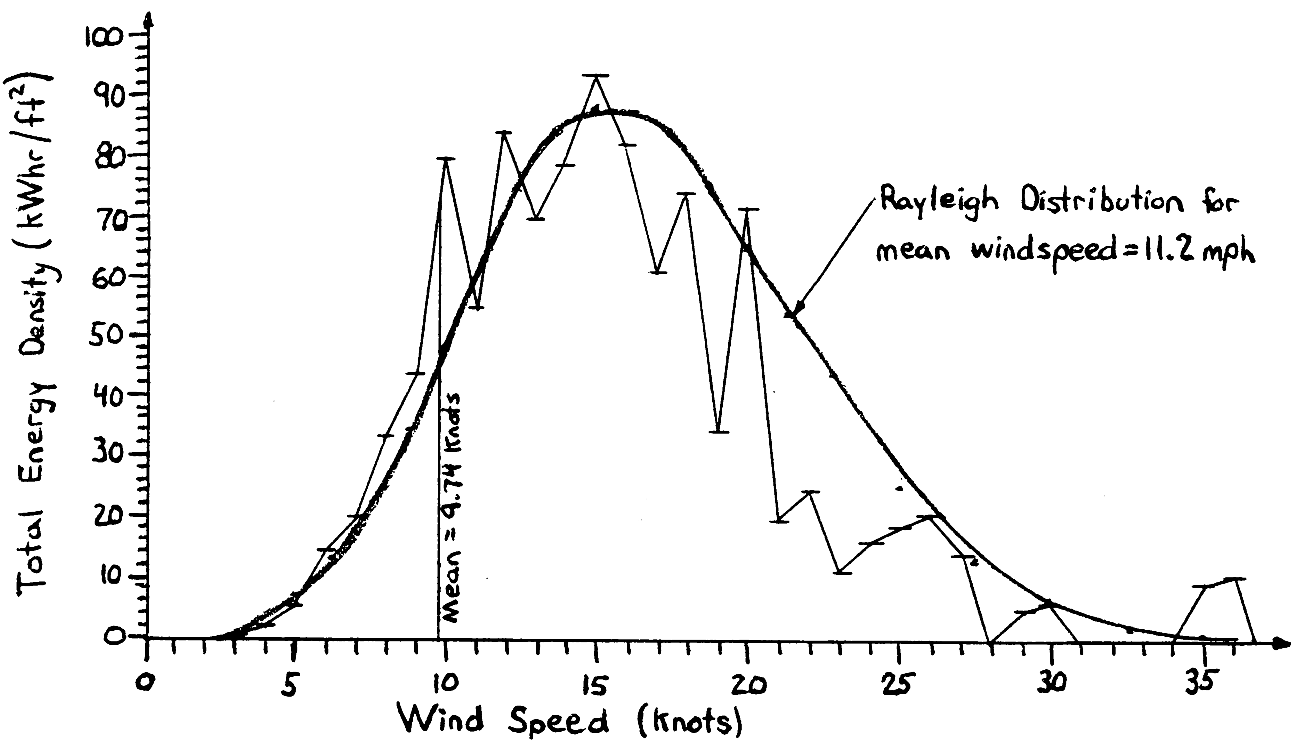
GRAPH 16 - Percentage of Total Wind Energy by Direction (Cape Hatteras, NC-1982)



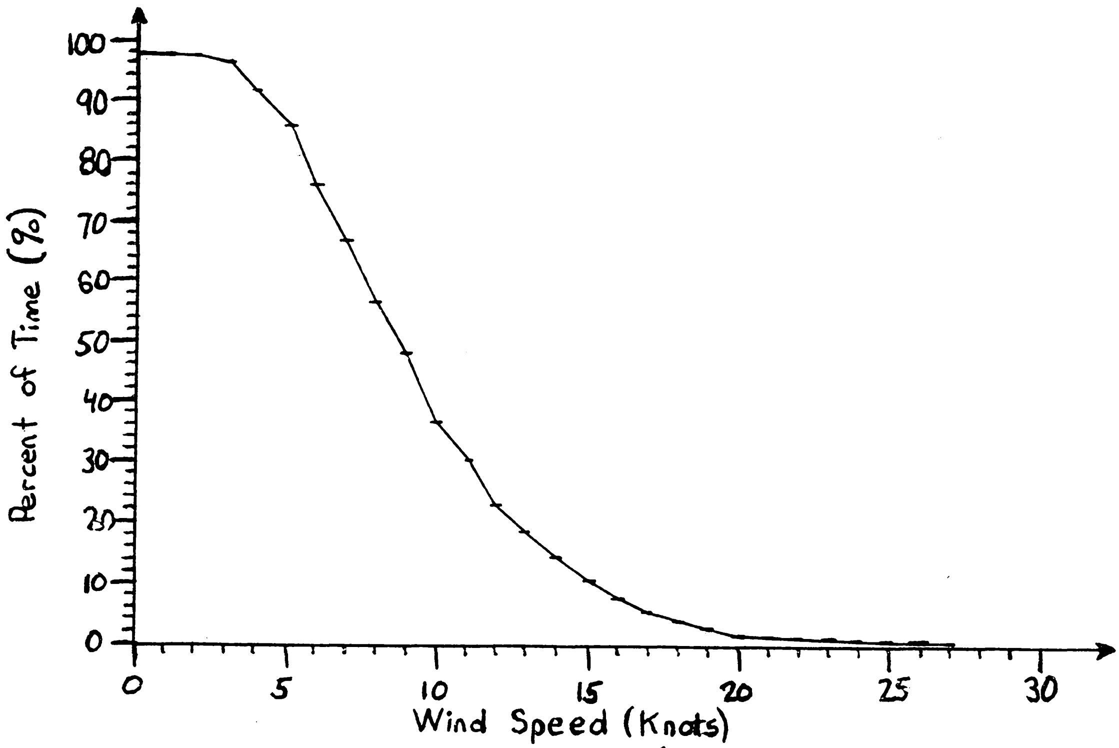
GRAPH 17 - Wind Rose Showing Same Information as Graph 16



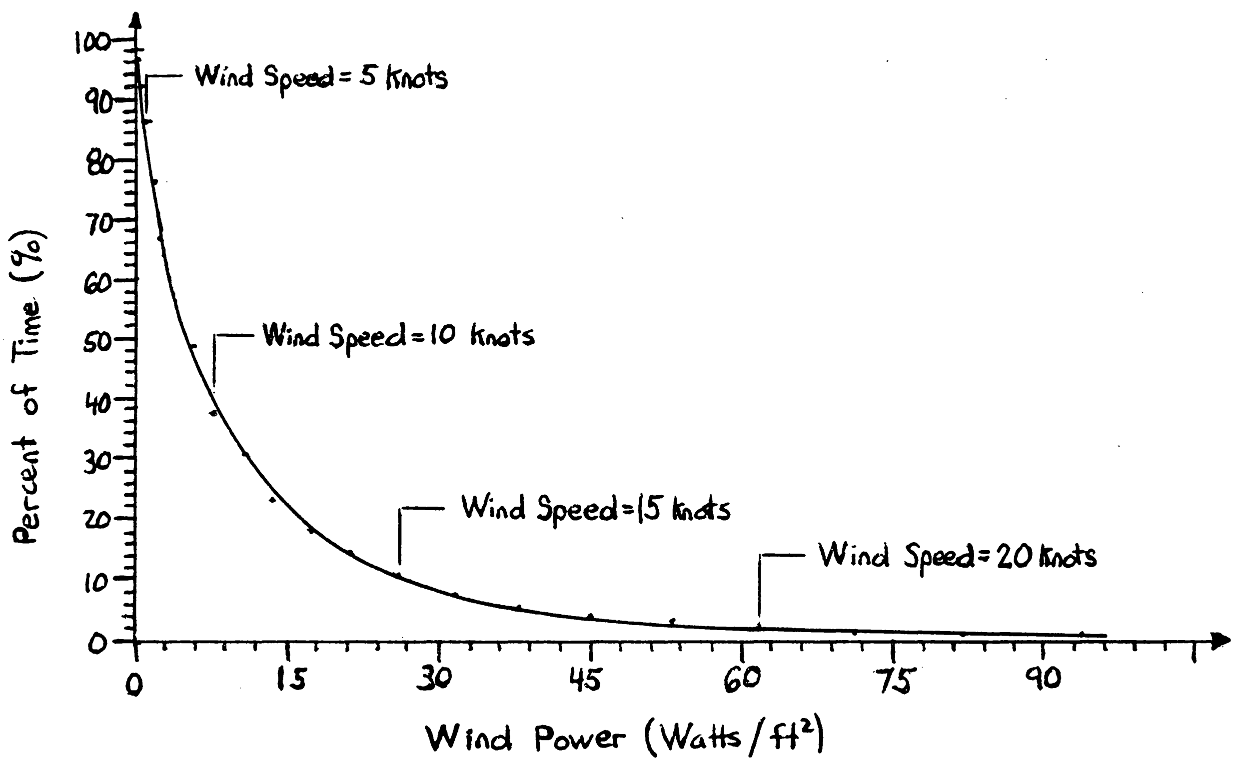
GRAPH 18 - Annual Average Wind Speed Frequency
(Cape Hatteras, NC-1982)



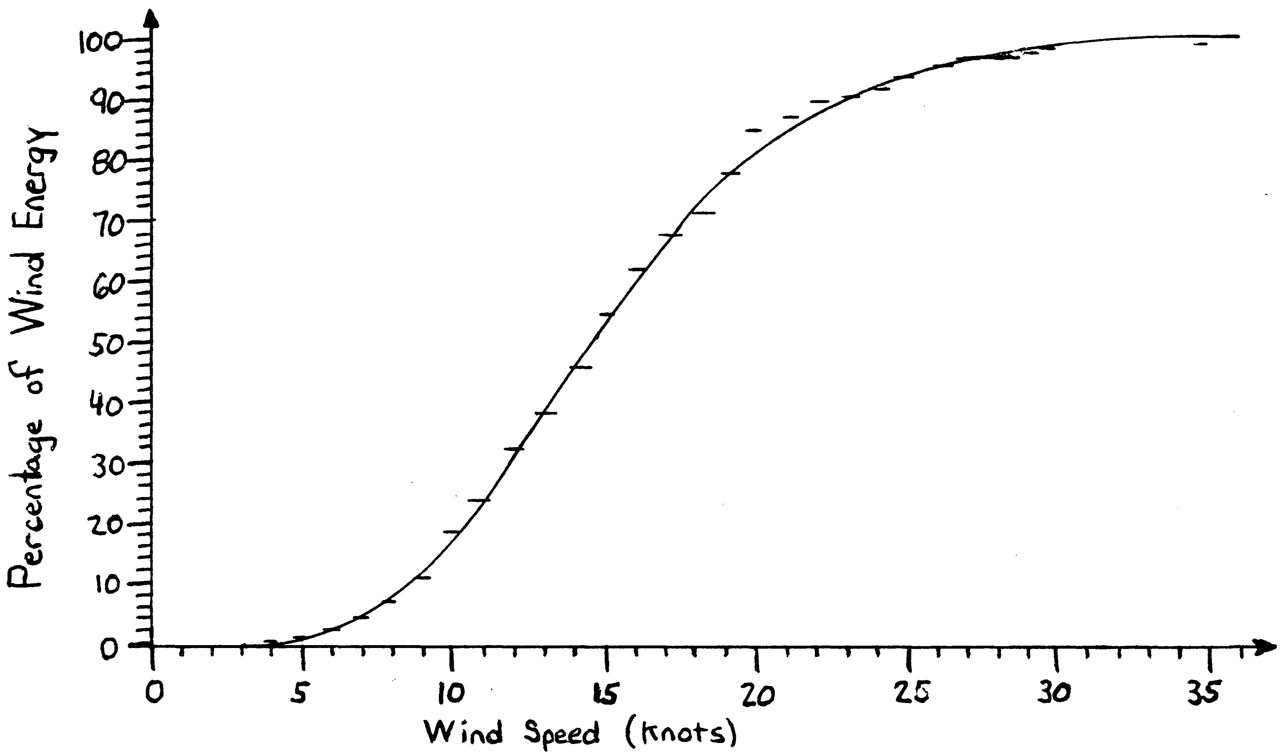
GRAPH 19 - Annual Total Energy Density versus Wind Speed
(Cape Hatteras, NC-1982)



GRAPH 20 - Annual Wind Speed Duration
(Cape Hatteras, NC-1982)



GRAPH 21 - Annual Wind Power Duration
(Cape Hatteras, NC-1982)



GRAPH 22 - Cumulative Frequency Diagram of Wind Energy versus Wind Speed (Cape Hatteras, NC-1982)

IX. TYPES OF WINDMILLS

A. GENERAL

Windmills can be broadly classified according to the means by which they intercept the wind's power. The windmill's rotor converts the passing wind power to mechanical power. There are two types of rotors available for use in windmills: drag-force driven rotors and lift-force driven rotors. Many configurations of these two types of rotors have been devised for use in windmills. These rotor configurations provide the basis for the classification of windmills. Windmills are classified as either (A) low speed, drag-force, (B) low speed, horizontal axis, (C) high speed, horizontal axis, or (D) high speed, vertical axis.

A windmill's rotor converts the wind power into mechanical power. As the wind strikes the rotor blades a drag force develops. The magnitude of this drag-force depends on (1) the size, shape and configuration of the rotor blades, (2) the angle at which the wind strikes the blades, (3) the relative speed of the wind to the blades, (4) the density of the air, and (5) the skin friction of the blades. Several configurations of windmills have been developed that utilize the drag-force as the driving force. These rotors are designed to develop the maximum drag-force. But, drag-force rotors have not been used for electrical generating windmills because (1) they are aerodynamically inefficient and (2) because the ratio of the rotor tip speed to the wind speed (tip-speed-ratio) is low. The rotor speed is a critical factor because most electrical generators must be driven at high rotational speeds. Lift-force rotors can be used to obtain high aerodynamic efficiencies and high tip-speed-ratios. These rotors are designed for maximum lift-force and minimum drag-force. The blades of lift-force rotors are actually airfoils. The shape of the airfoil is such that when the wind moves past, the force exerted on the airfoil has a larger component normal to the direction of flow (lift) than along the direction of flow (drag). This lift-force can be explained by Bernoulli's Principle. Daniel Bernoulli (1700-1782) discovered that the pressure of air decreases as its speed increases.[27] Therefore, airfoils are designed so that the air moving over the upper surface moves faster than the air moving under the lower surface. Hence, the air pressure above the airfoil is less than the air pressure beneath the airfoil. It is this pressure differential which results in the lift-force. There are three lift-force rotor configurations used in windmills. The low speed, horizontal axis rotor is not used in windmills which generate electricity because of its low speed and aerodynamic inefficiency. But, this rotor is widely used in mechanical power producing windmills because of the high torque it develops. Both the high speed, horizontal axis rotor and the high speed, vertical axis rotor are used in electrical generating windmills. Both configurations are[15,16,32,44] aerodynamically efficient and exhibit high tip-speed-ratios.

B. LOW SPEED, DRAG FORCE WINDMILLS

Drag-force rotors operate at low rotor speeds, with tip-speed-ratios in the range of 0.8 to 1.0. This fact, and the low aerodynamic efficiency of drag-force rotors has kept this type of rotor from being used in electrical generating windmills. But, drag-force rotors are ideal for converting wind power directly to mechanical power because they are self-starting and exhibit high torque. The Savonius rotor is the most common drag-force rotor, but there are many other possible rotor configurations. In Figure 25 various Savonius rotor design options are shown. These options include varying the number of blades or the aspect ratio. Intervane gaps and tip plates are two other options shown. Although they are not used to convert wind power to electrical power there are several advantages to drag-force rotors: (1) they are self-starting and have relatively high starting torques as compared to lift-force rotors; (2) they are ideally suited for mechanical power purposes; (3) the rotors can be easily manufactured; and (4) no yawing mechanism is required for most configurations. There are also several disadvantages to low speed, drag-force rotors: (1) tip-speed-ratios are very low; (2) the rotor is aerodynamically inefficient; (3) only low power outputs per rotor size, weight, and cost are obtained; (4) the rotor can be hard to control in high winds, with a brake being the most feasible control; and (5) the tower must be designed for lift-forces produced by the Magnus Effect. As air on one side of the rotor is slowed down, air on the other side is speeded up. This results in a lift force, or Magnus Effect, that causes the machine to move perpendicular to the wind. Even though drag-force rotors are not used to convert wind power to electrical power, an understanding of their features is valuable. For instance, drag-force rotors have been used as starter motors for high speed, vertical axis windmills.[16,32,44]

C. LOW SPEED, HORIZONTAL AXIS WINDMILLS

Most low speed, horizontal axis windmills are used to pump water. Basically, they consist of the following components: 30 to 40 blades, hub, power shaft, transmission, water pumping mechanism, tail vane or other yawing mechanism, brake and/or furling mechanism, tower, and foundation. A typical low speed, horizontal axis windmill is shown in Figure 26. The term "horizontal axis" comes from the fact that the rotor's axis of rotation is horizontal to the ground. High solidity windmills, such as the American water pumping windmill, operate at low tip-speed-ratios and high torque. The solidity ratio is defined as the ratio of blade area to total area swept by the rotor in one rotation. In general, high solidity windmills operate at low tip-speed-ratios while low solidity windmills operate at high tip-speed-ratios. Horizontal axis windmills are further classified as being upwind or downwind, depending on the position of the rotor relative to the tower during operation. The rotor diameter of low speed, horizontal axis windmills is usually in the range of 6 to 20 feet. There are several advantages to these low speed, horizontal axis windmills: (1) they are well suited for mechanical power applications due to the high torque they develop; (2) the blade configuration helps to maximize the lift-force produced; (3) design and construction is relatively simple; (4) they are self starting; (5) operation controls are relatively simple; (6) minimal maintenance is required; and (7) expected life time is 20 to 30 years. There are also several disadvantages to low speed, horizontal axis windmills: (1) the rotor is aerodynamically inefficient; (2) the aerodynamic efficiency is further reduced (by up to 10%) by the high swirl induced in the airstream downwind of the blades; (3) due to their low tip-speed-ratios, high solidity rotors are not readily adaptable for use in electrical producing windmills; (4) the high solidity rotor results in higher tower loads; and (5) low speed, horizontal axis windmills are static technology in that they show no sign for improvement.[16,32,44]

D. HIGH SPEED, HORIZONTAL AXIS WINDMILLS

In general, high speed, horizontal axis windmills are used to generate electricity. Basically, they consist of the following components: blades, hub, power shaft, transmission, generator, yawing mechanism, brake and/or governor and/or furling mechanism, tower, and foundation. A typical high speed, horizontal axis windmill is shown in Figure 27. The rotor diameter varies from several feet for very small windmills to several hundred feet for very large windmills. There are several advantages to high speed, horizontal axis windmills: (1) they are well suited for electrical generation due to the high tip-speed-ratios which they operate at; (2) transmission requirements are reduced because of the high tip-speed-ratios; (3) the aerodynamically efficient, high speed rotors develop more force per swept area than slower, lift-force rotors and drag-force rotors; (4) lower tower loads occur with low solidity rotors; (5) high power-output-to-weight ratios result in lower cost-to-power-output ratios; (6) high speed, horizontal axis rotors will self start; and (7) large diameter rotors with high power levels are more easily obtained. There are also several disadvantages to high speed, horizontal axis windmills: (1) careful attention must be paid to the aerodynamic design of the rotor; (2) blade flutter and vibration problems can occur; (3) a yawing mechanism must be used to turn the rotor into the wind; (4) only low starting torques are developed, but they are usually sufficient to start the machine; and (5) generating, gearing and other heavy mechanical equipment is located at the top of the tower. In addition to necessitating a stronger tower, this presents problems in the installation, maintenance and repair of tower top equipment. High speed, horizontal axis windmills are by far the most common wind machines used for generating electricity.[6,15,16,24,32,44]

E. HIGH SPEED, VERTICAL AXIS WINDMILLS

Most high speed, vertical axis windmills have the following basic components: blades, 2 hubs, center power shaft, transmission, generator, brakes/governor, starting motor, tower, guy wires, and foundation. The term "vertical axis" refers to the fact that the rotor's axis is vertical to the ground. Their low solidity and high tip-speed-ratio render high speed, vertical axis windmills well suited for electrical generation. The two basic types of high speed, vertical axis windmill are the Darrieus and the giromill.

An example of each of these is given in Figure 28. The troposkien shape (derived from the Greek; literally, "turing rope") of the Darrieus blades is the natural shape a flexible cable would assume if spun about a fixed axis. This shape helps to minimize the stresses in the blades. The Darrieus blades have a symmetric cross section. The giromill employs straight, symmetric cross section, variable pitch blades. Articulation of the blades during each rotation helps to maximize the driving lift-force. There are several advantages to high speed, vertical axis windmills: (1) they are well suited for electrical generation due to their high tip-speed-ratios; (2) transmission requirements are reduced because of the high tip-speed-ratios; (3) the aerodynamic efficiency is relatively high, and lift-force is produced over almost the entire circular path; (4) the tower structure is less massive than that associated with high speed, horizontal axis windmills; (5) high power-output-to-weigh ratios and low cost-to-power-output ratios are possible; (6) generating, gearing and other heavy mechanical equipment may be located on the ground which helps to reduce tower loads, and facilitates installation, maintenance and repair of the equipment; and (7) last but not least, no yawing mechanism is required because the windmill will respond to wind from any direction equally well. There are also several disadvantages to high speed, vertical axis windmills: (1) the Darrieus blades usually are long, precisely shaped and difficult to manufacture; (2) the ends of the Darrieus blades contribute little to power output; (3) controls for varying the giromills blade pitch increase the complexity of the system; (4) the blades are exposed to constantly varying loads during each revolution; (5) a starter motor or other starting mechanism is usually required to put the blades in motion, but they have also been known to unexpectedly self-start; and (6) the rotor is easily stalled when overloaded or in gusty winds. In comparison to high speed, horizontal axis windmills, high speed, vertical axis windmills are in an early stage of development. Future improvements may lead to expanded use of high speed, vertical axis windmills.[6,15,16,24,32,44]

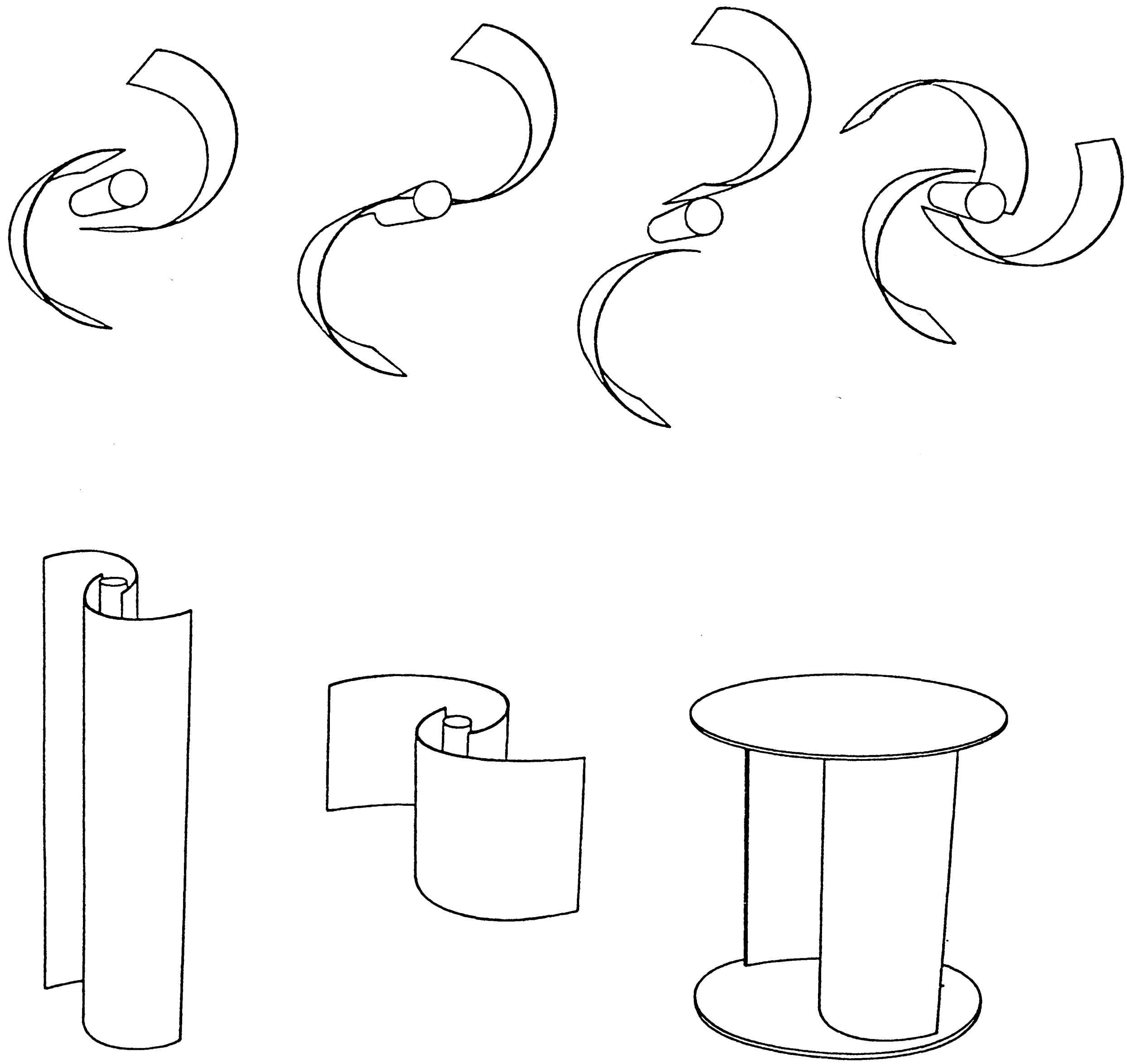


FIGURE 25 - Various Savonius Rotor Design Options. 32

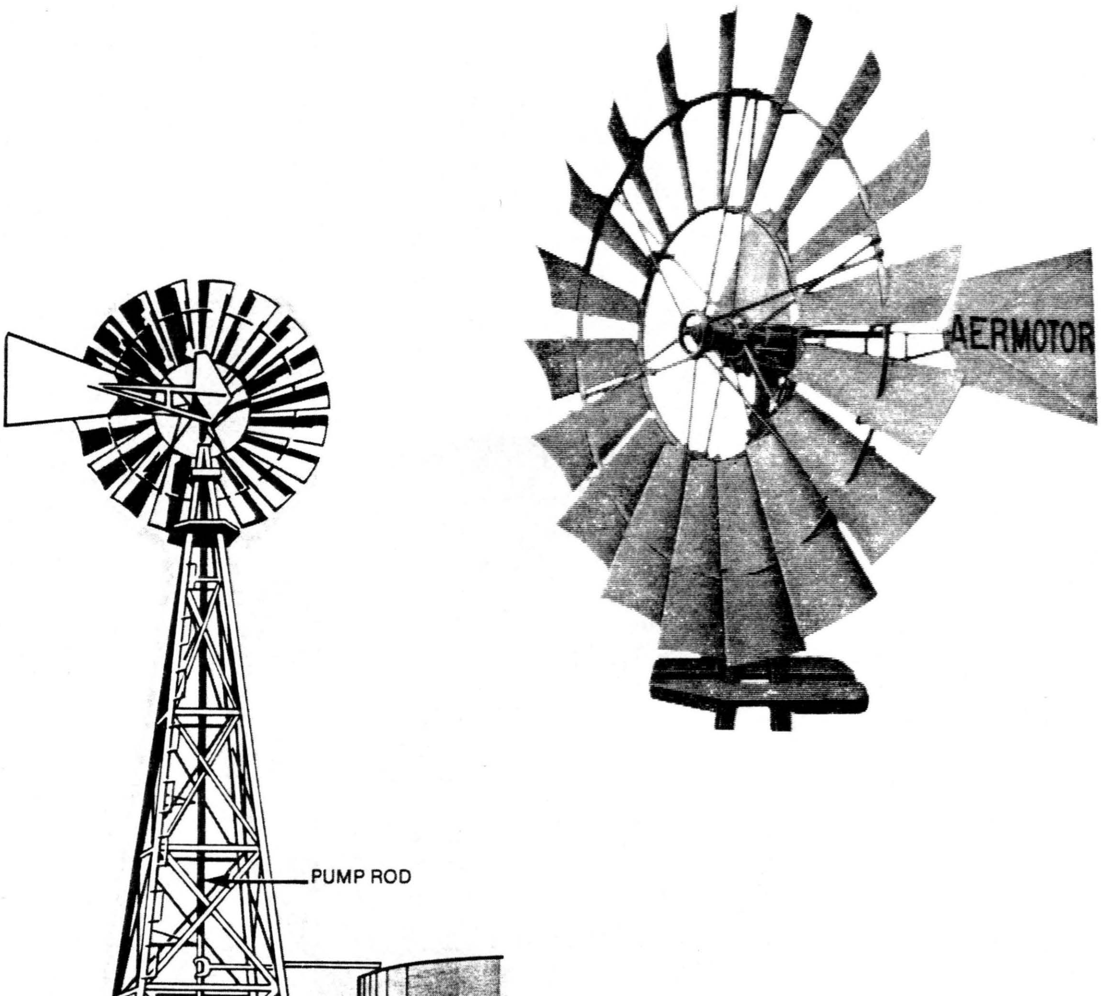


FIGURE 26 - Typical Low Speed, Horizontal Axis Windmill. [36]

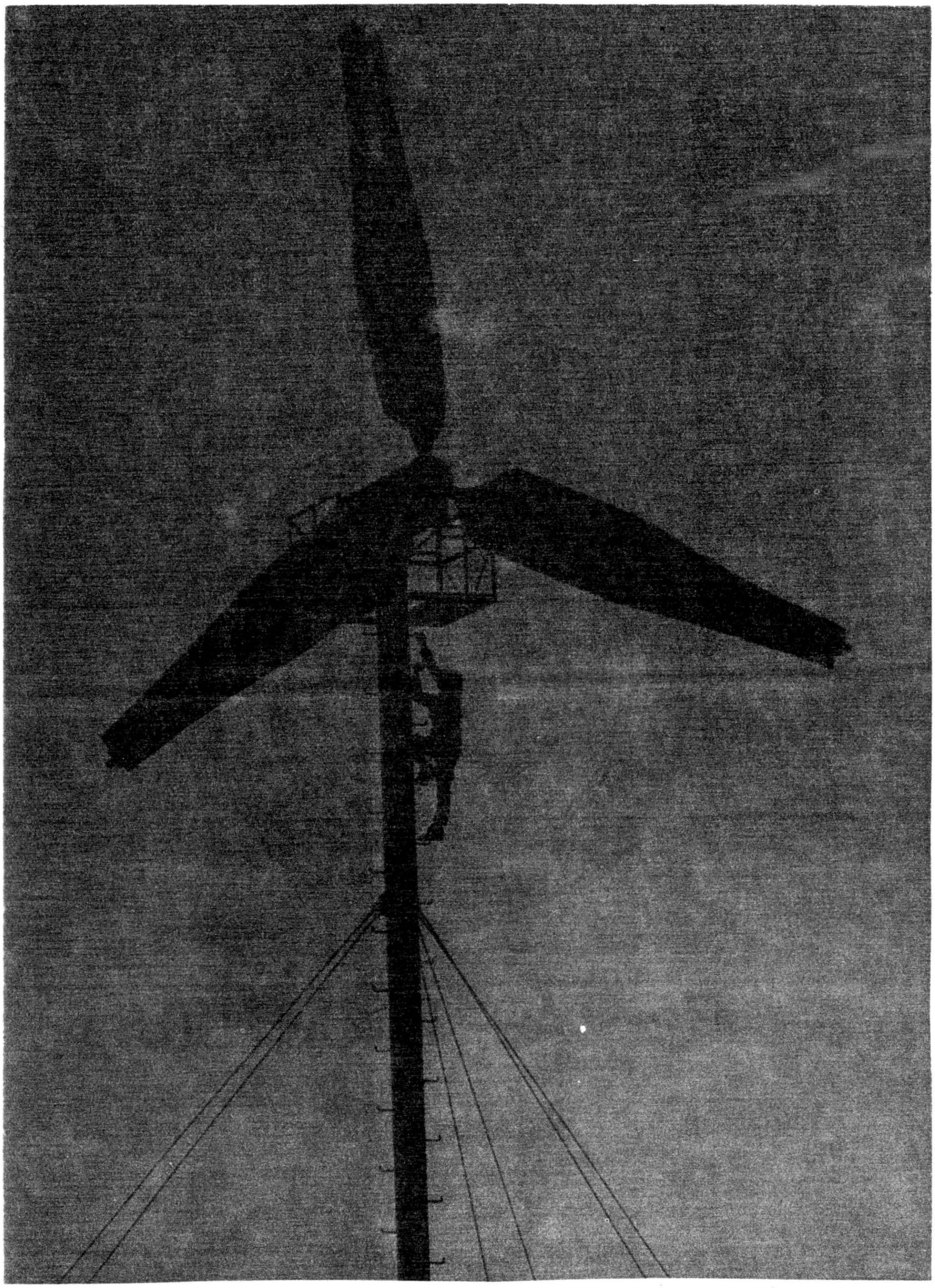
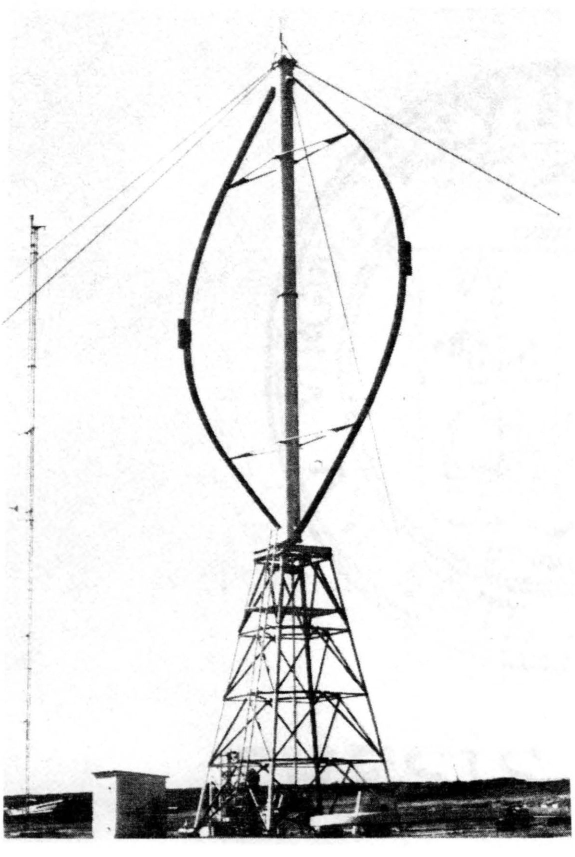
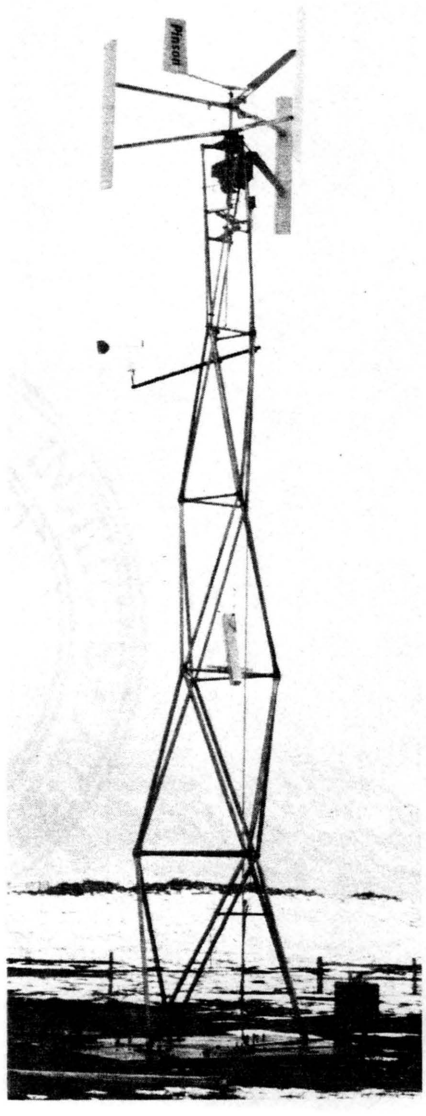


FIGURE 27 - Typical High Speed, Horizontal Axis Windmill.



(a) Darrieus



(b) Giromill

FIGURE 28 - Typical High Speed, Vertical Axis Windmills.

X. REVIEW OF FIVE WIND POWER SYSTEMS

A. GENERAL

The following windpower systems are reviewed:

Jacobs Model 1023

Enertech 44

ESI-54-S

DOE/NASA MOD-OA-4

DOE/NASA MOD-2

The review consist of pictures and schematics of each system. A written description breaks the systems down into their component parts. Two graphs are given for each system. The first graph plots system output versus wind speed and system efficiency versus wind speed. The second graph is the result of an analysis done to estimate the yearly system output at each wind speed if the system were located at Cape Hatteras.

The information for the system output versus wind speed graph was supplied by the systems manufacturer. The following procedure was used to estimate how these systems would perform if located at Cape Hatteras. The Cape Hatteras wind data analyzed in Section VIII was used to estimate what the yearly system output would be at each wind speed. First, the number of hours the wind blew at each speed during the year was determined by using a computer to sort the wind speed data. No reduction for system unavailability was taken. It is important to note that each wind data point used is a three hour average wind speed. Due to the cubic relationship of wind power to wind speed this can result in underestimates of total system output. More accurate estimates can be obtained by using wind speeds averaged over shorter time intervals, such as five minutes.

Second, graphs of system output versus wind speed were used to estimate system output at each wind speed. These graphs were drawn for the wind speed at the windmill hub. The graphs were small and difficult to read with accuracy. In addition, the graphs were plotted as a function of wind speed in miles-per-hour while the wind data was given in knots. This added to the difficulty of reading the graphs.

Third, the wind data which was obtained at 30 feet above ground level had to be adjusted to agree with the height that the graphs in Step 2 were drawn for. Equation 18 from Section VI was used to accomplish this:

$$(V1/V2) = (H1/H2)^n$$

A value of n=1/7 was used. This step was difficult because the adjusted wind speeds were not integer values and therefore could not be directly correlated with the system output data. To get around this problem, plots of adjusted wind speed versus hours-per-year were drawn. The number of hours of wind at integer values of wind speed were then determined.

Fourth, the yearly system output at each wind speed was determined. A computer program was used to multiply system output at wind speed X by the number of hours of wind speed X during the year to determine the yearly system output at wind speed X. A "FOR NEXT" statement was used to cover all wind speeds. The yearly system outputs at each wind speed could easily be improved by using more wind data and more accurate system output estimates.

The system efficiency, n(e), at each wind speed was determined using Equations 16 and 17 from Section V:

n(e) = (usable power produced / wind power available)

n(e) = (P)out / [rho*A*(V1^3)/2]

As in the fourth step above, a computer program was used to determine the system efficiency. The system output at each wind speed, (P)out, was determined in the second step above. The total power available, [rho*A*(V1^3)/2], was determined for each value of wind speed, V, as follows. The swept area, A, was entered for each system and the air density, rho, was assumed to be constant at 0.08 lb/ft3. The computer then stepped through each wind speed and determined the efficiency.

Additional graphs similar to those in Section VIII could be developed. For instance, the following graphs could be drawn: Average Monthly System Output, Diurnal System Output by Season, Average System Output by Wind Direction, Total System Output by Wind Direction, System Output by Percent of Time, and Cumulative Frequency Diagram of System Output versus Wind Speed. Computer programs used in this section are listed in Appendix B.

B. JACOBS MODEL 1023 [20]

Manufacturer: Jacobs Wind Electric Company; Minneapolis, MN

Model: 1023 - Shown in Figure 29.

Rated Output: 10 kW

Design Life: 20 years

Warranty: 2 year limited warranty - Dealer installed

Years in Business: Over 50

ROTOR

Type: Horizontal Axis, Upwind

Diameter: 23 feet Swept Area: 413 sq. ft.

Rated Output/Swept Area: Approximately 24 Watts/sq. ft.

Number of Blades: 3

Material of Blades: Laminated wood, painted

Blade Chord: Varies from 4 inches at the tip to 8.5 inches at the root

Rotor Speed: 0 to 210 (+/-) rpm

Comments: The use of a 3 bladed, tail vaned system eliminates the jerking motions during yawing and reduces the blade pitching motions found in 2 bladed, tail vaned systems.

TRANSMISSION

Type: Offset hypoid gear with tapered roller bearings in a steel case gear box. Shown in Figure 30.

Comments: This transmission allows the hub to be close to the tower, which allows the blades to pass above and behind the tower center. This also allows the rotor to pivot quickly about the tower axis to avoid the full force of gusting winds. The power shaft is angled upward to reduce vibration, increase power, and equalize power.

GENERATOR

Type: Alternator (Definition: Polyphase synchronous machine used as a generator)

Rated Output: 20 kW

Speed: 1800 (+/-) rpm

Number of Phases: 3

Frequency: Variable

Comments: No brushes, slip rings or other rotating electric connections which may flash or burn are used. The generator is mounted inside the tower stub which helps to stabilize the tower by placing the greatest weight inside the tower at the center axis. A line commutated frequency changer is required.

TOWER and FOUNDATION

Type: 3 legs, open truss, free standing - Designed and manufactured by UNR-ROHN Inc.

Material: Galvanized steel, all bolted

Available Heights: 60 feet, 80 feet, 100 feet, 120 feet, 140 feet, and 160 feet.

Foundation: 3 concrete anchor blocks, engineer for site

Comments: The Jacobs 7 foot tower stub mounts to the top of the tower. The tower stub is shipped from the factory completely assembled. At the site only the blades and the tail vane must be fastened to the tower stub, the complete assembly is lifted to the tower top and bolted to the base plates.

GENERAL

Design/Survival Wind Speed: 100 mph

Weather Shielding: 3 removable aluminum covers

Graph 23 shows the system output versus wind speed, and the approximate system efficiency versus wind speed.

Graph 24 shows the estimated system output for a one year period using the wind data from Section VIII.

CONTROL and PROTECTION

Blade Pitch: Variable blade pitch is controlled by an automatic, blade actuated governor. All 3 blades are mechanically interconnected to feather equally at a preset speed. The centrifical force of the blades power the feathering mechanism with no strain on the hub. Bushings are used.

Yaw: The unit freely tracks the wind. A tail vane is used at low wind speeds to orient the rotor into the wind. The turntable assembly uses a tapered roller bearing and bushing. Equipment which tracks the wind weighs less than 500 pounds.

Brake: Disk brake, single calipers, manually operated

Control System: The rotor axis is offset from the tower center so that excessive wind thrust will cause the rotor to pivot around the tower laterally to the wind. The Automatic Spring Snubber Control controls this movement. The windmill operates continuously in all winds. Through a combination of blade feathering and rotating the rotor out of the wind, the wind pressure on the rotor never exceeds that of a 40 (+/-) mph wind.

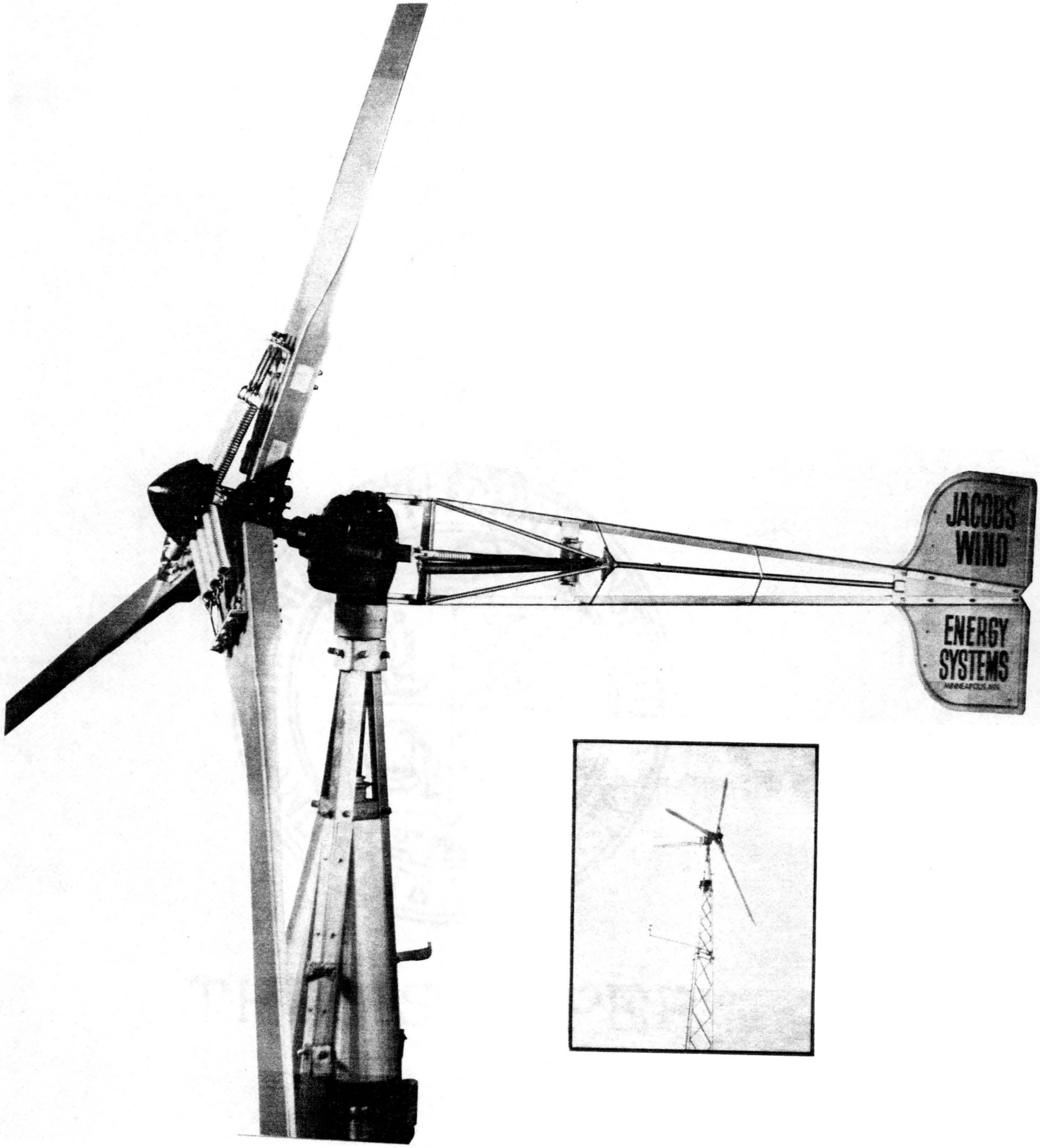


FIGURE 29 - Jacobs Model 1023.

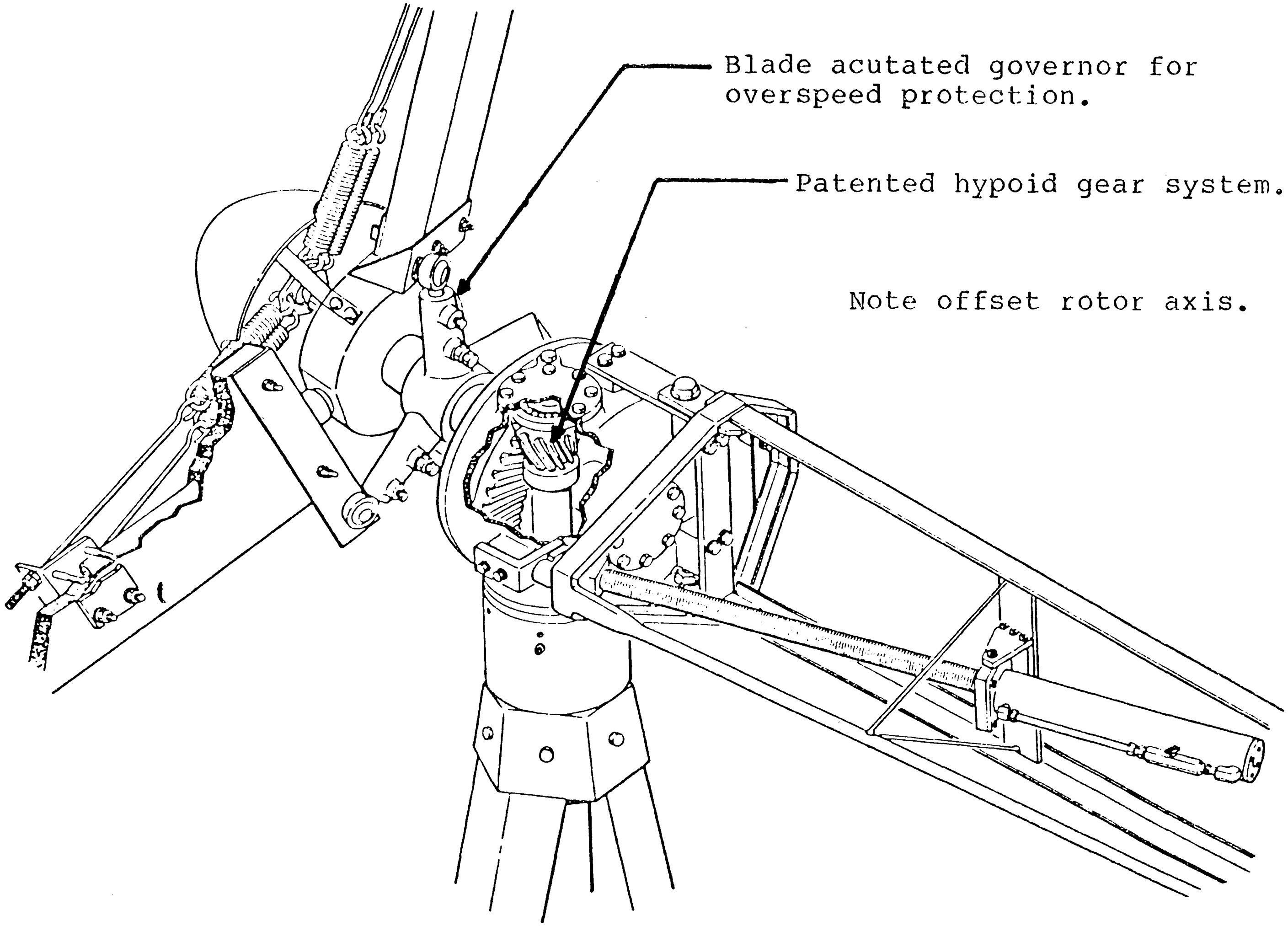
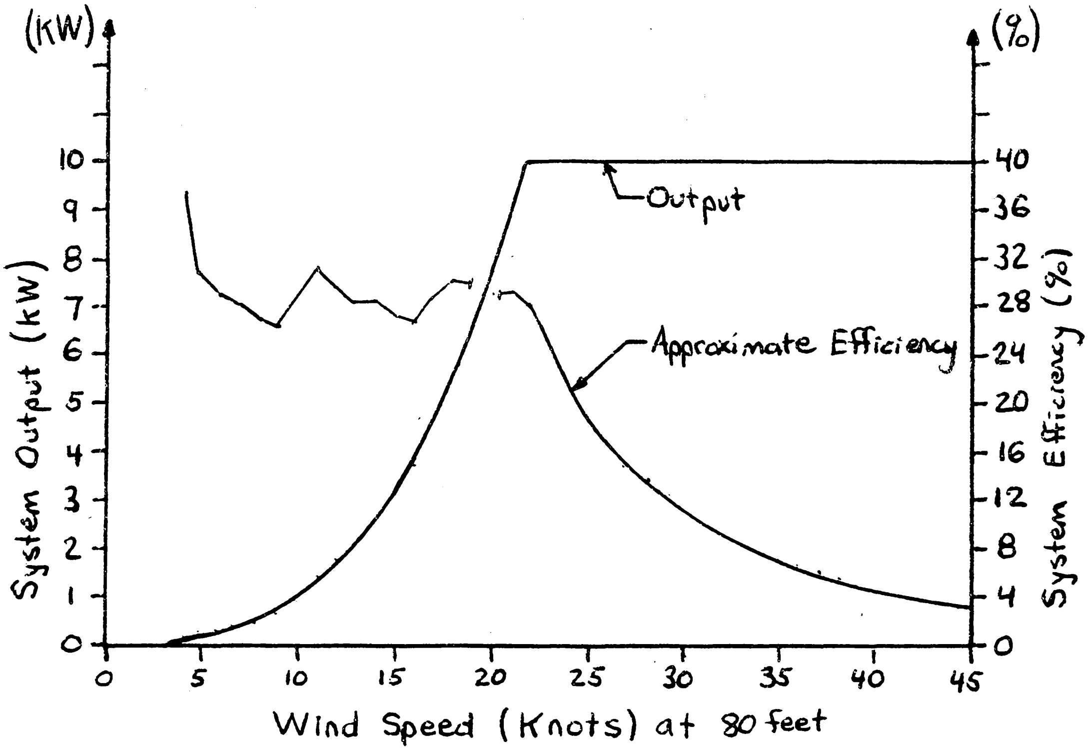
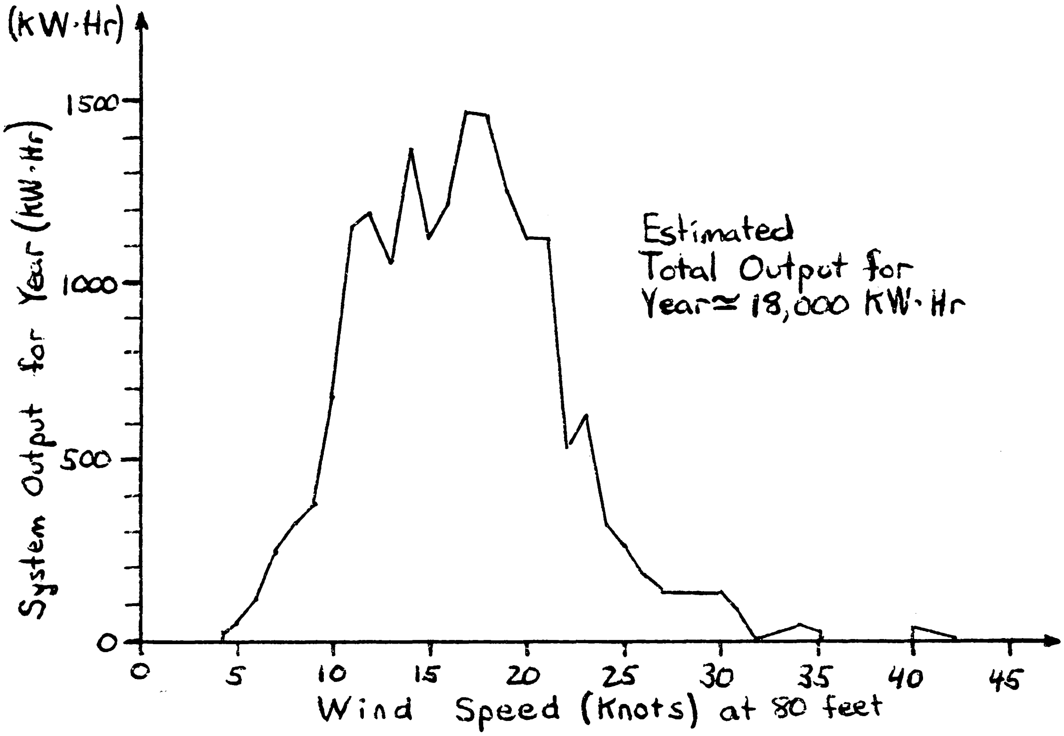


FIGURE 30 - Cutaway Drawing of the Power System of the Jacobs Model 1023.



GRAPH 23 - Jacobs Model 1023: System Output versus Wind Speed; Approximate System Efficiency versus Wind Speed.



GRAPH 24 - Jacobs Model 1023, Estimated System Output versus Wind Speed for Year Using Wind Data from Section VIII (Cape Hatteras, NC-1982).

C. ENERTECH MODEL 44 [12]

Manufacturer: Enertech Corporation; Norwich, VT

Model: Enertech 44 - Shown in Figures 31 and 32.

Rated Output: 25 kW in a 30 mph wind

Design Life: 20 years

ROTOR

Type: Horizontal Axis, Downwind

Diameter: 44 feet Swept Area: 1520 sq. ft.

Rated Output/Swept Area: Approximately 16 Watts/sq. ft.

Number of Blades: 3 - provides better stability and results in less fatigue than 2 blade systems

Material of Blades: Wood/Epoxy laminate - will not create electromagnetic interference

Design TSR: 6 to 1

Blade Weight (Including tip brake): 230 pounds each

Total Rotor Weight: 1140 pounds

Hub: Cast steel

TRANSMISSION

Type: Three stage, helical gear box

Input Speed from Low Speedshaft: 53 rpm

Output Speed to High Speedshaft: 1800 rpm

Gearing Ratio: 1 to 34.5

Weight: 690 pounds

GENERATOR

Type: Induction

Rated Output: 25 kW in a 30 mph wind

Speed: 1800 (+/-) rpm

Number of Phases: Both 1 and 3 are available

Frequency: 60 Hz

Output Voltage: 220/240 VAC - 1 phase
460/480 VAC - 3 phase

Comments: Utility synchronized

TOWER and FOUNDATION

Type: 3 leg, open truss, free standing

Material: Galvanized steel

Height: 80 feet

Weight: 5900 pounds

Foundation: Engineered for site

GENERAL

Design/Survival Wind Speed: 120 mph

Nacelle: Fiberglass, front hinged for easy access. A schmatic of the nacelle interior is shown in Figure 33.

Maintenance: 1 day per year, repairs done at tower top

Graph 25 shows the system output versus wind speed, and the approximate system efficiency versus wind speed.

Graph 26 shows the estimated system output for a one year period using the wind data from Section VIII.

CONTROL and PROTECTION

Blade Pitch: Fixed

Blades: Aerodynamically designed to go into progressive stall as wind speed increases, and to shed excess power in strong gusts.

Yaw: Free yaw, yaw lock provided, slip rings used

Blade Tip Brake: Centrifugally activated as overspeed failsafe

Brake: Control system automatically applies brake

Control System: Two (2) anemometers feed signals into a solid-state logic board in the control box. Start-up and shut-down are controlled by the control system. A relay in the system deenergizes the generator and actuates the brake in the event of a power failure or winds over 50 mph. The control system automatically restarts the machine when power is restored or the wind drops to an average of 35 mph. Overall operation is controlled as follows:

- -Normal Operating Speed: Aerodynamic stall of blades
- -High Wind Speed Shut-Down: Control system applies brake
- -Emergency Rotor Overspeed: Blade Tip Brakes deploy

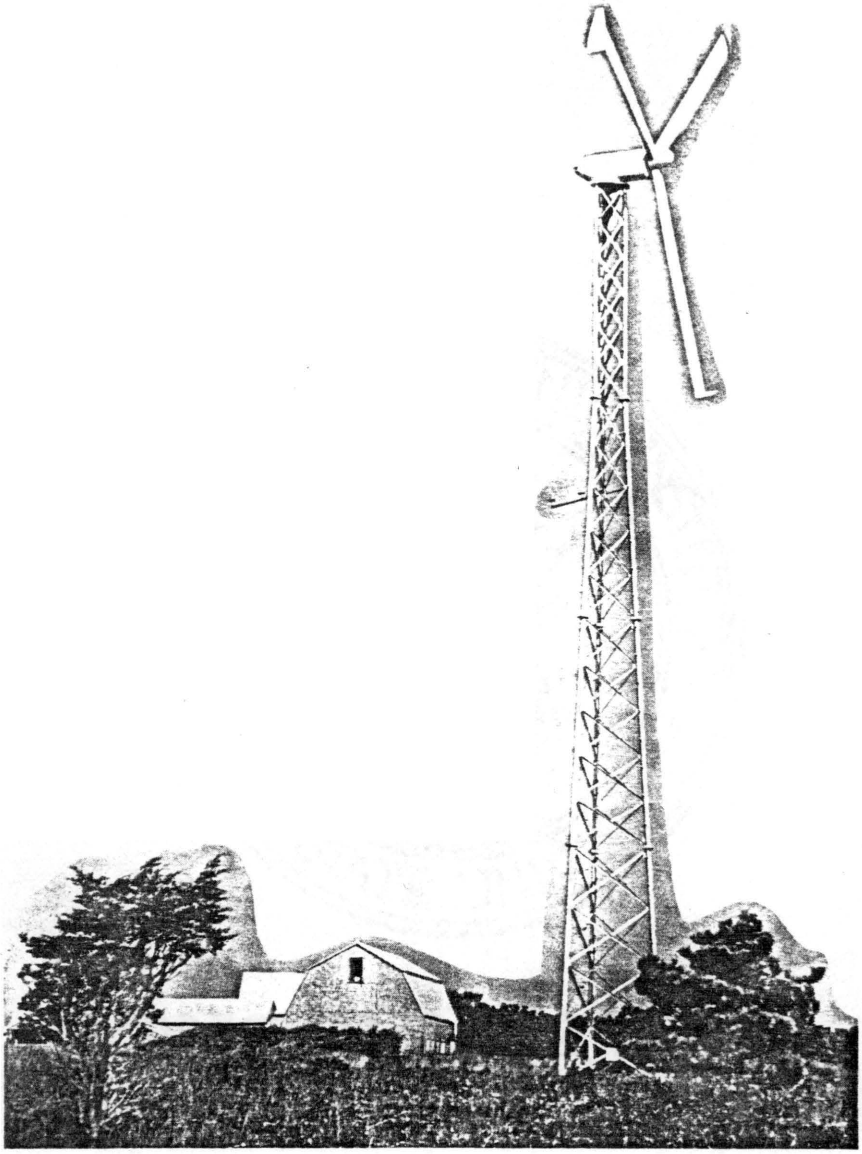
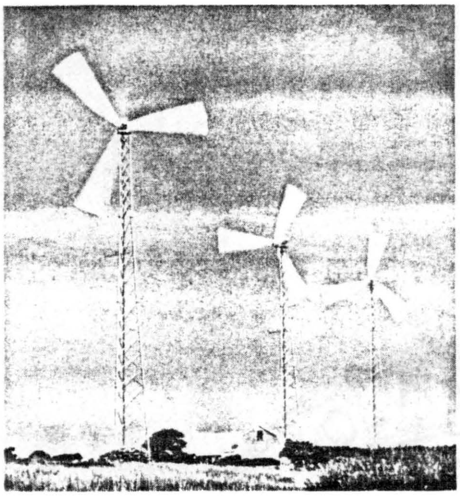


FIGURE 31 - Enertech Model 44



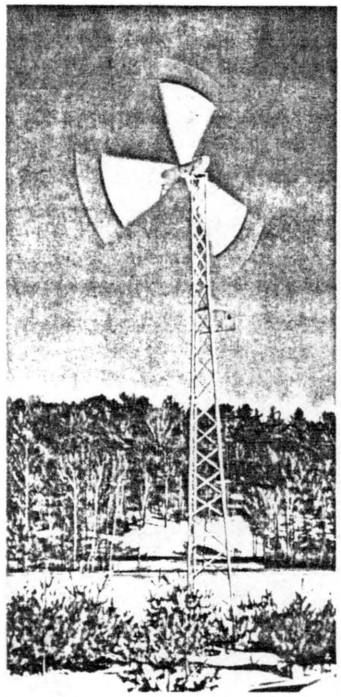


FIGURE 32 - Enertech Model 44 In Action.

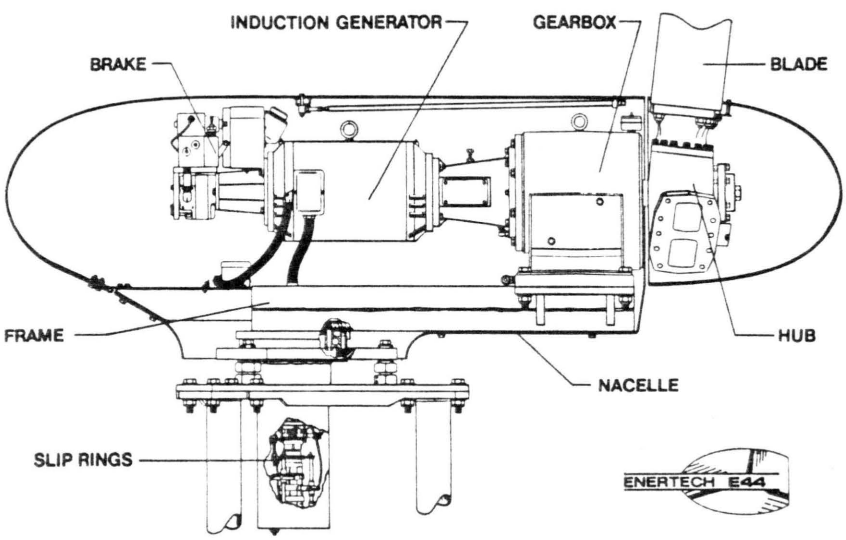
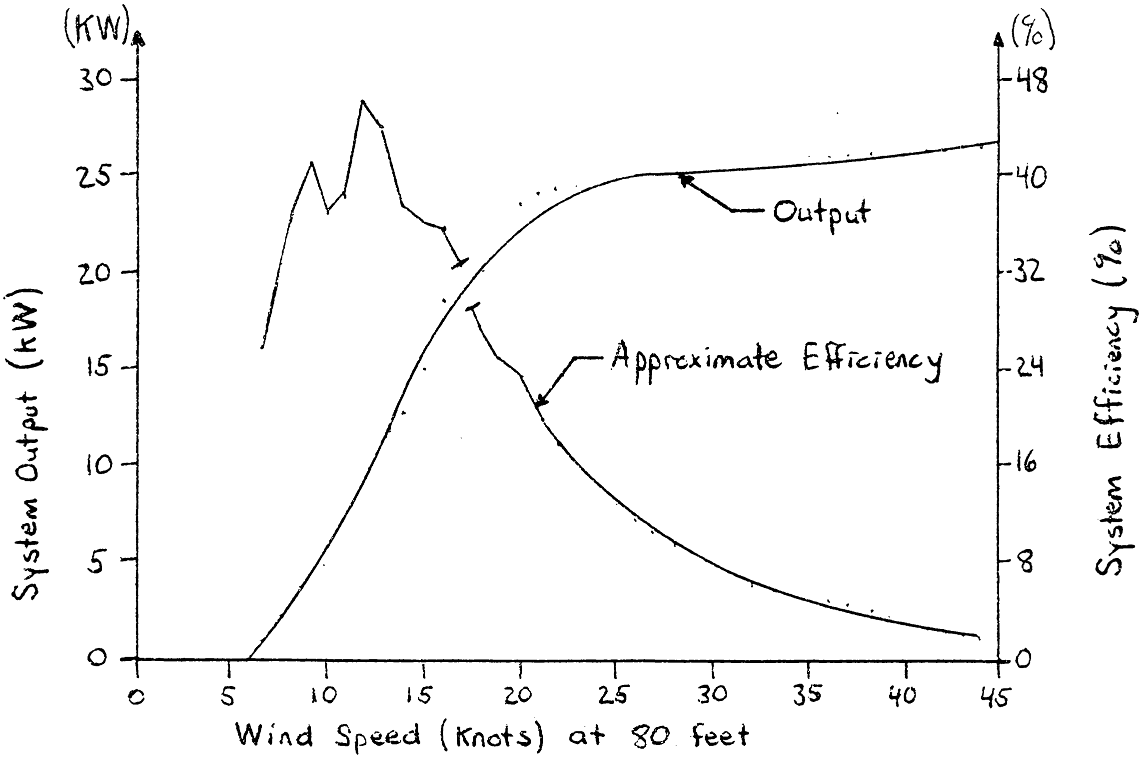
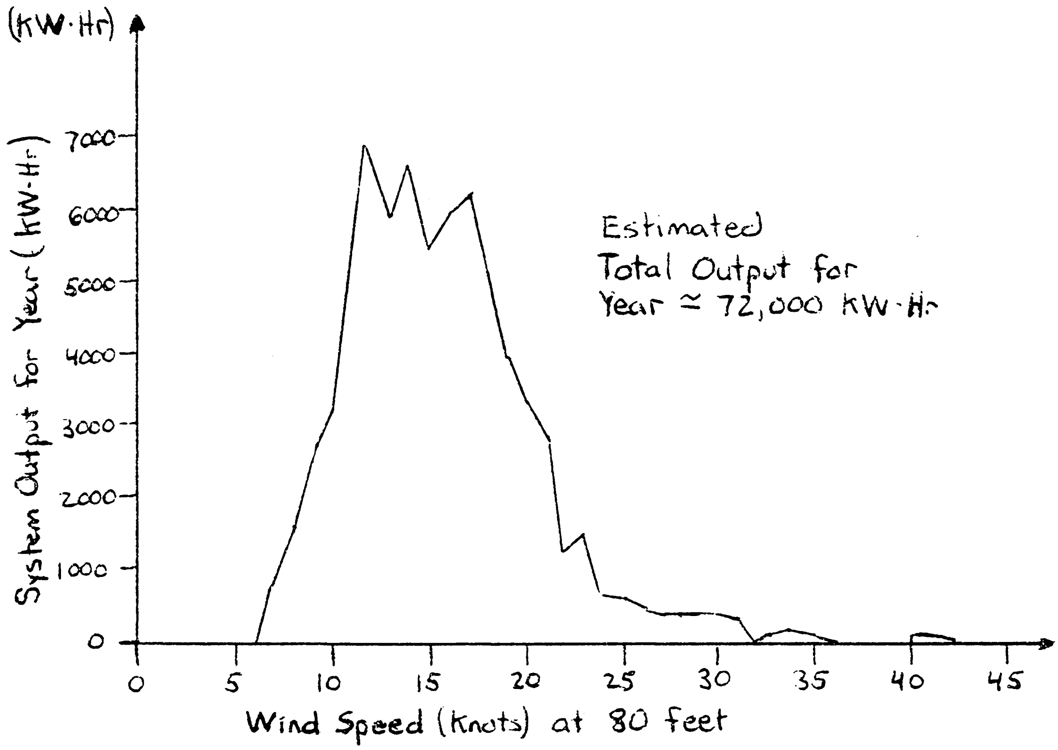


FIGURE 33 - Schematic of the Enertech 44 Nacelle Interior.



GRAPH 25 - Enertech Model 44: System Output versus Wind Speed; Approximate System Efficiency versus Wind Speed.



GRAPH 26 - Enertech Model 44, Estimated System Output versus Wind Speed for Year Using Wind Data from Section VIII (Cape Hatteras, NC-1982).

D. ESI-54-S [11]

Manufacturer: ESI, Inc.; Boulder, CO

Manufacturing Plant Location: Danville, IL

Model: ESI-54-S - Shown in Figure 34.

Rated Output: 85 kW

Warranty: 5 years against defects in design, materials, workmanship

Comments: Designed for use at sites with annual average wind speeds of 16 mph or greater.

ROTOR

Type: Horizontal Axis, Downwind

Diameter: 54 feet Swept Area: 2290 sq. ft.

Rated Output/Swept Area: Approximately 37 Watts/sq. ft.

Number of Blades: 2

Material of Blades: Wood/Epoxy laminate, smooth finish

Hub: Teetered - allows articulation of hub to relieve cyclic pitching moments on the rotor shaft

TRANSMISSION

Type: Single speed, self-aligning, planetary drive gear box

Input Speed from Low Speedshaft: 90 rpm

Output Speed to High Speedshaft: 1800 rpm

Gearing Ratio: 1 to 20.6

GENERATOR

Type: Induction

Rated Output: 85 kW

Speed: 1800 rpm

Number of Phases: 3

Frequency: 60 Hz

Power Factor Correction: 15 KVAR cap/unit

Comments: Utility synchronized. Generator used as a motor to bring rotor up to speed.

TOWER and FOUNDATION

Type: 3 leg, open truss, free standing - SSV tilt down/tilt up manufactured by UNR-ROHN Inc, shown in Figure 35.

Material: Galvanized steel

Height: 80 feet

Foundation: Engineered for local conditions

Comments: Tower is designed to avoid the natural frequency of the rotor (1.50 Hz). The tower was analyzed using SAP IV finite element analysis computer program developed by the University of California, Berkeley.

GENERAL

Design/Survival Wind Speed: 100 mph

Components of the ESI-54-S are shown in Figure 36.

Graph 27 shows the system output versus wind speed, and the approximate system efficiency versus wind speed.

Graph 28 shows the estimated system output for a one year period using the wind data from Section VIII.

CONTROL and PROTECTION

Blade Pitch: Fixed

Yaw: Free yaw, slip rings or drooped cable used

Blade Tip Brake: Centrifugally activated as overspeed failsafe

Brake: The mechanical, multi-disc brake is on the same shaft as the generator, and is spring applied and air released. The brake is held off by utility power.

Control System: An anemometer is used to detect windspeed and operating conditions. A small compressor is used to automatically release the brake. The brake is applied in case the wind drops, too much power is generated in a pre-set time (high wind), or if any of the following faults occur in the system: over or under voltage, over or under frequency, over or under current, phase failure or reversal, power factor correction, overheating, low brake air pressure, excessive disc wear, or excessive vibration.

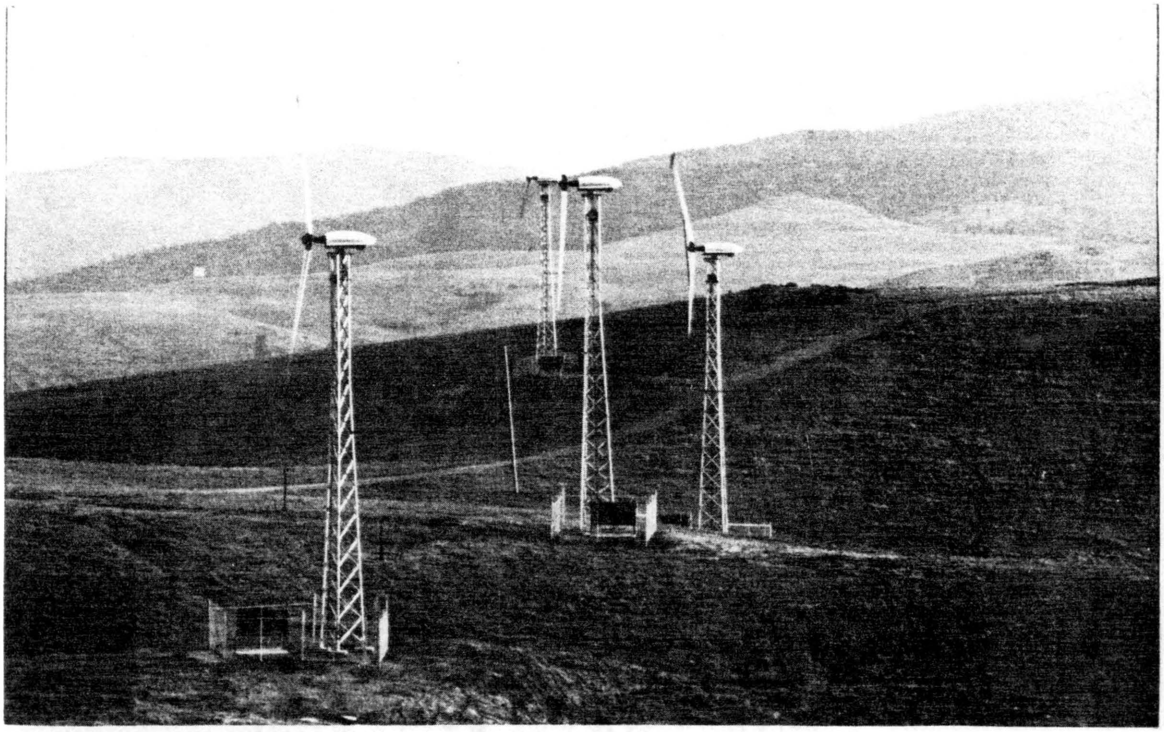


FIGURE 34 - ESI-54-S.

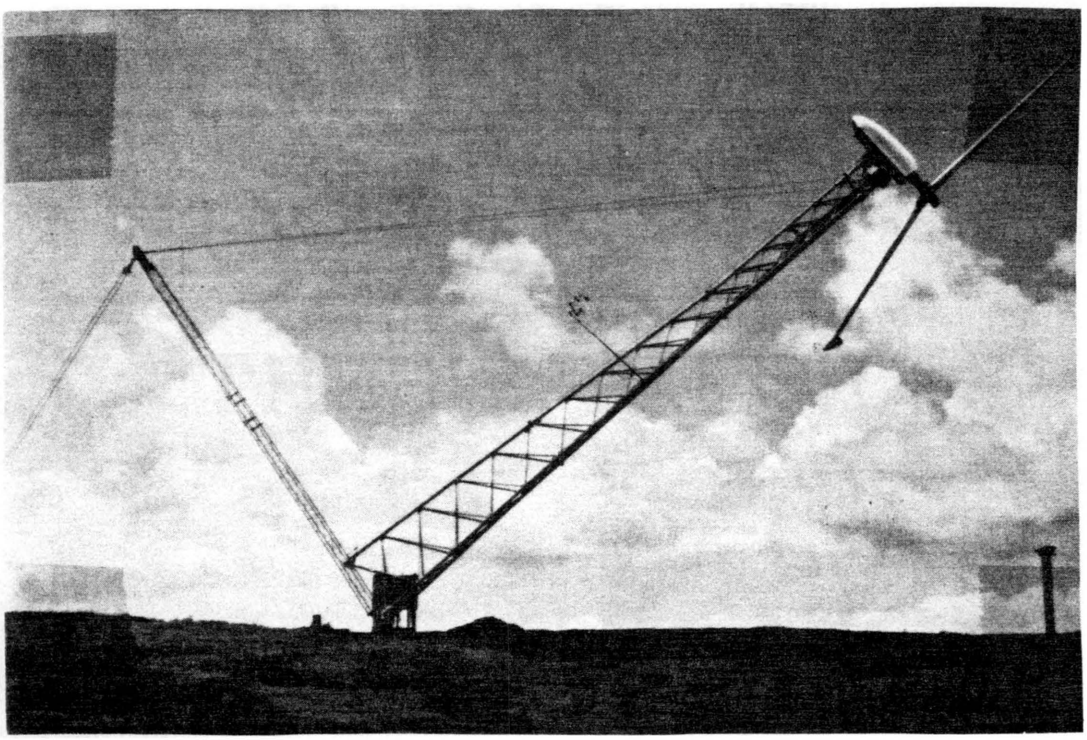
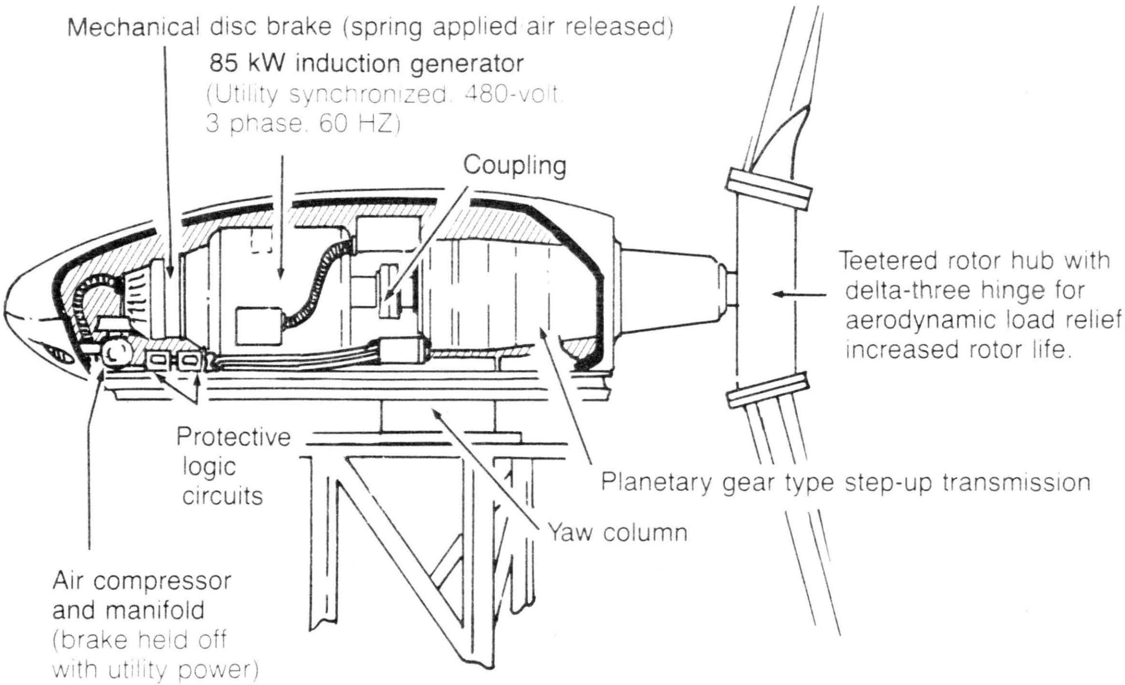


FIGURE 35 - Tilt Down/Tilt Up Tower Used With ESI-54-S.



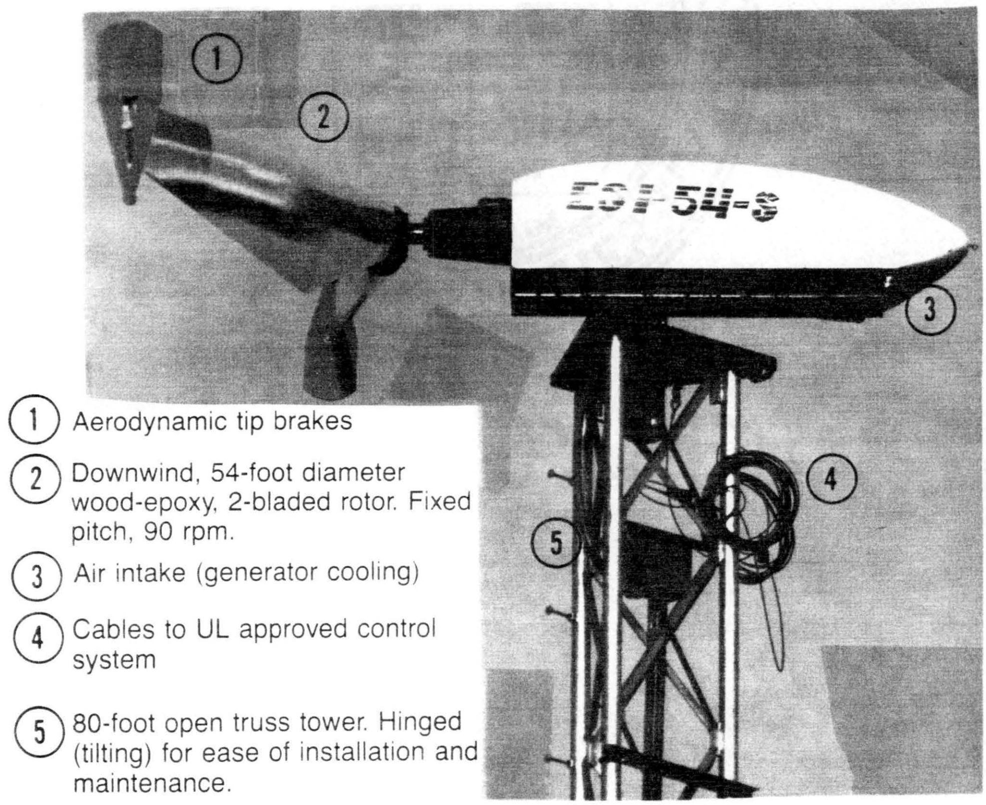
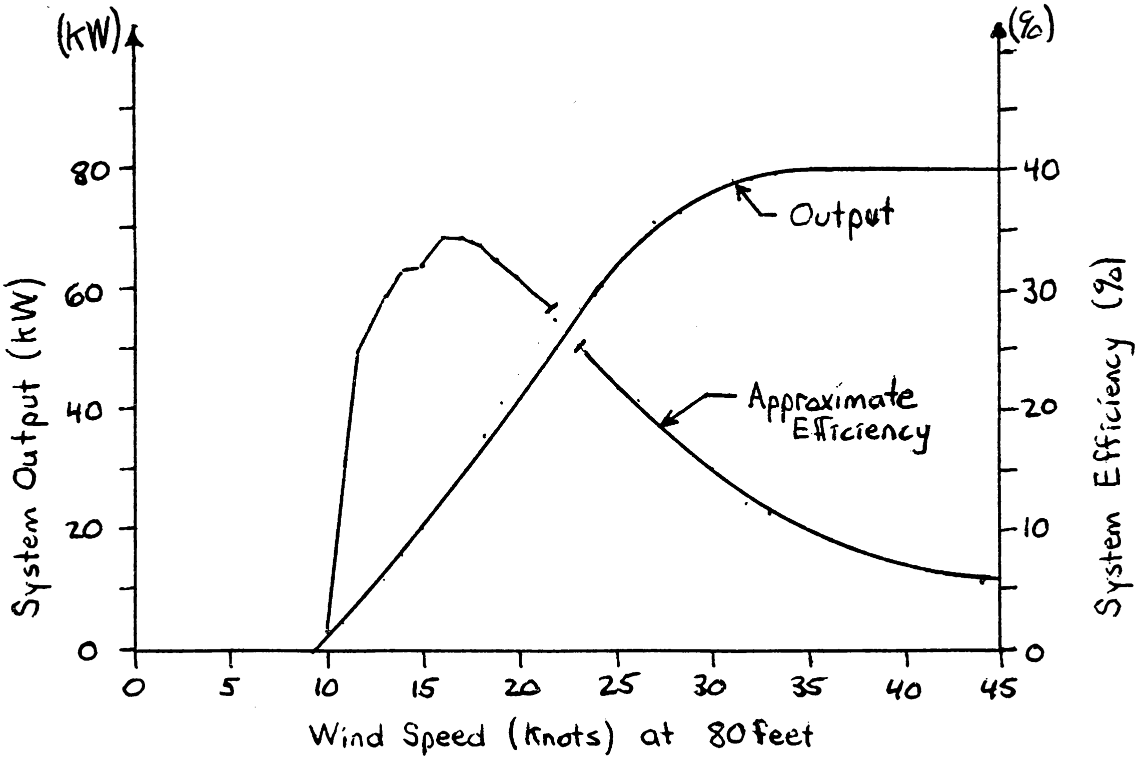
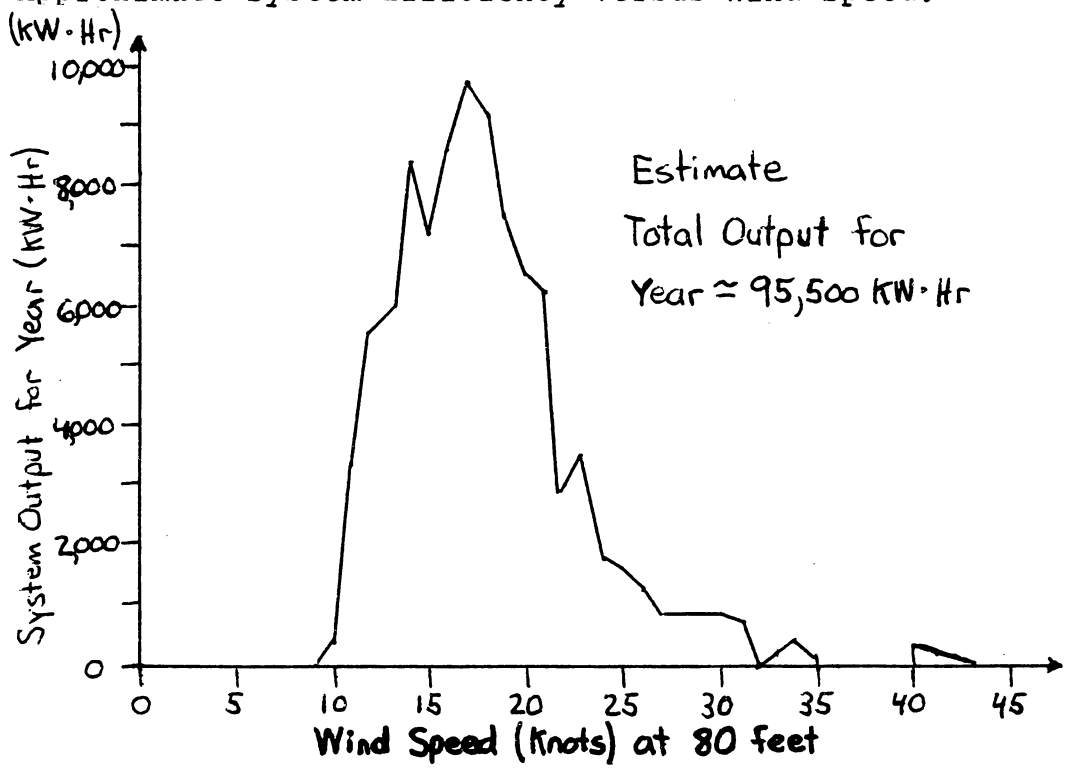


FIGURE 36 - Components of the ESI-54-S.



GRAPH 27 - ESI-54-S: System Output versus Wind Speed; Approximate System Efficiency versus Wind Speed.



GRAPH 28 - ESI-54-S, Estimated System Output versus Wind Speed for Year Using Wind Data from Section VIII (Cape Hatteras, NC-1982).

E. MOD-OA-4 [45]

Owner: U.S. Government; Department of Energy

Model: MOD OA 4 - Shown in Figure 37.

Rated Output: 200 kW

Design Life: 30 years

Comments: Four (4) MOD OA's have been installed. There are some differences between the four. The locations, in order of installation, are as follows:

MOD OA 1 - Clayton, NM
MOD OA 2 - Island of Culebra, Puerto Rico
MOD OA 3 - Block Island, RI
MOD OA 4 - Kahuka, Oahu, HI

ROTOR

Type: Horizontal Axis, Downwind

Diameter: 125 feet Swept Area: 12,272 sq. ft.

Rated Output/Swept Area: Approximately 16 Watts/sq. ft.

Number of Blades: 2

Material of Blades: Wood composite

Weight of Blades: 3,000 pounds each

Blade Chord: 5.2 feet at root tapering linearly to 2 feet at the tip

Airfoil: NACA 23000 Blade Twist: 8 degrees

Solidity: 4 percent Cone Angle: 7 degrees

Rotor Speed: 40 rpm

Hub: Rigid Hub Height: 100 feet

Weight of Rotor: 13,600 pounds

TRANSMISSION

Type: 3 stage conventional gear box

Input Speed from Low Speedshaft: 40 rpm

Output Speed to High Speedshaft: 1800 rpm

Gearing Ratio: 1 to 45

Rating: 460 hp

Comments: Fluid coupling on high speed shaft to damp out power oscillations due to tower shadow and wind shear effects.

GENERATOR

Type: Synchronous AC

Rated Output: 200 kW

Speed: 1800 rpm

Number of Phases: 3

Frequency: 60 Hz

Output Voltage: 480 V

Power Factor: 0.8

TOWER and FOUNDATION

Type: 4 legs, open truss, free standing

Material: Round steel pipe - maximizes air flow through tower

Weight of Tower: 44,000 pounds

Height: 93 feet

Foundation: Concrete slab

Access: Hoist

GENERAL

Design/Survival Wind Speed: 150 mph at hub

Bedplate: Steel structural member which supports rotor and nacelle assembly.

Total Weight Above Tower: 46,300 pounds

The basic layout of the MOD-OA-4 is shown in Figure 38. A schematic of the nacelle interior is shown in Figure 39.

Graph 29 shows the system output versus wind speed, and the approximate system efficiency versus wind speed.

Graph 30 shows the estimated system output for a one year period using the wind data from Section VIII.

CONTROL and PROTECTION

Blade Pitch: Variable pitch change assembly consists of a hydraulic supply, a rack and pinion actuator, and gears to rotate the blades in the hub. A microprocessor controls the blade pitch. Blades are feathered below cut-in wind speeds and above cut-out wind speeds. Blades are held at a fixed setting between cut-in and rated speeds. Pitch is adjusted between rated and cut-out wind speeds to maintain a constant power output of 200 kW.

Yaw: Entire machine on top of tower is supported on a turntable bearing. Rotation is achieved by driving a disk with the use of movable brakes and hydraulic linear actuators. Yaw rate is 24 degrees per minute. Two (2) fixed yaw brakes hold machine in desired position.

Disc Brake: Located on an extension of the high speed shaft, serves as a parking brake and a dynamic brake in case of emergency shutdown.

Control System: A microprocessor monitors the output of two (2) wind speed sensors and one (1) wind direction sensor. This information is used to control blade pitch and yawing. The microprocessor also controls start-up, shutdown, and synchronization to the grid.

Safety System: Automatic shutdown system that operates independently of all other controls. Key parameters such as rotor speed, generator current, electric load, vibration, yaw error, fluid levels, temperatures, and microprocessor status are monitored by sensors. If any sensor signal is outside safe range the windmill will be shutdown.

Remote Control and Monitoring System: Located at the utility power dispatcher's center, permits manual start-stop control of the microprocessor. A digital readout of key parameters is given.

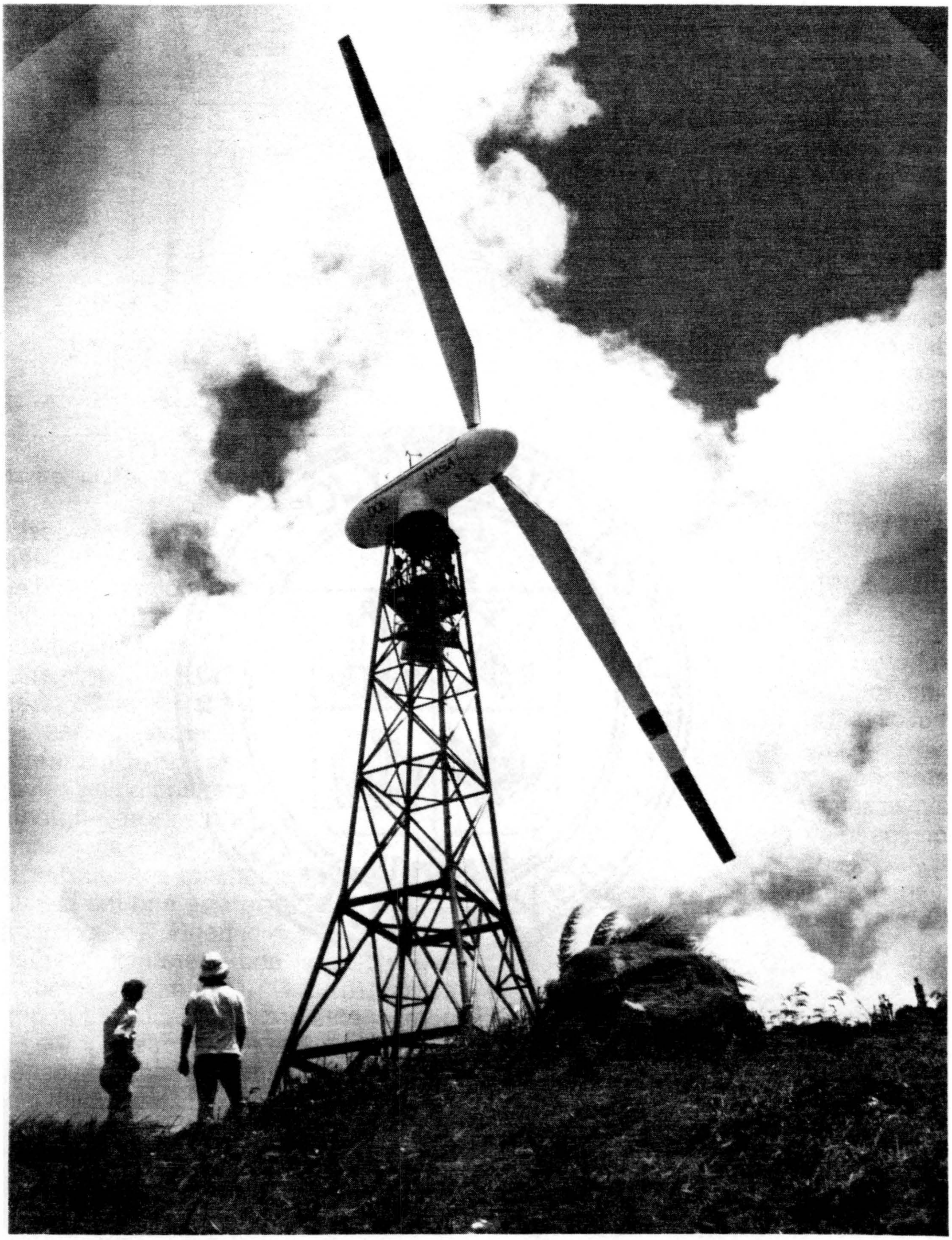


FIGURE 37 - DOE/NASA 200 kW MOD-OA-4.

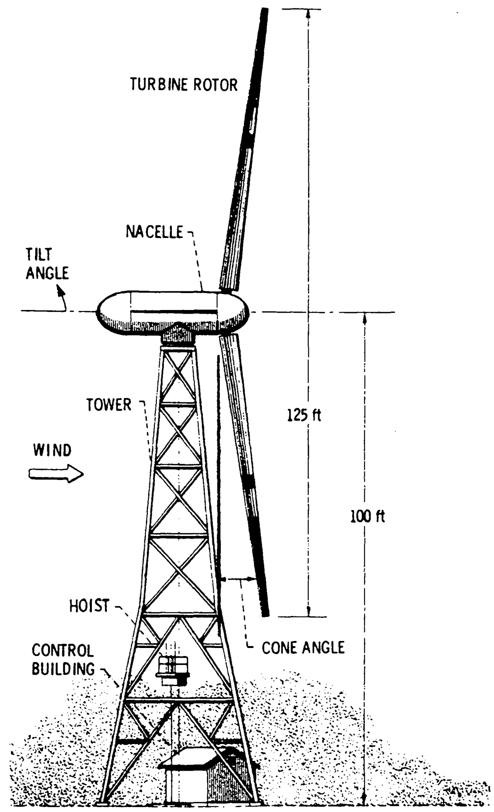


FIGURE 38 - Basic Layout of the MOD-OA-4.

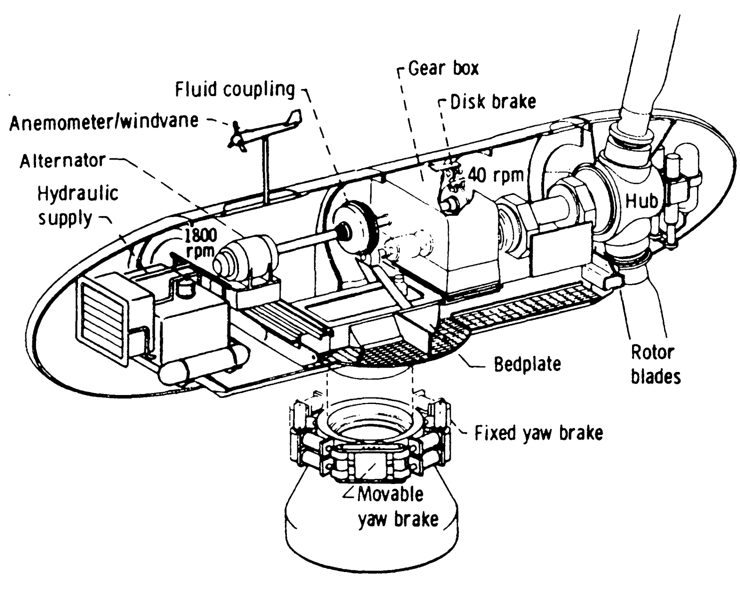
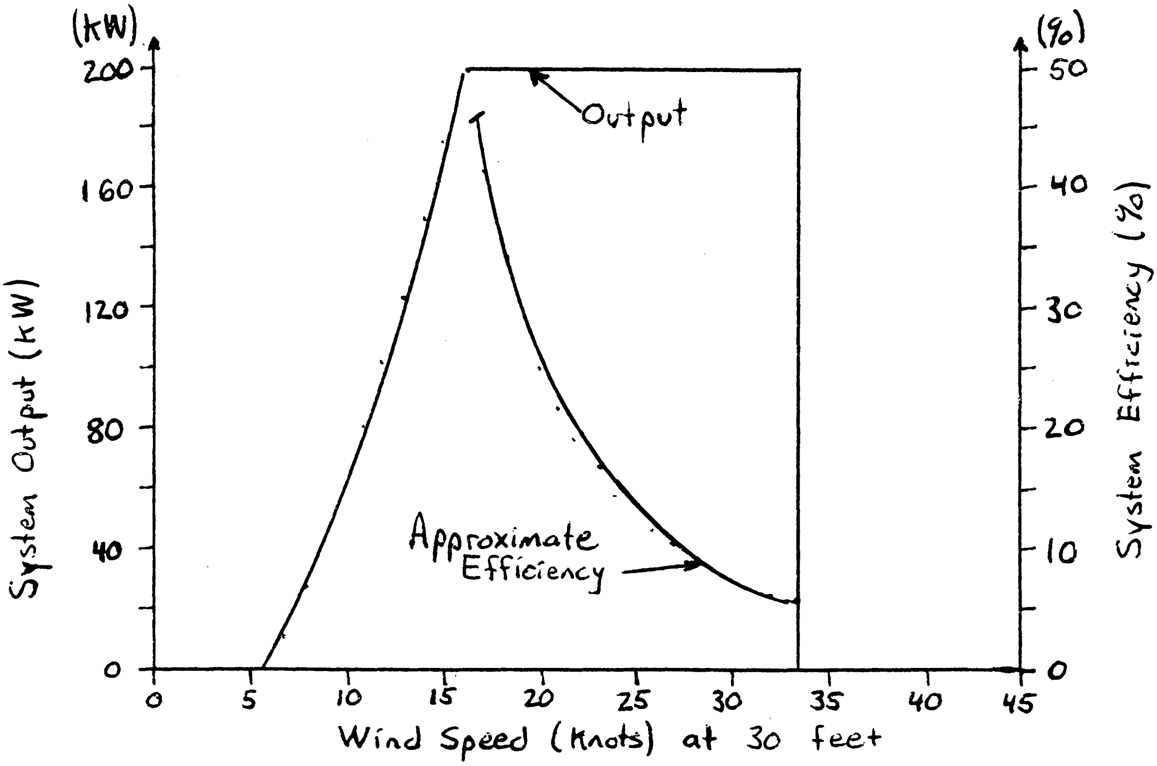
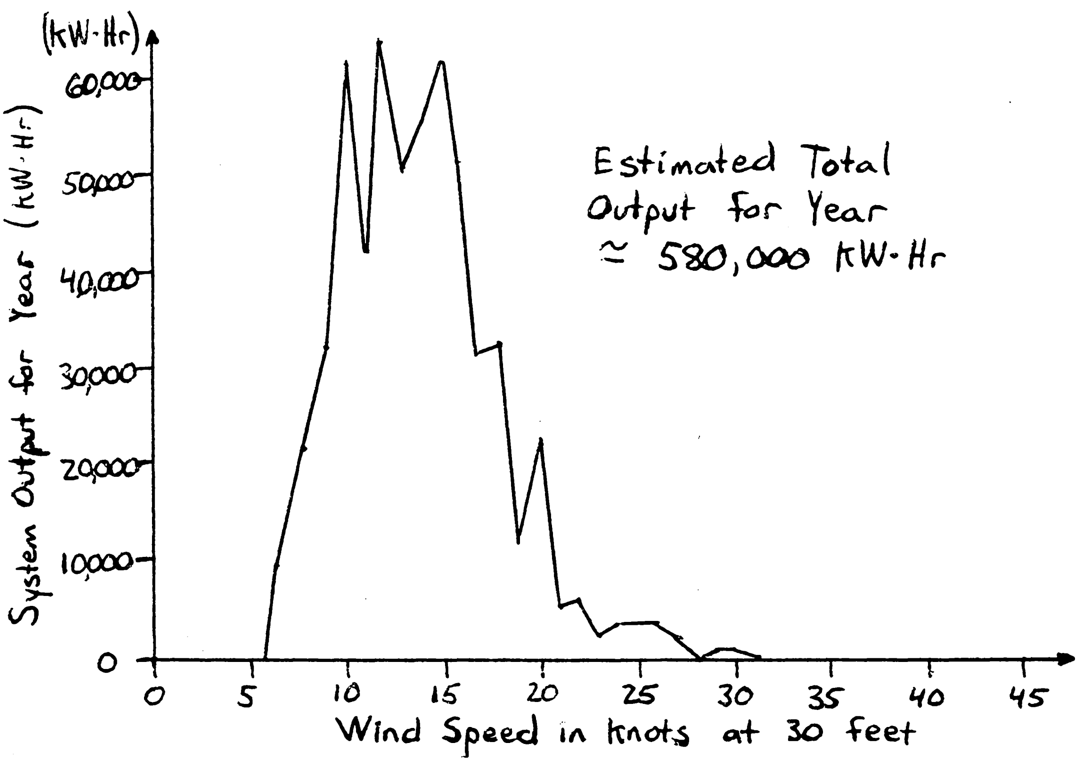


FIGURE 39 - Schematic of the MOD-OA-4 Nacelle Interior.



GRAPH 29 - MOD-OA-4: System Output versus Wind Speed; Approximate System Efficiency versus Wind Speed.



GRAPH 30 - MOD-OA-4, Estimated System Output versus Wind Speed for Year Using Wind Data from Section VIII (Cape Hatteras, NC-1982).

F. MOD-2 [26,28,29]

Owner: U.S. Government; Department of Energy

Designed, Built, Installed By: Boeing Engineering and Construction Company

Operated By: Bonneville Power Administration operates a cluster of three (3) at Goldendale, WA.

Model: MOD-2 - Shown in Figure 40.

Design Life: 30 years   Rated Output: 2500 kW

Site Locations: 3 at Goldendale, WA; 1 at Salerno County, CA; 1 at Medicine Bow, WY

ROTOR

Type: Horizontal Axis, Upwind

Diameter: 300 feet   Swept Area: 70,685 sq. ft.

Rated Output/Swept Area: Approximately 35 Watts/sq. ft.

Number of Blades: 2   Material of Blades: Steel

Airfoil: NACA 230XX   Weight of Blades: 109,800 pounds

Blade Construction: Welded, hollow steel shell with steel spar members. Five (5) blade sections - 2 tips, 2 midsections, 1 hub section

Rotor Speed: 17.5 rpm   Rotor Tip Speed: 275 feet/second

Tilt Angle of Rotor Axis: Up 2.5 degrees

Hub: Teeters up to 6.5 degrees. Reduces effects of blade forces which are not strictly rotational. Reduces overall windmill weight requirements.

Hub Weight: 80,500 pounds   Hub Height: 200 feet

TRANSMISSION

Type: 3 stage epicyclic, compact planetary gear box

Input Speed from Low Speedshaft: 17.5 rpm

Output Speed to High Speedshaft: 1800 rpm

Gearing Ratio: 1 to 103.1

Gear Box Weight: 37,000 pounds

Comments: Torque from the low speed shaft is transmitted to a flexible quill shaft which reduces extraneous motion and rotor torque oscillations at the gear box. The transmission is flexibly mounted to the nacelle.

GENERATOR

Type: Synchronous - widely used by utilities in other applications

Rated Output: 2500 kW

Speed: 1800 rpm

Number of Phases: 3

Number of Poles: 4 salient poles, brushless

Frequency: 60 Hz

Output Voltage: 4160 volts

Rating: 3125 KVA

Power Factor: 0.8

TOWER and FOUNDATION

Type: "Soft" shell, cyclindrical

Material: Steel, welded

Height: 193 feet

Dimensions: 150 foot long, 10 foot diameter cyclindrical tube flares hyperbolically to a 21 foot base

Foundation: Base of reinforced concrete. MOD-2's at Goldendale are held by 72 earth anchors each 28 feet long.

Comments: The use of a "soft" tower as compared to a "stiff" truss tower, reduces weight requirements, is less expensive to fabricate, and reduces vibration problems throughout the wind power system. Dynamically soft towers have a lower natural frequency of vibration than the blade passing frequency while a stiff tower has a higher frequency. Therefore, the soft tower is less likely to reinforce vibrations established by the rotation of the rotor.

GENERAL

Design/Survival Wind Speed: 120 mph at 30 feet

Nacelle: Welded steel truss construction with corrugated steel sheets for roof and sides and steel safety plate for floor. Houses major components, cooling, fire prevention and maintenance equipment.

Nacelle Weight: 82,600 pounds

Total System Weight: 631,300 pounds

Access: Both an internal lift and a ladder with safety rail are inside the tower and provide access to the top.

Temperature Range: -40 degrees F to 120 degrees F

The basic layout of the MOD-2 is shown in Figure 41. A schematic of the nacelle interior is shown in Figure 42.

Graph 31 shows the system output versus wind speed, and the approximate system efficiency versus wind speed.

Graph 32 shows the estimated system output for a one year period using the wind data from Section VIII.

CONTROL and PROTECTION

Blade Pitch: The outer 45 feet of the blades (tips) are variable pitch through 100 degrees. Pitch is controlled by an electric-motor-driven pump and a hydraulic system. Blades are feathered below cut-in wind speeds and above cut-out wind speeds. Blades are set at the most aerodynamically efficient position between cut-in and rated wind speeds. Pitch is adjust between rated and cut-out wind speeds to maintain a constant rotor speed.

Yaw: Yaw control system consists of a hydraulic drive motor, speed reducer, gear box, drive pinion, ring gear, six (6) parking brakes, and a hydraulic brake. The six parking brakes prevent inadvertent yawing, while the hydraulic brake provides damping during yawing. Wind direction sensors are monitored, thirty second average wind directions computed, and the heading changed whenever wind direction changes exceed 20 degrees.

Parking Brake: A disk mounted on the high speed shaft and a spring actuated brake attached to the generator frame hold the system in place while not in operation.

Control System: A microprocessor initiates start-up, implements fail safe actions, monitors wind conditions, controls blade pitch and yawing, monitors operating conditions and shuts system down in the event of out-of-tolerance conditions. Oscilloscopes located at the tower base and at the utility substation provide displays of operating and failure data and allow manual operation of the system.

Independent Fail Safe Shutdown System: Electrical system relays provide system shutdown redundancy

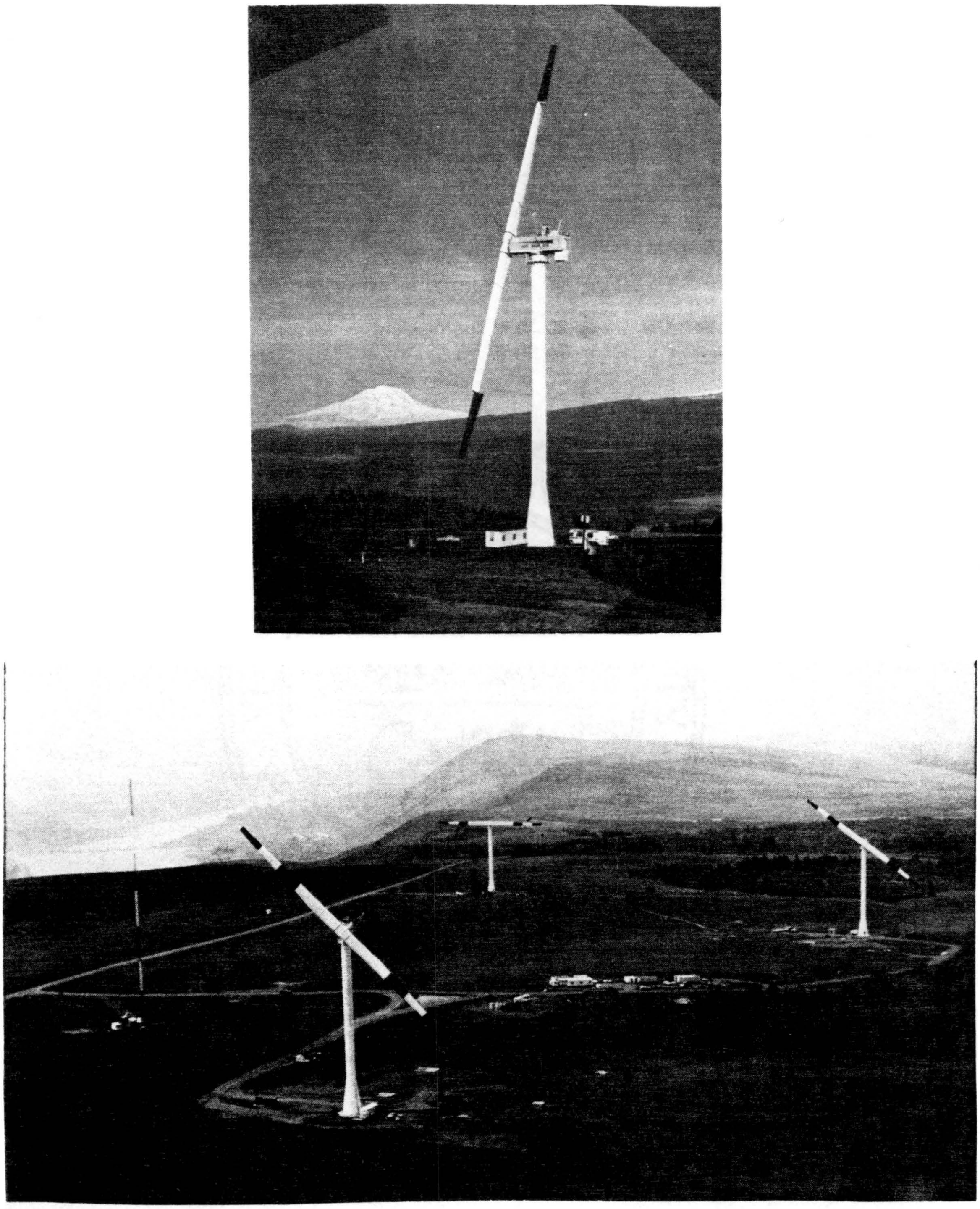


FIGURE 40 - Close Up and Distant Views of MOD-2's

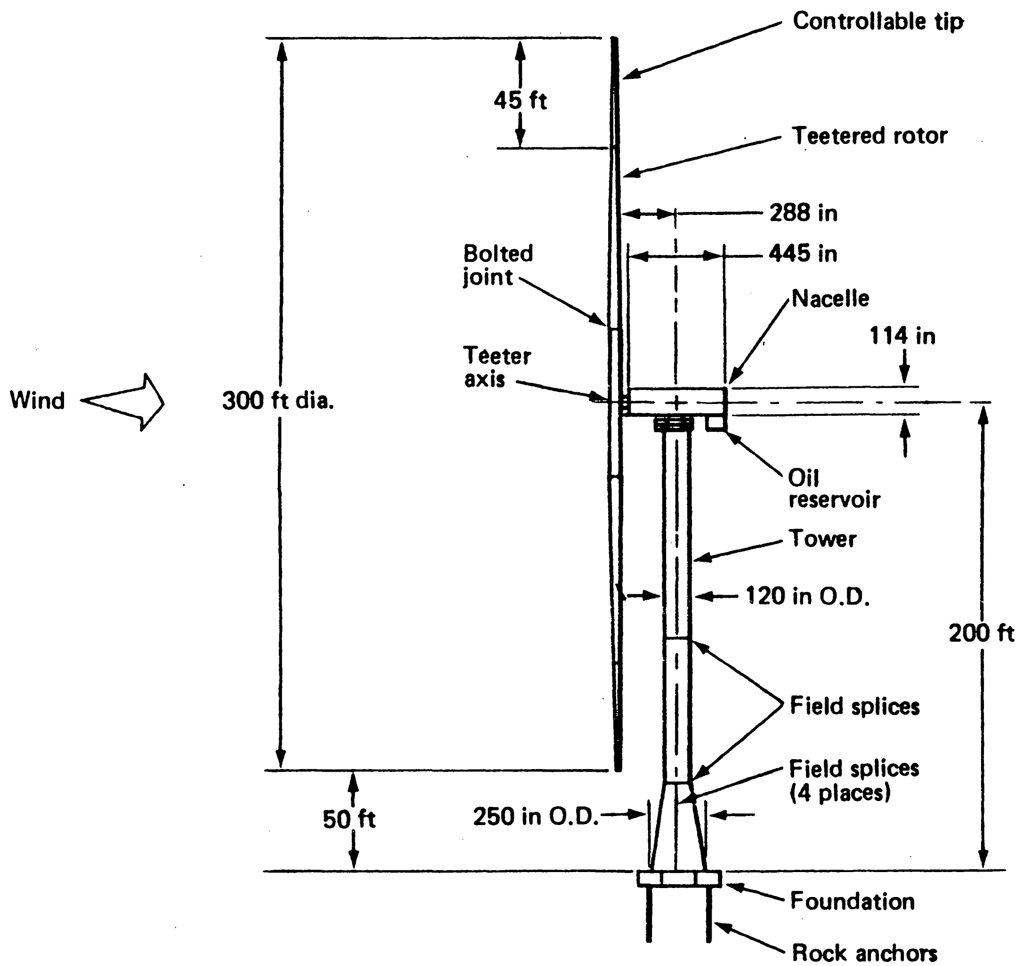


FIGURE 41 - Basic Layout of MOD-2.

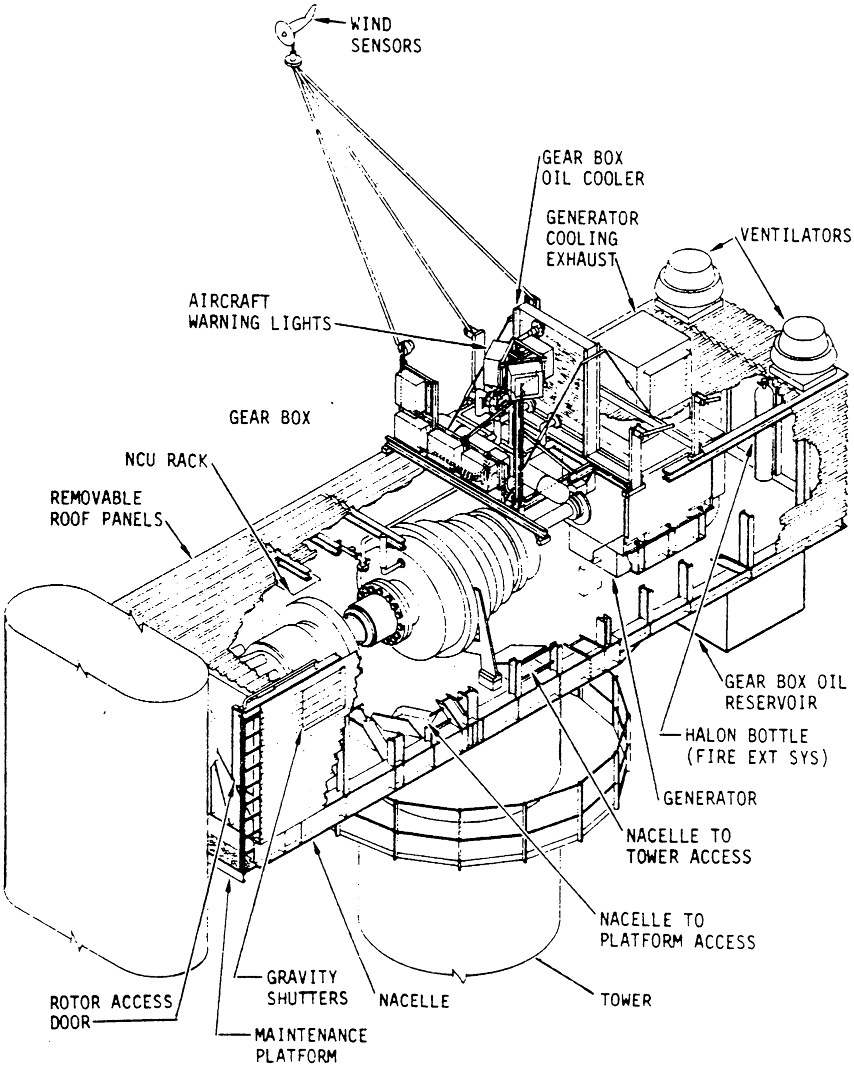
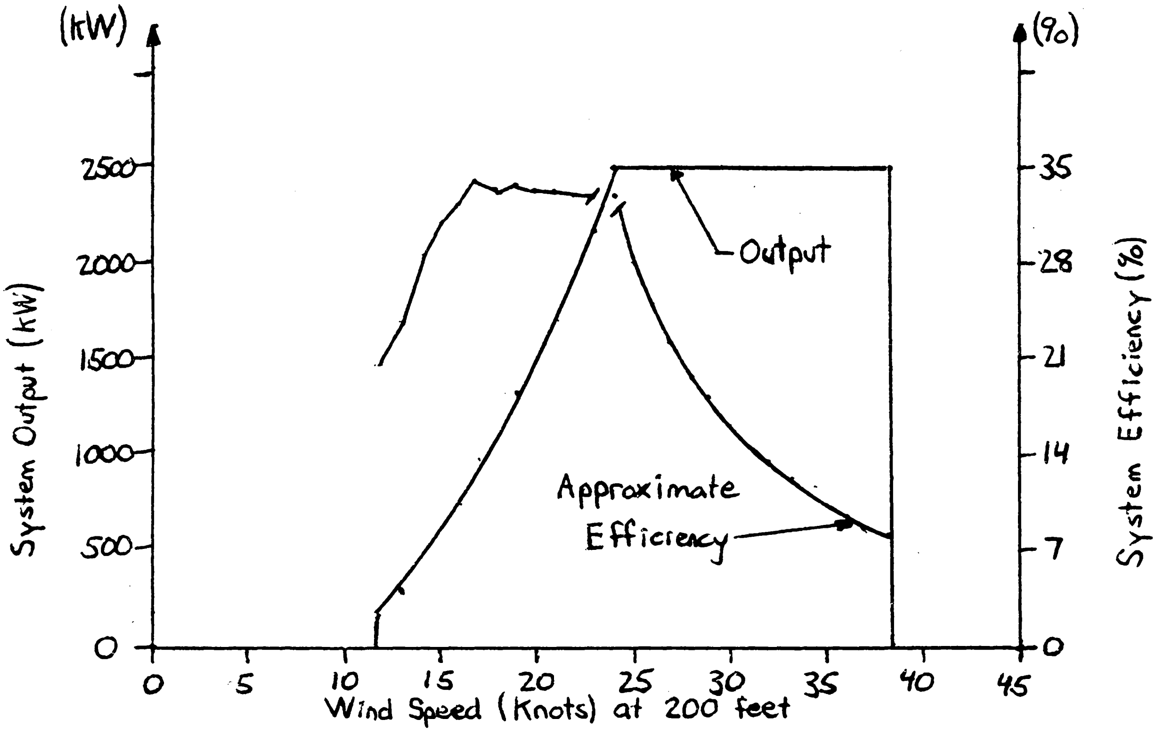
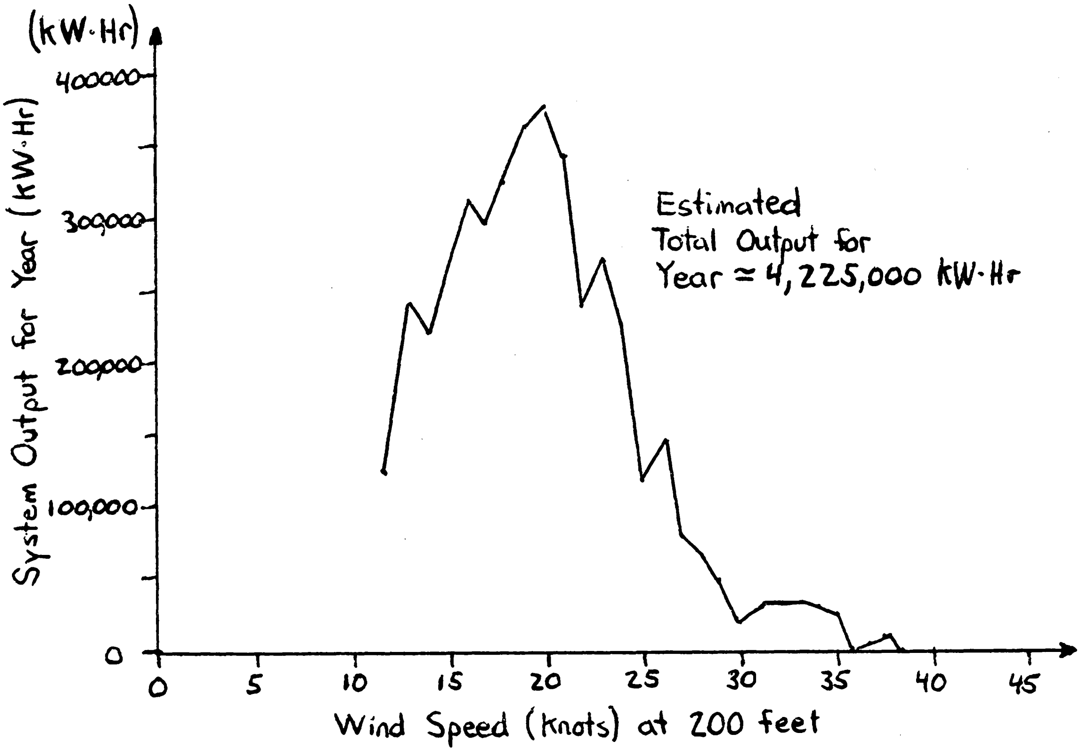


FIGURE 42 - Schematic of the MOD-2 Nacelle Interior.



GRAPH 31 - MOD-2: System Output versus Wind Speed; Approximate System Efficiency versus Wind Speed.



GRAPH 32 - MOD-2, Estimated System Output versus Wind Speed for Year Using Wind Data from Section VIII (Cape Hatteras, NC-1982).

XI. CONCLUSION

The electrical-producing windmill industry boomed during 1983. It was estimated that "unit sales during 1983 would be twice those of the prior 10 years combined." Most of the activity has been in the development of windfarms in the western states and Hawaii. The boom is largely due to (1) tax breaks given to alternative energy producers and (2) the Public Utilities Regulatory Policies Act (PURPA) of 1978. PURPA requires public utilities to purchase electricity from small producers. In many instances, the investors main interest was the tax break and as a result the development was of inferior quality.[40]

Electrical-producing windmills are delicate machines in that lightweight components are used to move large forces. Domestically, there are about 50 manufacturers of electrical-producing windmills. Most of these manufacturers have just entered the field. As such, they have not had time to perfect their machines. And as a result, 50% downtimes are not uncommon and failures are frequent.[40]

In the mid-70's, the U.S. Department of Energy (DOE) embarked on a large scale program for the research and development of windmills. In 1982 the program was drastically cut by the Reagan administration. While the program was in full swing, significant steps were made in developing safe, reliable wind energy systems.

Wind energy systems could probably supply up to ten percent of the nation's annual electrical demands, but one to two percent is a more reasonable goal. For this to happen the government must not cut its existing financial incentives, existing windfarms must prove to be economical, private manufacturers must develop high quality wind energy systems, and windfarms must be developed at sites throughout the country.

XII. REFERENCES

1. Argue, R., Emanuel, B., Graham, S., The Sun Builders: A People's Guide to Solar, Wind, and Wood Energy in Canada, Renewable Energy in Canada, Toronto, 1978.

2. Beedell, Suzanne, Windmills, Charles Scribner's Sons, 1975.

3. Brown, J., Brown, A., Harness the Wind: The Story of Windmills, Dodd, Mead & Commpany, New York, 1977.

4. Calvert, Norman G., Windpower Principles, Their Applications on the Small Scale, Wiley, New York, 1979.

5. Chapman, Alan J., Heat Transfer, Third Edition, Macmillan Publishing Company, Inc., New York, 1974.

6. Cheremisinoff, Nicholas P., Fundamentals of Wind Energy, Ann Arbor Science Publishers, Ann Arbor, MI., 1978.

7. Cole, Franklyn, Introduction to Meteorology, John Wiley and Sons, Inc., New York, 1980.

8. Durand, William F., Editor-in Chief, Aerodynamic Theory: A General Review of Progress, Volume IV, Berlin, Julius Springer, 1935.

   Betz, A., "General Properties of the Wing," pp. 3-25.

   Betz, A., "Properties of Typical Profiles," pp. 26-46.

   Glavert, H., "Airscrew Theory," pp. 170-181.

   Glavert, H., "Windmills and Fans," pp. 324-340.

9. Eldridge, Frank R., Wind Machines, Report Prepared for the National Science Foundation by the MITRE Corporation, October 1975.

10. Eldridge, Frank R., Wind Machines, Van Nostrand Rheinhold Co., New York, 1980.

11. Energy Sciences Incorporated (ESI), Product Literature, Boulder, CO.

12. Enertech Corporation, Product Literature, Norwich, CT.

13. Glossary of Meteorology, Edited by Ralph Huschke, American Meteorological Society, Boston, MA., 1959.

14. "Going With the Wind," EPRI Journal, March 1980, pp. 7-18.

15. Golding, E.W., The Generation of Electricity by Wind Power, John Wiley and Sons, Inc., New York, 1977.

16. Gourieres, Desire Le, Wind Power Plants - Theory and Design, University of Dakar, Dakar, Senegal, Pergamon Press, 1982.

17. "Guide to Solar Energy," Virginia Polytechnic Institute and State University, Energy Management Division.

18. Hackleman, Michael A., The Homebuilt, Wind-Generated Electricity Handbook, Earthmind, Saugus, CA., October 1975.

19. Hickok, Floyd, Handbook of Solar and Wind Energy, Cahner Books International, Inc., Boston, 1975.

20. Jacobs Wind Electric Company, Product Literature, Minneapolis, MN.

21. Jarass, L., Hoffmann, L., Jarass, A., Obermair, G., Wind Energy - An Assessment of the Technical and Economic Potential, A Case Study for the Federal Republic of Germany by the International Energy Agency, Springer-Verlag, Berlin, Heidelberg, New York, 1981.

22. Justus, C.G., Winds and Wind System Performance, The Franklin Institute Press, Philadelphia, PA., 1978.

23. Koeppl, Gerald W., Putnam's Power from the Wind, Second Edition, Van Nostrand Rheinhold Co., New York, 1982.

24. Kovarik, T., Pipher, C., Hurst, J., Wind Energy, Domus Books, Chicago, New York, 1979.

25. "Legal-Institutional Implications of Wind Energy Conversion Systems (WECS) - Executive Summary, September 1977," Prepared for the National Science Foundation by the Program of Policy Studies in Science & Technology, George Washington University, Washington, D.C., 1977.

26. Linscott, B., Dennett, J., Gordon, L., "The MOD-2 Wind Turbine Development Project," Prepared for the U.S. Department of Energy, Conservation and Renewable Energy Division of Wind Energy Systems by NASA, July 1981.

27. McKelvey, John P., Grotch, Howard, Physics for Science and Engineering, Harper & Row, Publishers, New York, 1978.

28. "MOD-2 Wind Turbine System Development Final Report: Volume I Executive Summary," Prepared by Boeing Engineering and Construction Company for NASA and the U.S. Department of Energy, September 1982.

29. "MOD-2 Wind Turbine System Development Final Report: Volume II Detailed Report," Prepared by Boeing Engineering and Construction Company for NASA and the U.S. Department of Energy, September 1982.

30. Moretti, P., Thresher, R., "Overview of Wind Energy Systems: Issues in Development and Application," Journal of Solar Energy Engineering, ASME, Volume 103, Febuary 1981, pp. 3-10.

31. Noll, Edward M., Wind/Solar Energy for Radio Communications and Low-Power Electronic/Electric Application, Howard W. Sams & Co. Inc., Indianapolis, 1975.

32. Park, Jack, The Wind Power Book, Cheshire Books, Palo Alto, CA., 1981.

33. "Summary Report: January 1, 1977, Federal Wind Energy Program," ERDA, Division of Solar Energy, Wind Systems Branch, Washington, D.C., 1977.

34. Thomas, Percey H., Aerodynamics of the Wind Turbine, Adapted for Use of Power Engineers, Office of the Chief Engineer, Federal Power Commission, January 1949.

35. Torrey, Volta, Wind-Catchers: American Windmills of Yesterday and Tomorrow, The Stephen Greene Press, Brattleboro, VT., 1976.

36. Valley Pump Group, Manufacturer of Aermotor Windmills, Conway, AK.

37. Virginia Pilot & Ledger Star, 30 August 1982.

38. Wailes, Rex, Windmills in England: A Study of Their Origin, Development and Future, The Architectural Press, London, 1948.

39. Wind Data for Selected U.S. Cities, U.S. Department of Commerce, Weather Bureau, National Weather Records Center, Asheville, NC., April 1956.

40. "Wind Energy '84," Renewable Energy News, P.O. Box 690, Ogdensburg, NY, 13669.

41. "Wind Energy Developments in the 20th Century," NASA, Lewis Research Center, Cleveland, OH, Revised 1981.

42. Wind Energy Resource Atlas: Volume 5, The East Central Region, Prepared by the NUS Corporation, Published by the Pacific Northwest Laboratory, 1980, Republished by Solar Energy Information Services, Sacramento, CA., 1981.

43. Wind Power: Recent Developments, Noyes Data Corporation, Park Ridge, N.J., 1979.

44. Wolff, B., Meyer, H., Wind Energy, Franklin Institute Press, Philadelphia, 1978.

45. "200-Kilowatt Wind Turbine Project: A Part of the U.S. Department of Energy, Federal Wind Energy Program," NASA, Lewis Research Center, Cleveland, OH, July 1980.

The following companys or institutions also supplied information for this project:

American Wind Energy Association
Battelle, Pacific Northwest Laboratory
Bechtel National, Incorporated
Boeing Engineering and Construction Company
California State Energy Commission
Concept Development Institute, Incorporated
Department of Agriculture
    Conservation & Production Research Laboratory
Department of Commerce/National Climatic Data Center
Department of Energy/Wind Energy Technology Division
Department of Interior/Bureau of Reclamation
Hawaiian Electric Company
Hercules Incorporated
Idaho Power Company
Kaman Aerospace Corporation
Los Alamos Scientific Laboratories
NASA-Langley Research Center
NASA-Lewis Research Center
Oklahoma State University/Dr. Peter Moretti
Pacific Gas & Electric Company
Pennsylvania Power & Light Company
Pioneer Wind Power, Incorporated
Pittsburg Des Moines Steel
Rockwell International
Sandia Laboratories
Solar Energy Research Institute
Southern California Edison
Stanford University/Holt Ashley
Stone & Webster Engineering Corporation
Tennessee Valley Authority
Texas Tech University/Dr. Edgar O'Hair
The Aerospace Corporation
United Technologies/Hamilton Standard
Utah Power & Light Company
Washington University/Kurt Hohenemser

XIII. APPENDICES

Appendix A: Wind and Weather Data

Appendix B: Computer Programs Used For Reducing Wind Data

APPENDIX A

Wind and Weather Data from

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data and Information Service
National Climatic Data Center
Asheville, North Carolina

---------------------------Index------------------------------

Subject | Page

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL ENVIRONMENTAL SATELLITE, DATA AND INFORMATION SERVICE

(Stations for which Local Climatological Data are issued, as of January 1, 1982)

ALABAMA

- abc BIRMINGHAM AIRPORT
- ac BIRMINGHAM CITY OFFICE
- abc HUNTSVILLE
- abc MOBILE
- abc MONTGOMERY

ALASKA

- abc ANCHORAGE
- abc ANNETTE
- abc BARROW
- abc BARTER ISLAND
- abc BETHEL
- abc BETTLES
- abc BIG DELTA
- abc COLD BAY
- abc FAIRBANKS
- abc GULKANA
- abc HOMER
- ac JUNEAU
- abc KING SALMON
- abc KODIAK
- abc KOTZEBUE
- abc McGRATH
- abc NOME
- abc ST PAUL ISLAND
- abc TALKEETNA
- abc UNALAKLEET
- abc VALDEZ
- abc YAKUTAT

ARIZONA

- abc FLAGSTAFF
- abc PHOENIX
- abc TUCSON
- ac WINSLOW
- ac YUMA

ARKANSAS

- abc FORT SMITH
- abc LITTLE ROCK
- ac NO LITTLE ROCK

CALIFORNIA

- abc BAKERSFIELD
- abc BISHOP
- abc BLUE CANYON
- ac EUREKA
- abc FRESNO
- abc LONG BEACH
- abc LOS ANGELES AIRPORT
- ac LOS ANGELES CIVIC CENTER
- abc MT SHASTA
- abc RED BLUFF
- abc SACRAMENTO
- abc SAN DIEGO
- abc SAN FRANCISCO AIRPORT
- ac SAN FRANCISCO CITY
- abc SANTA MARIA
- abc STOCKTON

COLORADO

- abc ALAMOSA
- abc COLORADO SPRINGS
- abc DENVER
- abc GRAND JUNCTION
- abc PUEBLO (4)

CONNECTICUT

- abc BRIDGEPORT
- abc HARTFORD

DELAWARE

- abc WILMINGTON

DISTRICT OF COLUMBIA

- abc WASHINGTON - NATIONAL AP
- abc WASHINGTON - DULLES INT'L AP

FLORIDA

- abc APALACHICOLA
- abc DAYTONA BEACH
- abc FORT MYERS
- abc JACKSONVILLE
- abc KEY WEST
- abc MIAMI
- abc ORLANDO
- abc PENSACOLA
- abc TALLAHASSEE
- abc TAMPA
- abc WEST PALM BEACH

GEORGIA

- abc ATHENS
- abc ATLANTA
- abc AUGUSTA
- abc COLUMBUS
- abc MACON
- abc SAVANNAH

HAWAII

- abc HILO
- abc HONOLULU
- abc KAHULUI
- abc LIHUE

IDAHO

- abc BOISE
- abc LEWISTON
- abc POCATELLO

ILLINOIS

- ac CAIRO
- abc CHICAGO O'HARE AIRPORT
- abc MOLINE
- abc PEORIA
- abc ROCKFORD
- abc SPRINGFIELD

INDIANA

- abc EVANSVILLE
- abc FORT WAYNE
- abc INDIANAPOLIS
- abc SOUTH BEND

IOWA

- abc DES MOINES
- abc DUBUQUE (2)
- abc SIOUX CITY
- abc WATERLOO

KANSAS

- abc CONCORDIA
- abc DODGE CITY
- abc GOODLAND
- abc TOPEKA
- abc WICHITA

KENTUCKY

- abc JACKSON
- abc LEXINGTON
- abc LOUISVILLE

LOUISIANA

- abc BATON ROUGE
- abc LAKE CHARLES
- abc NEW ORLEANS
- abc SHREVEPORT

MAINE

- abc CARIBOU
- abc PORTLAND

MARYLAND

- abc BALTIMORE

MASSACHUSETTS

- abc BOSTON
- ac BLUE HILL OBS
- abc WORCESTER

MICHIGAN

- abc ALPENA
- abc DETROIT CITY AIRPORT
- abc DETROIT METRO AP
- abc FLINT
- abc GRAND RAPIDS
- abc HOUGHTON LAKE
- abc LANSING
- ac MARQUETTE
- abc MUSKEGON
- abc SAULT STE MARIE

MINNESOTA

- abc DULUTH
- abc INTERNATIONAL FALLS
- abc MINNEAPOLIS - ST PAUL
- abc ROCHESTER
- abc ST CLOUD

MISSISSIPPI

- abc JACKSON
- abc MERIDIAN

MISSOURI

- abc COLUMBIA
- abc KANSAS CITY INT'L AP
- abc KANSAS CITY DOWNTOWN AP
- abc ST JOSEPH (3)
- abc ST LOUIS
- abc SPRINGFIELD

MONTANA

- abc BILLINGS
- abc GLASGOW
- abc GREAT FALLS
- abc HAVRE
- abc HELENA
- abc KALISPELL
- abc MILES CITY
- abc MISSOULA

NEBRASKA

- abc GRAND ISLAND
- abc LINCOLN
- abc NORFOLK
- abc NORTH PLATTE
- abc OMAHA
- ac OMAHA (NORTH)
- abc SCOTTSBLUFF
- ac VALENTINE

NEVADA

- abc ELKO
- abc ELY
- abc LAS VEGAS
- abc RENO
- abc WINNEMUCCA

NEW HAMPSHIRE

- abc CONCORD
- ac MT WASHINGTON

NEW JERSEY

- abc ATLANTIC CITY AIRPORT
- ac ATLANTIC CITY STATE MARINA
- abc NEWARK
- ac TRENTON (6)

NEW MEXICO

- abc ALBUQUERQUE
- abc CLAYTON
- abc ROSWELL

NEW YORK

- abc ALBANY
- abc BINGHAMTON
- abc BUFFALO
- abc NEW YORK CENTRAL PARK
- abc N.Y. J.F. KENNEDY INT'L AIRPORT
- abc N.Y. LaGUARDIA FIELD
- abc ROCHESTER
- abc SYRACUSE

NORTH CAROLINA

- abc ASHEVILLE
- abc CAPE HATTERAS
- abc CHARLOTTE
- abc GREENSBORO
- abc RALEIGH
- abc WILMINGTON

NORTH DAKOTA

- abc BISMARCK
- abc FARGO
- abc WILLISTON

OHIO

- abc AKRON-CANTON
- ac CINCINNATI ABBE OBS
- abc CINCINNATI AIRPORT
- abc CLEVELAND
- abc COLUMBUS
- abc DAYTON
- abc MANSFIELD
- abc TOLEDO
- abc YOUNGSTOWN

OKLAHOMA

- abc OKLAHOMA CITY
- abc TULSA

OREGON

- abc ASTORIA
- abc BURNS
- abc EUGENE
- abc MEDFORD
- abc PENDLETON
- abc PORTLAND
- abc SALEM
- abc SEXTON SUMMIT

PACIFIC ISLANDS

- abc GUAM
- abc JOHNSTON
- abc KOROR
- abc KWAJALEIN
- abc MAJURO
- abc PAGO PAGO
- abc PONAPE
- abc TRUK (MOEN)
- abc WAKE
- abc YAP

PENNSYLVANIA

- abc ALLENTOWN
- abc AVOCA, WILKES-BARRE SCRANTON AP
- abc ERIE
- abc HARRISBURG
- abc PHILADELPHIA
- abc PITTSBURGH AIRPORT
- abc WILLIAMSPORT

RHODE ISLAND

- ac BLOCK ISLAND
- abc PROVIDENCE

SOUTH CAROLINA

- abc CHARLESTON AIRPORT
- a CHARLESTON CITY
- abc COLUMBIA
- abc GREENVILLE SPARTANBURG

SOUTH DAKOTA

- abc ABERDEEN (1)
- abc HURON
- abc RAPID CITY
- abc SIOUX FALLS

TENNESSEE

- abc BRISTOL
- abc CHATTANOOGA
- abc KNOXVILLE
- abc MEMPHIS
- abc NASHVILLE
- ac OAK RIDGE

TEXAS

- abc ABILENE
- abc AMARILLO
- abc AUSTIN
- abc BROWNSVILLE
- abc CORPUS CHRISTI
- abc DALLAS FORT WORTH
- ac DEL RIO
- abc EL PASO
- a GALVESTON
- abc HOUSTON
- abc LUBBOCK
- abc MIDLAND
- abc PORT ARTHUR
- abc SAN ANGELO
- abc SAN ANTONIO
- abc VICTORIA
- abc WACO
- abc WICHITA FALLS

UTAH

- abc MILFORD
- abc SALT LAKE CITY

VERMONT

- abc BURLINGTON

VIRGINIA

- abc LYNCHBURG
- abc NORFOLK
- abc RICHMOND
- abc ROANOKE
- ab WALLOPS ISLAND

WASHINGTON

- abc OLYMPIA
- abc QUILLAYUTE AIRPORT
- abc SEATTLE TACOMA AP
- ac SEATTLE URBAN SITE
- abc SPOKANE
- abc STAMPEDE PASS
- ac WALLA WALLA
- abc YAKIMA

WEST INDIES

- abc SAN JUAN, P.R.

WEST VIRGINIA

- abc BECKLEY
- abc CHARLESTON
- abc ELKINS
- abc HUNTINGTON
- a PARKERSBURG

WISCONSIN

- abc GREEN BAY
- abc LA CROSSE
- abc MADISON
- abc MILWAUKEE

WYOMING

- abc CASPER
- abc CHEYENNE
- abc LANDER
- abc SHERIDAN

a. Monthly summary issued. b. Monthly summary includes available 3-hourly observations. c. Annual Summary issued.

SUBSCRIPTION: Price and ordering information available through: National Climatic Center, Federal Building Asheville, North Carolina 28801, ATTN: Publications.

(1) NWS Operations Terminated September 1, 1981. Publications Discontinued.
(2) NWS Operations Terminated September 4, 1981. Publications Discontinued.
(3) NWS Operations Terminated November 1, 1981. Publications Discontinued.
(4) NWS Operations Terminated January 1, 1982. Publications Discontinued.
(5) NWS Operations Terminated December 1, 1981. Publications Discontinued.

Stations for which Local Climatological Data (LCD) is issued.

Local Climatological Data

Annual Summary With Comparative Data

1982

CAPE HATTERAS, NORTH CAROLINA

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE / NATIONAL CLIMATIC DATA CENTER ASHEVILLE, N.C.

STATION LOCATION

CAPE HATTERAS, NORTH CAROLINA

Location	Occupied from	Occupied to	Airline distance and direction from previous location	Latitude North	Longitude West	Elevation above: Sea level: Ground at temperature site	Elevation above Ground: Wind instruments	Extreme thermometers	Psychrometer	Sunshine Switch	Tipping bucket rain gage	Weighing rain gage	8" rain gage	Hygrothermometer	Automatic Observing Equipment *	Remarks
Light House Dwelling Cape Hatteras	8/16/74	12/1/80	NA	35° 15'	75° 31'	2	33	8	8				1			
Life Saving Stn., No.23 Hatteras	12/1/80	10/1/83	8.5 mi. SSW	35° 14'	75° 40'	3	36	6	6				1			
O'Neale's House Hatteras	10/1/83	4/1/87	1.5 mi. W	35° 14'	75° 40'	6	23	7	7				2			
Styron's House Hatteras	4/1/87	1/1/02	0.5 mi. NE	35° 15'	75° 40'	Unk	36	7	7				2			
Weather Bureau Bldg. Hatteras	1/1/02	4/1/46	1300 ft. NE	35° 15'	75° 40'	7	47	16	18		34 a4					a - Effective 4/5/21.
Weather Bureau Bldg. Hatteras	4/1/46	3/1/57	700 ft. SSE	35° 13'	75° 41'	4	b47 c54	6	5		b4					b - Not moved 4/1/46. Moved to new location 12/12/46.
Weather Bureau Bldg. † Buxton, N. C.	3/1/57	Present	10 mi. ENE	35° 16'	75° 33'	7	32	6 16	6 16	17 h31	3 g5 i5	NA d3 g5 i5	2 e f3 g4 i5	NA j6	NA	c - Raised 12/1/55. d - Installed 1958. e - Removed 1958. f - Installed 12/24/60. g - Moved 50' NW 9/30/65. h - Moved from tower to roof 6/1977. i - Minor move 4/1979. j - Installed at temp. site 4/1980.
† NWS Building (Effective 1970)																

* Type
M = AMOS
T = AUTOB

SUBSCRIPTION:
Price and ordering information available through: National Climatic Data Center, Federal Building, Asheville, North Carolina 28801, ATTN: Publications.

I certify that this is an official publication of the National Oceanic and Atmospheric Administration, and is compiled from records received at the National Climatic Data Center, Asheville, North Carolina 28801.

Acting Director
National Climatic Data Center

USCOMM-NOAA-ASHEVILLE - 1050

Local Climatological Data, Annual Summary With Comparative Data, for Cape Hatteras, North Carolina, 1982.

Meteorological Data For The Current Year

Station: CAPE HATTERAS, NORTH CAROLINA # 93729 WEATHER SERVICE BUILDING Standard time used: EASTERN Latitude: 35° 16' N Longitude: 75° 33' W Elevation (ground): 7 feet Year: 1982

Month	Temperature °F Averages: Daily maximum	Daily minimum	Monthly	Extremes: Highest	Date	Lowest	Date	Degree days Base 65 °F: Heating	Cooling	Precipitation in inches, Water equivalent: Total	Greatest in 24 hrs.	Date	Snow, Ice pellets: Total	Greatest in 24 hrs.	Date
JAN	50.1	32.5	41.3	68	31	11	10	727	0	5.85	1.82	3-4	T	T	26
FEB	54.2	41.0	47.6	69	3	27	14	482	0	7.03	2.19	12-13	0.0	0.0	
MAR	60.1	44.0	52.1	74	31	27	9	392	1	6.04	2.91	6	0.0	0.0	
APR	65.5	49.3	57.4	78	17	34	7	237	15	5.85	3.89	26-27	0.0	0.0	
MAY	77.5	60.0	68.8	87	29	41	1	44	168	0.90	0.87	24-25	0.0	0.0	
JUN	80.1	66.5	73.3	86	30	54	15	0	259	5.50	3.49	18-19	0.0	0.0	
JUL	84.6	71.9	78.3	89	27	60	2	0	419	6.76	1.91	23-24	0.0	0.0	
AUG	84.4	70.4	77.4	88	7	60	27	0	393	2.14	1.64	12	0.0	0.0	
SEP	78.7	66.8	72.8	86	3	53	24	0	239	4.53	2.94	26-27	0.0	0.0	
OCT	70.7	56.7	63.7	80	9	50	17	86	53	3.90	3.61	24	0.0	0.0	
NOV	66.3	53.0	59.7	79	3	37	9	176	24	2.50	0.77	13	0.0	0.0	
DEC	61.5	46.6	54.1	77	6	26	23	341	8	5.84	2.22	11-12	0.0	0.0	
YEAR	69.5	54.9	62.2	89	JUL 27	11	JAN 10	2485	1579	56.84	3.89	APR 26-27	T	T	JAN 26

Month	Relative humidity pct. Hour 01	Hour 07	Hour 13	Hour 19 (Local time)	Wind Resultant: Direction	Speed m.p.h.	Average speed m.p.h.	Fastest mile: Speed m.p.h.	Direction	Date	Percent of possible sunshine	Average sky cover, tenths, sunrise to sunset	Number of days, Sunrise to sunset: Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperature °F Maximum: (b) 90° and above	32° and below	Minimum: 32° and below	0° and below	Average station pressure mb Elev 11 feet m.s.l.
JAN	79	79	68	79	32	5.3	14.1	32	35	26	44	6.8	7	8	16	9	0	0	5	0	3	16	0	1019.3
FEB	85	84	75	82	36	6.7	14.0	31	07	13	33	7.2	6	6	16	19	0	2	5	0	0	1	0	1020.3
MAR	84	84	69	82	02	4.1	11.6	24	19	7	46	7.0	6	9	16	9	0	3	7	0	0	1	0	1019.0
APR	76	75	56	70	36	1.4	12.9	35	23	3	69	5.8	8	9	13	9	0	3	0	0	0	0	0	1018.0
MAY	92	86	61	82	23	2.1	9.2	21	22	31	73	4.6	12	13	6	3	0	0	1	0	0	0	0	1017.3
JUN	90	85	71	83	19	2.1	10.4	25	18	19	65	6.0	6	15	9	10	0	4	0	0	0	0	0	1014.2
JUL	95	91	77	87	23	4.7	10.6	26	22	3	57	5.8	10	9	12	17	0	9	0	0	0	0	0	1017.6
AUG	89	88	68	82	23	1.3	9.8	25	27	1	60	5.4	13	9	9	5	0	6	0	0	0	0	0	1018.0
SEP	89	88	73	84	03	5.1	11.0	26	05	5	49	5.6	12	7	11	7	0	3	0	0	0	0	0	1017.3
OCT	85	86	68	81	02	7.0	11.2	44	02	24	50	5.7	8	11	12	5	0	0	1	0	0	0	0	1019.0
NOV	82	84	70	79	03	4.1	10.2	26	03	24	49	6.1	8	8	14	10	0	1	2	0	0	0	0	1022.7
DEC	83	84	71	82	35	3.5	9.6	30	36	12	42	6.9	6	6	19	9	0	1	2	0	0	2	0	1022.7
YEAR	86	85	69	81	36	2.2	11.2	44	02	OCT 24	55	6.1	102	110	153	112	0	32	23	0	3	20	0	1018.8

Normals, Means, And Extremes

Month	Temperatures °F Normal: Daily maximum	Daily minimum	Monthly	Extremes: Record highest	Year	Record lowest	Year	Normal Degree days Base 65 °F: Heating	Cooling	Precipitation in inches, Water equivalent: Normal	Maximum monthly	Year	Minimum monthly	Year	Maximum in 24 hrs.	Year	Snow, Ice pellets: Maximum monthly	Year	Maximum in 24 hrs.	Year
(a)				25		25					25		25		25		25		25	
J	52.3	38.2	45.3	75	1972	11	1982	611	0	4.26	9.72	1979	1.75	1981	5.00	1979	3.5	1962	3.5	1962
F	53.1	38.5	45.8	76	1971	14	1958	538	0	4.15	7.48	1963	1.42	1976	2.92	1970	4.4	1978	4.4	1978
M	57.9	43.2	50.6	79	1977	19	1967	458	6	3.84	8.94	1980	0.98	1967	2.91	1982	8.5	1960	7.3	1980
A	66.3	51.5	58.9	85	1967	26	1972	188	12	3.07	7.10	1962	0.59	1976	5.60	1963	0.0		0.0	
M	73.8	60.2	67.0	88	1962	39	1971	47	96	3.28	11.44	1972	0.61	1962	3.28	1958	0.0		0.0	
J	80.5	68.1	74.3	95	1978	44	1966	0	270	4.83	10.80	1962	0.38	1978	6.63	1962	0.0		0.0	
J	83.8	72.1	78.0	95	1969	54	1972	0	409	5.90	9.99	1965	0.45	1958	5.53	1967	0.0		0.0	
A	83.4	71.5	77.5	94	1968	56	1979	0	409	6.75	11.73	1976	1.04	1978	8.11	1962	0.0		0.0	
S	79.5	67.8	73.7	92	1978	45	1970	0	276	5.76	12.78	1979	0.73	1978	5.46	1979	0.0		0.0	
O	71.3	59.1	65.2	86	1959	32	1979	76	72	4.79	11.24	1971	1.34	1973	5.35	1974	0.0		0.0	
N	63.1	48.8	56.0	81	1971	22	1967	277	6	4.45	14.63	1962	1.23	1973	7.59	1977	T	1970	T	1970
D	54.6	40.5	47.7	77	1982	18	1981	536	0	4.54	8.63	1962	2.07	1971	3.59	1979	2.5	1970	2.5	1970
YR	68.3	55.0	61.7	95	JUN 1978	11	JAN 1982	2731	1556	55.62	14.63	NOV 1962	0.38	JUN 1978	8.11	AUG 1962	8.5	MAR 1960	7.3	MAR 1980

Month	Relative humidity pct. Hour 01	Hour 07	Hour 13	Hour 19 (Local time)	Wind: Mean speed m.p.h.	Prevailing direction	Fastest mile #: Speed m.p.h.	Direction	Year	Pct. of possible sunshine	Mean sky cover, tenths, sunrise to sunset	Mean number of days, Sunrise to sunset: Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperatures °F Max: (b) 90° and above	32° and below	Min.: 32° and below	0° and below	Average station pressure mb Elev. 11 feet m.s.l.
(a)	25	25	25	25	25	6	12	12		20	25	25	25	25	25	25	25	25	25	25	25	25	10
J	79	80	68	78	12.5	NNE	32	N35	1982	50	6.2	9	7	15	11	*	1	3	0	1	11	0	1018.7
F	79	80	65	76	12.8	NNE	44	S04	1973	53	6.0	9	5	14	10	*	2	3	0	*	10	0	1018.8
M	80	80	62	76	12.2	SW	48	N02	1980	60	6.0	10	7	14	10	*	2	3	0	0	*	0	1017.2
A	81	78	59	76	12.2	SW	35	S23	1982	65	5.5	10	9	11	8	0	3	1	0	0	*	0	1017.2
M	86	82	66	80	11.2	SW	35	18	1972	61	6.1	8	10	13	10	0	6	1	0	0	0	0	1015.5
J	88	83	69	80	10.8	SSW	37	N29	1972	61	6.3	7	10	13	9	0	5	*	1	0	0	0	1016.3
J	89	85	70	82	10.3	SW	26	22	1982	61	6.5	6	10	15	12	0	9	*	1	0	0	0	1016.8
A	89	86	69	83	9.7	SW	41	16	1971	61	6.2	8	10	13	10	0	8	*	2	0	0	0	1018.0
S	85	84	67	80	10.6	NE	44	12	1971	60	5.7	9	10	11	9	0	4	*	*	0	0	0	1017.2
O	82	82	65	79	11.3	NNE	44	N02	1982	59	5.4	11	7	13	9	0	2	1	0	0	*	0	1018.3
N	80	82	64	78	11.2	NNE	35	18	1971	56	5.4	11	7	12	9	0	1	1	0	0	1	0	1019.4
D	79	81	66	78	11.8	NNE	39	N22	1972	47	5.9	10	7	14	10	*	1	2	0	*	7	0	1019.3
YR	83	82	66	79	11.4	SW	48	N02	MAR 1980	58	5.9	108	99	158	120	1	43	16	4	1	34	0	1017.7

Means and extremes above are from existing and comparable exposures. Annual extremes have been exceeded at other sites in the locality as follows: Highest temperature 97 in June 1952; lowest temperature 8 in December 1880; maximum monthly precipitation 20.95 in June 1949; minimum monthly precipitation T in November 1890; maximum precipitation in 24 hours 14.73 in June 1949; maximum monthly snowfall 12.0 in December 1917; maximum snowfall in 24 hours 12.0 in December 1917; fastest mile wind 110 W in September 1944.

(a) Length of record, years, through the current year unless otherwise noted, based on January data.
(b) 70° and above at Alaskan stations.
* Less than one half.
T Trace.

NORMALS - Based on record for the 1941-1970 period.
DATE OF AN EXTREME - The most recent in cases of multiple occurrence.
PREVAILING WIND DIRECTION - Record through 1963.
WIND DIRECTION - Numerals indicate tens of degrees clockwise from true north. 00 indicates calm.
FASTEST MILE WIND - Speed is fastest observed 1-minute value when the direction is in tens of degrees.

For period Feb. 1971 to date.

Local Climatological Data, Annual Summary With Comparative Data, for Cape Hatteras, North Carolina, 1982, continued.

JAN 1982 CAPE HATTERAS, NORTH CAROLINA

JAN 1982 93729
CAPE HATTERAS, NORTH CAROLINA
WEATHER SERVICE BUILDING

ISSN 0198-3725

LOCAL CLIMATOLOGICAL DATA

Monthly Summary

NATIONAL WEATHER SERVICE OFC

LATITUDE 35° 16' N LONGITUDE 75° 33' W ELEVATION (GROUND) 7 TIME ZONE EASTERN WBAN #93729

DATE	TEMPERATURE °F: MAXIMUM	MINIMUM	AVERAGE	DEPARTURE FROM NORMAL	AVERAGE DEW POINT	DEGREE DAYS BASE 65°F: HEATING (SEASON BEGINS WITH JUL)	COOLING (SEASON BEGINS WITH JAN)	WEATHER TYPES: 1 FOG 2 HEAVY FOG 3 THUNDERSTORM 4 ICE PELLETS 5 HAIL 6 GLAZE 7 DUSTSTORM 8 SMOKE, HAZE 9 BLOWING SNOW	SNOW ICE PELLETS OR ICE ON GROUND AT 07AM INCHES	PRECIPITATION: WATER EQUIVALENT (INCHES)	SNOW, ICE PELLETS (INCHES)	AVERAGE STATION PRESSURE IN INCHES ELEV. 11 FEET ABOVE M.S.L.	WIND (M.P.H.): RESULTANT DIR	RESULTANT SPEED	AVERAGE SPEED	FASTEST MILE: SPEED	FASTEST MILE: DIRECTION	SUNSHINE: MINUTES	PERCENT OF TOTAL POSSIBLE	SKY COVER (TENTHS): SUNRISE TO SUNSET	MIDNIGHT TO MIDNIGHT	DATE
1	2	3	4	5	6	7A	7B	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	60	44	52	6	46	13	0	1	0	T	0	29.85	26	14.3	15.4	30	16	256	43	9	7	1
2	47	40	44	-2	34	21	0		0	0	0	30.31	03	14.9	15.2	20	03	475	82	[illegible]	6	2
3	61	43	52	6	50	13	0	1	0	1.51	0	30.22	13	10.7	15.7	23	17	0	0	10	9	3
4	67	54	61	15	58	4	0	1	0	.55	0	29.90	20	20.2	22.6	28	19	0	0	10	10	4
5	54	30	42	-4	29	23	0		0	0	0	30.14	30	11.8	12.5	21	27	569	96	0	2	5
6	62	30	46	0	40	19	0		0	0	0	30.16	23	6.2	8.8	17	23	183	31	9	8	6
7	63	50	57	11	55	8	0	1	0	T	0	29.99	25	12.9	13.1	18	36	280	47	7	9	7
8	50	27	39	-7	28	26	0		0	0	0	30.17	01	14.4	16.0	26	01	23	4	10	10	8
9	48	26	37	-9	26	28	0		0	0	0	29.79	29	11.0	11.7	23	32	552	93	6	4	9
10	32	11*	22	-23	3	43	0		0	0	0	29.91	32	15.3	15.7	21	29	484	81	5	4	10
11	23	12	18*	-27	1	47	0		0	0	0	30.04	29	16.1	16.7	23	27	543	91	[illegible]	[illegible]	11
12	36	21	29	-16	16	36	0		0	T	0	30.23	34	12.6	13.1	18	35	134	22	8	7	12
13	60	33	47	2	46	18	0	2	0	73	0	29.93	20	4.2	17.4	25	22	0	0	10	10	13
14	47	31	39	-6	36	26	0	2	0	83	T	29.53	34	9.6	12.5	23	01	0	0	10	10	14
15	37	25	31	-14	22	34	0		0	0	0	29.95	30	12.7	13.4	21	31	602	100	0	[illegible]	15
16	52	23	38	-7	31	27	0		0	0	0	30.03	25	11.1	13.8	23	26	81	13	10	5	16
17	43	20	32	-13	13	33	0		0	0	0	30.22	35	14.2	16.0	23	35	471	78	4	5	17
18	49	19	34	-11	25	31	0		0	0	0	30.29	06	5.7	8.9	12	10	442	73	5	6	18
19	48	38	43	-2	40	22	0	1	0	.26	0	30.19	04	6.6	7.8	12	05	0	0	10	10	19
20	44	36	40	-5	36	25	0	2	0	0	0	30.19	36	10.8	10.9	17	36	0	0	10	10	20
21	56	36	46	1	41	19	0	2	0	.47	0	30.13	01	11.7	14.5	21	24	0	0	10	10	21
22	51	39	45	0	38	20	0	1	0	0	0	30.44	02	17.7	18.7	23	01	52	8	10	10	22
23	60	51	56	11	54	9	0	2	0	1.47	0	30.02	19	11.7	16.8	22	16	0	0	10	10	23
24	56	39	48	3	34	17	0	1	0	0	0	29.78	28	16.7	17.0	21	27	562	91	3	4	24
25	41	32	37	-8	19	28	0		0	0	0	30.02	33	5.0	9.5	15	34	453	73	7	5	25
26	43	26	35	-10	25	30	0		0	T	T	29.99	36	17.6	22.4	32	35	0	0	10	8	26
27	31	20	26	-19	16	39	0		0	0	0	30.39	01	16.3	16.4	23	36	465	75	3	3	27
28	51	20	36	-9	30	29	0		0	0	0	30.33	27	5.4	7.6	15	23	302	49	1	1	28
29	47	37	42	-3	34	23	0	8	0	0	0	30.40	35	10.8	13.1	18	01	623	100	0	0	29
30	67	37	52	7	46	13	0	1 8	0	.01	0	30.34	04	2.3	9.4	16	23	444	71	5	6	30
31	68*	56	62*	17	56	3	0	8	0	.02	0	30.13	20	13.8	14.4	22	19	210	34	10	7	31

SUM	SUM				TOTAL	TOTAL	NUMBER OF DAYS	TOTAL	TOTAL	FOR THE MONTH:						TOTAL	%	SUM	SUM
1554	1006				727	0		5.85	T	30.10	32	5.3	14.1	32	35	8206	FOR	210	198
AVG	AVG	AVG	DEP	AVG	DEP	DEP	PRECIPITATION	DEP						DATE: 26		POSSIBLE	MONTH	AVG	AVG
50.1	32.5	41.3	-4.0	33	116	0	> .01 INCH 9	1.59								18764	44	6.8	6.4

NUMBER OF DAYS				SEASON TO DATE						
				TOTAL	TOTAL	SNOW, ICE PELLETS > 1.0 INCH 0	GREATEST IN 24 HOURS AND DATES			GREATEST DEPTH ON GROUND OF SNOW, ICE PELLETS OR ICE AND DATE
MAXIMUM TEMP.		MINIMUM TEMP.		1836	0	THUNDERSTORMS 0	PRECIPITATION		SNOW, ICE PELLETS	
≥ 90°	≤ 32°	≤ 32°	≤ 0°	DEP	DEP	HEAVY FOG 5	1.82	3-4	T 26+	T 27+
0	3	16	0	336	0	CLEAR 7 PARTLY CLOUDY 8 CLOUDY 16				

* EXTREME FOR THE MONTH - LAST OCCURRENCE IF MORE THAN ONE.
T TRACE AMOUNT.
+ ALSO ON EARLIER DATE(S).
HEAVY FOG: VISIBILITY 1/4 MILE OR LESS.
BLANK ENTRIES DENOTE MISSING DATA.

MINIMUM TEMP. IS NEW MONTHLY & ALL TIME RECORD AT THIS LOCATION.

DATA IN COLS 6 AND 12-15 ARE BASED ON 7 OR MORE OBSERVATIONS AT 3-HOUR INTERVALS. RESULTANT WIND IS THE VECTOR SUM OF WIND SPEEDS AND DIRECTIONS DIVIDED BY THE NUMBER OF OBSERVATIONS. ONE OF THREE WIND SPEEDS IS GIVEN UNDER FASTEST MILE: FASTEST MILE - HIGHEST RECORDED SPEED FOR WHICH A MILE OF WIND PASSES STATION (DIRECTION IN COMPASS POINTS). FASTEST OBSERVED ONE MINUTE WIND - HIGHEST ONE MINUTE SPEED (DIRECTION IN TENS OF DEGREES). PEAK GUST - HIGHEST INSTANTANEOUS WIND SPEED (A ' APPEARS IN THE DIRECTION COLUMN). ERRORS WILL BE CORRECTED AND CHANGES IN SUMMARY DATA WILL BE ANNOTATED IN THE ANNUAL PUBLICATION.

I CERTIFY THAT THIS IS AN OFFICIAL PUBLICATION OF THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, AND IS COMPILED FROM RECORDS ON FILE AT THE NATIONAL CLIMATIC CENTER, ASHEVILLE, NORTH CAROLINA, 28801.

Daniel B. Mitchell
DIRECTOR
NATIONAL CLIMATIC CENTER

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / ENVIRONMENTAL DATA AND INFORMATION SERVICE / NATIONAL CLIMATIC CENTER ASHEVILLE, NORTH CAROLINA

Local Climatological Data Monthly Summary for January 1982, Cape Hatteras, North Carolina.

OBSERVATIONS AT 3-HOUR INTERVALS

JAN 1982
CAPE HATTERAS, NORTH CAROLINA

HOUR L.S.T.	SKY COVER (TENTHS)	CEILING IN HUNDREDS OF FEET	VISIBILITY WHOLE MILES	VISIBILITY 16THS MILE	WEATHER	TEMPERATURE AIR °F	TEMPERATURE WET BULB °F	TEMPERATURE DEW POINT °F	REL HUMIDITY %	WIND DIRECTION	WIND SPEED (KNOTS)
					DAY 01						
01	10	18	5		RF	59	58	57	93	22	17
04	10	18	4		F	52	51	50	93	25	19
07	10	15	5		F	50	48	47	89	27	15
10	10	15	8			47	45	44	89	27	16
13	10	UNL	10			48	46	43	83	29	15
16	7	UNL	10			50	46	42	74	28	10
19	0	UNL	10			47	45	44	89	27	7
22	0	UNL	10			45	44	43	93	27	8
					DAY 04						
01	10	13	2		RF	61	60	60	97	17	20
04	10	28	4		F	63	61	59	87	13	20
07	10	100	7			64	62	60	87	18	20
10	10	20	7			66	63	61	84	18	21
13	10	15	4		RW	65	64	63	93	19	24
16	10	80	6		F	63	62	61	93	22	16
19	10	200	6		F	62	60	59	90	22	18
22	10	200	7			56	49	41	57	26	18
					DAY 07						
01	10	100	10			62	58	56	81	23	15
04	10	100	7			59	56	54	84	24	15
07	10	100	7			57	55	54	90	24	12
10	1	UNL	7			61	58	55	81	25	12
13	10	UNL	7			63	58	55	75	25	14
16	10	100	7			59	57	56	90	25	11
19	8	200	5		F	55	54	54	96	26	7
22	9	80	7			59	57	56	90	26	5
					DAY 10						
01	0	UNL	10			30	24	09	41	33	14
04	0	UNL	10			27	22	06	41	30	9
07	0	UNL	10			28	23	09	45	30	10
10	0	UNL	10			29	24	10	45	31	16
13	8	250	10			26	21	05	40	33	14
16	8	UNL	12			17	13	-03	41	33	16
19	6	UNL	12			12	09	-08	40	33	16
22	3	UNL	10			11	08	-06	46	33	14
					DAY 13						
01	10	15	4		R	35	34	32	89	02	13
04	10	15	3		F	34	34	33	96	35	11
07	10	70	5		F	40	40	39	96	02	13
10	10	20	7			50	47	45	83	17	12
13	10	15	6		RF	56	54	53	90	17	21
16	10	10	5		F	58	58	58	100	18	20
19	10	8	5		RF	59	59	59	100	22	22
22	10	1	0	4	F	46	46	46	100	31	9
					DAY 16						
01	0	UNL	10			25	24	22	88	01	6
04	0	UNL	10			23	23	21	92	10	5
07	3	UNL	10			25	25	23	92	00	0
10	10	200	10			45	39	32	60	25	15
13	10	200	10			49	43	35	59	26	20
16	10	80	12			51	45	38	61	25	20
19	2	UNL	12			48	44	39	71	24	18
22	0	UNL	12			45	41	35	68	26	12

HOUR L.S.T.	SKY COVER (TENTHS)	CEILING IN HUNDREDS OF FEET	VISIBILITY WHOLE MILES	VISIBILITY 16THS MILE	WEATHER	TEMPERATURE AIR °F	TEMPERATURE WET BULB °F	TEMPERATURE DEW POINT °F	REL HUMIDITY %	WIND DIRECTION	WIND SPEED (KNOTS)
					DAY 02						
01	0	UNL	7			45	43	41	86	02	12
04	0	UNL	7			42	38	33	71	02	12
07	0	UNL	10			40	36	31	70	02	16
10	4	UNL	12			45	39	32	60	03	17
13	10	UNL	12			46	40	33	61	04	15
16	10	UNL	10			43	38	32	65	02	11
19	10	UNL	7			41	37	32	70	05	11
22	6	UNL	7			41	38	35	79	05	12
					DAY 05						
01	4	UNL	10			52	43	32	47	28	15
04	0	UNL	10			48	40	30	50	29	15
07	0	UNL	10			44	37	26	49	29	15
10	0	UNL	10			45	38	27	49	30	13
13	0	UNL	12			48	40	29	48	32	13
16	2	UNL	12			49	40	27	43	34	8
19	6	UNL	10			34	33	30	85	27	6
22	3	UNL	8			31	30	29	92	34	2
					DAY 08						
01	10	14	7			47	45	43	86	01	18
04	10	15	7			41	38	34	76	01	18
07	10	20	7			40	36	29	65	01	20
10	10	100	10			40	34	24	53	02	18
13	10	250	10			41	34	22	47	01	15
16	10	200	10			38	32	21	50	03	10
19	10	180	10			33	30	24	70	30	6
22	10	200	8			30	28	25	82	28	6
					DAY 11						
01	0	UNL	10			12	09	-05	46	30	15
04	0	UNL	10			14	11	-06	40	28	17
07	0	UNL	10			16	13	01	51	28	16
10	1	UNL	10			20	16	03	47	27	20
13	1	UNL	10			22	17	01	40	28	14
16	1	UNL	10			23	18	03	42	30	12
19	0	UNL	10			21	17	04	48	30	9
22	0	UNL	10			21	17	05	50	32	13
					DAY 14						
01	10	1	0	4	F	38	38	37	96	29	9
04	10	0	0	1	F	35	35	35	100	33	7
07	10	3	1		RF	35	35	34	96	35	9
10	10	2	0	12	RF	34	34	33	96	01	10
13	10	3	1		RF	45	45	45	100	34	9
16	10	10	0	8	F	44	44	44	100	05	7
19	10	1	0	2	RF	33	33	32	96	01	20
22	10	15	7		S	32	31	28	85	28	16
					DAY 17						
01	0	UNL	10			40	38	35	82	28	14
04	4	UNL	10			38	36	33	82	34	16
07	0	UNL	10			29	23	08	41	33	19
10	0	UNL	10			28	23	09	45	01	14
13	7	UNL	10			25	21	07	46	36	15
16	10	220	12			22	18	05	48	01	13
19	10	120	12			20	17	04	50	36	12
22	0	UNL	12			20	17	04	50	36	8

HOUR L.S.T.	SKY COVER (TENTHS)	CEILING IN HUNDREDS OF FEET	VISIBILITY WHOLE MILES	VISIBILITY 16THS MILE	WEATHER	TEMPERATURE AIR °F	TEMPERATURE WET BULB °F	TEMPERATURE DEW POINT °F	REL HUMIDITY %	WIND DIRECTION	WIND SPEED (KNOTS)
					DAY 03						
01	10	250	7			43	41	38	83	05	16
04	3	UNL	7			44	43	42	93	06	14
07	10	100	7			47	46	45	93	08	7
10	10	25	10			55	51	48	77	13	11
13	10	20	3		RF	55	54	53	93	14	14
16	10	10	2		RF	57	57	57	100	15	15
19	10	16	3		RF	59	58	58	97	16	13
22	10	18	3		RF	60	59	59	97	18	19
					DAY 06						
01	0	UNL	10			30	29	28	92	20	4
04	7	200	10			32	31	30	92	31	6
07	7	100	7			36	35	34	92	24	5
10	6	250	10			52	42	30	43	08	6
13	10	250	10			60	53	46	60	21	6
16	10	250	10			56	50	45	67	25	9
19	10	200	10			55	53	51	86	22	10
22	10	200	10			61	57	54	78	23	15
					DAY 09						
01	3	UNL	10			30	28	24	78	30	8
04	4	UNL	10			28	27	24	85	28	6
07	7	100	10			27	27	25	92	27	6
10	7	100	10			41	37	30	65	29	8
13	7	250	10			45	36	23	42	27	16
16	3	UNL	12			48	39	26	42	28	9
19	0	UNL	10			44	40	34	68	30	9
22	0	UNL	10			38	31	18	44	32	19
					DAY 12						
01	0	UNL	10			22	18	05	48	31	10
04	0	UNL	10			23	19	05	46	32	9
07	0	UNL	10			21	18	08	57	36	7
10	9	20	10			26	24	18	72	35	16
13	10	20	10			29	27	21	72	35	12
16	10	20	10			30	27	22	72	35	14
19	10	23	10			30	28	25	82	35	11
22	10	20	10			31	29	26	92	36	12
					DAY 15						
01	4	UNL	10			30	28	24	78	31	18
04	3	UNL	10			30	28	23	75	30	13
07	0	UNL	10			28	25	18	66	29	11
10	0	UNL	8			32	28	20	61	31	14
13	0	UNL	10			35	30	21	57	33	14
16	0	UNL	10			36	31	23	59	27	9
19	0	UNL	10			34	31	26	73	28	8
22	0	UNL	10			32	29	23	69	28	6
					DAY 18						
01	10	250	10			24	21	13	63	10	10
04	0	UNL	10			24	21	14	66	35	8
07	3	UNL	10			21	20	16	81	36	8
10	2	UNL	10			38	32	21	50	09	8
13	2	UNL	10			46	40	31	56	10	7
16	9	UNL	10			47	43	39	74	10	7
19	10	UNL	10			34	33	31	89	10	7
22	10	250	7			40	39	37	89	35	7

WEATHER CODES

*	TORNADO	ZL	FREEZING DRIZZLE	IPW	ICE PELLET SHOWERS	BN	BLOWING SAND
T	THUNDERSTORM	S	SNOW	A	HAIL	BS	BLOWING SNOW
Q	SQUALL	SW	SNOW SHOWERS	F	FOG	BY	BLOWING SPRAY
R	RAIN	SG	SNOW GRAINS	IF	ICE FOG	K	SMOKE
RW	RAIN SHOWERS	SP	SNOW PELLETS	GF	GROUND FOG	H	HAZE
ZR	FREEZING RAIN	IC	ICE CRYSTALS	BD	BLOWING DUST	D	DUST
L	DRIZZLE	IP	ICE PELLETS				

CEILING: UNL INDICATES UNLIMITED
WIND DIRECTION: DIRECTIONS ARE THOSE FROM WHICH THE WIND BLOWS, INDICATED IN TENS OF DEGREES FROM TRUE NORTH: I.E., 09 FOR EAST, 18 FOR SOUTH, 27 FOR WEST. AN ENTRY OF 00 INDICATES CALM
SPEED: EXPRESSED IN KNOTS, (MPH = KNOTS X 1.15) IS THE fastest OBSERVED 1-MINUTE VALUE

Local Climatological Data Monthly Summary for January 1982, Cape Hatteras, North Carolina, continued.

OBSERVATIONS AT 3-HOUR INTERVALS

JAN 1982
CAPE HATTERAS, NORTH CAROLINA

Day	Hour L.S.T.	Sky cover (tenths)	Ceiling in hundreds of feet	Visibility: Whole miles	Visibility: 16ths mile	Weather	Temperature: Air °F	Temperature: Wet bulb °F	Temperature: Dew point °F	Rel. humidity %	Wind: Direction	Wind: Speed (knots)
DAY 19	01	10	70	7			39	37	35	86	36	6
	04	10	70	7			38	37	35	89	02	7
	07	10	50	7			42	40	37	83	35	4
	10	10	50	6		LF	40	39	38	93	02	6
	13	10	50	7			42	42	41	96	06	7
	16	10	35	5		F	47	46	46	96	08	10
	19	10	13	4		F	48	48	48	100	07	8
	22	10	1	0	8	F	43	43	43	100	01	6
DAY 20	01	10	1	1		F	40	40	40	100	34	3
	04	10	1	0	4	F	39	39	39	100	35	6
	07	10	2	0	8	F	38	38	38	100	34	7
	10	10	15	1		F	36	36	35	96	36	14
	13	10	10	2		F	37	36	34	89	36	14
	16	10	6	1	8	F	38	37	35	89	36	14
	19	10	6	2		F	38	37	35	89	01	9
	22	10	17	2		F	37	36	35	92	35	9
DAY 21	01	10	10	3		F	36	36	35	96	35	11
	04	10	8	2		F	41	41	41	100	02	12
	07	10	8	1		F	41	41	41	100	01	6
	10	10	3	0	4	RF	55	55	55	100	09	10
	13	10	10	4		F	43	43	42	96	08	13
	16	10	3	0	8	F	40	40	39	96	35	15
	19	10	3	0	8	F	38	37	36	93	35	17
	22	10	2	0	8	F	37	37	37	100	36	17
DAY 22	01	10	2	0	8	F	39	39	39	100	36	15
	04	10	2	2		F	39	39	38	96	36	16
	07	10	8	5		F	39	38	37	93	01	16
	10	7	100	7			43	40	37	79	01	20
	13	10	10	7			41	39	36	82	02	18
	16	10	15	7			39	37	34	82	02	16
	19	10	60	7			43	41	38	83	04	14
	22	10	70	6		F	46	44	42	86	06	15
DAY 23	01	10	100	7			51	48	45	80	12	15
	04	10	100	7			53	50	48	83	15	16
	07	10	25	7			57	55	53	87	16	19
	10	10	15	3		RF	57	56	56	96	19	18
	13	10	10	1		RF	58	58	58	100	24	11
	16	10	10	2		F	59	59	59	100	23	13
	19	10	10	1		RF	58	58	58	100	23	14
	22	10	10	2		RF	59	58	57	93	27	11
DAY 24	01	10	25	2		F	55	55	55	100	26	14
	04	8	UNL	7			47	45	43	86	28	16
	07	5	UNL	8			45	42	38	77	27	15
	10	4	UNL	10			46	41	35	66	27	17
	13	7	200	10			47	39	29	50	27	18
	16	0	UNL	10			45	38	27	49	29	15
	19	0	UNL	10			42	35	22	45	29	12
	22	0	UNL	10			40	34	23	51	29	11
DAY 25	01	0	UNL	10			36	31	21	55	34	8
	04	0	UNL	10			35	29	18	50	34	8
	07	0	UNL	10			33	27	14	45	32	7
	10	7	100	10			38	30	14	37	33	12
	13	5	UNL	10			39	31	14	36	33	9
	16	9	100	10			39	31	15	38	21	10
	19	6	250	10			32	29	24	72	04	6
	22	10	100	10			36	33	29	76	13	6
DAY 26	01	10	80	8			39	35	30	70	16	10
	04	8	80	7			42	39	35	76	25	10
	07	4	UNL	10			38	36	34	86	01	18
	10	10	8	4		S	33	32	29	85	36	25
	13	10	5	0	8	S	28	27	23	92	01	27
	16	10	15	7			27	25	18	69	01	24
	19	7	100	9			27	24	15	61	01	22
	22	10	100	10			26	23	14	60	36	20
DAY 27	01	10	29	10			27	24	15	61	01	18
	04	10	24	8			27	24	16	63	01	17
	07	3	UNL	8			27	24	16	63	36	16
	10	3	UNL	10			30	26	17	58	01	17
	13	4	UNL	8			31	27	17	56	01	17
	16	0	UNL	10			30	26	16	56	01	14
	19	0	UNL	10			27	24	16	63	01	10
	22	0	UNL	10			26	24	18	72	34	5
DAY 28	01	0	UNL	10			21	20	18	88	34	7
	04	0	UNL	10			24	23	20	85	36	8
	07	0	UNL	10			21	20	18	88	00	0
	10	0	UNL	10			41	36	27	58	00	0
	13	0	UNL	8			51	44	36	57	25	8
	16	4	UNL	8			50	44	38	64	24	11
	19	0	UNL	8			46	43	40	80	25	10
	22	0	UNL	7			47	44	40	77	26	9
DAY 29	01	0	UNL	10			47	42	36	66	26	8
	04	0	UNL	8			43	40	35	73	30	8
	07	0	UNL	8			37	35	33	85	32	10
	10	0	UNL	6		H	41	37	32	70	36	14
	13	0	UNL	6		H	45	40	34	65	01	14
	16	0	UNL	8			42	38	32	68	01	15
	19	0	UNL	10			38	36	32	79	01	12
	22	0	UNL	7			38	37	35	89	02	10
DAY 30	01	0	UNL	7			40	38	36	86	03	13
	04	3	UNL	7			40	39	37	89	02	11
	07	4	UNL	6		F	39	38	37	93	01	8
	10	7	UNL	7			51	47	44	77	05	7
	13	5	UNL	7			66	58	52	61	14	5
	16	5	UNL	10			65	58	52	63	23	7
	19	8	100	10			56	54	52	87	19	5
	22	10	100	7			58	56	55	90	21	9
DAY 31	01	10	29	6		RW	56	55	54	93	24	8
	04	4	UNL	7			58	55	53	94	21	10
	07	4	UNL	7			58	55	53	84	21	10
	10	10	250	7			66	61	57	73	19	12
	13	10	250	7			68	61	56	66	18	14
	16	10	100	8			65	60	57	75	19	14
	19	4	UNL	7			61	59	57	87	19	16
	22	5	UNL	7			60	58	57	90	19	16

CAPE HATTERAS N C 82 01

SUMMARY BY HOURS

Hour L S T	Averages: Sky cover (tenths)	Averages: Station pressure (inches)	Temperature: Air temp °F	Temperature: Wet bulb °F	Temperature: Dew point °F	Rel humidity %	Wind speed (mph)	Resultant wind: Direction	Resultant wind: Speed (mph)
01	6	30.09	39	37	33	79	13.7	32	5.1
04	5	30.09	38	36	32	79	13.5	32	6.4
07	5	30.11	38	35	31	79	12.8	33	6.1
10	6	30.14	43	39	33	69	15.5	33	5.5
13	7	30.08	45	41	34	68	16.1	32	5.0
16	7	30.07	44	41	34	70	14.7	31	4.6
19	6	30.09	41	39	35	79	13.5	31	4.3
22	6	30.11	40	38	34	78	12.9	31	5.9

Local Climatological Data Monthly Summary for January 1982, Cape Hatteras, North Carolina, continued.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE - EASTERN REGION
585 Stewart Avenue
Garden City, New York 11530

October 20, 1983 W/ERx2:RE

Mr. James P. Needham

Springfield, VA 22152

Dear Mr. Needham:

Our National Climatic Data Center in Asheville has referred to us your recent request for information on Cape Hatteras wind equipment. I'm providing some specifics below:

1) Our Cape Hatteras Weather Service Office uses a Standard F 420-C anemometer. The wind system is not located at our office site, but is remoted from the local Coast Guard base, out on the Cape.

2) The instruments are mounted 30 feet above ground.

3) Unfortunately, the instrument exposure is not the best. Pine trees in the area that were previously non-existent or very small have grown considerably; this can affect the quality of the wind data--the speed recorded from some directions could be somewhat lower than the true speed.

You may find it helpful to discuss this with the Meteorologist in Charge of our Cape Hatteras office, Mr. . He can be reached at . Should you prefer to write to Mr. , his mailing address is:

National Weather Service Office
National Oceanic and Atmospheric Administration

Buxton, North Carolina 27920.

Sincerely,

Special Programs Manager

Letter from U.S. Department of Commerce concerning type, location and exposure of wind instruments at Cape Hatteras, North Carolina station.

APPENDIX B

Computer Programs Used For Reducing Wind Data

----------------------------Index----------------------------

----

```
10 REM  COMPUTER PROGRAM #1
20 REM
30 REM  ALLOWS WIND SPEED DATA TO BE TRANSFERRED
40 REM  FROM HARDCOPY TO MAGNETIC TAPE SO THAT IT
50 REM  CAN BE PROCESSED AND REDUCED BY COMPUTER.
60 REM
70 REM  INPUT WIND SPEED DATA IN A SEQUENTIAL FILE
80 REM
90  OPEN "SPEEDJAN" FOR OUTPUT AS #1
100 INPUT "WINDSPEED"; S%
110 IF S%=1000 THEN CLOSE: END
120 WRITE #1, S%
130 PRINT: GOTO 100
```

```
10 REM  COMPUTER PROGRAM #2
20 REM
30 REM  ALLOWS WIND DIRECTION DATA TO BE TRANSFERRED
40 REM  FROM HARDCOPY TO MAGNETIC TAPE SO THAT IT CAN
50 REM  BE PROCESSED AND REDUCED BY COMPUTER PROGRAMS.
60 REM
70 REM INPUT WIND DIRECTION DATA IN A SEQUENTIAL FILE
80 REM
90  OPEN "DIRJAN" FOR OUTPUT AS #1
100 INPUT "WIND DIRECTION"; S%
110 IF S%=1000 THEN CLOSE: END
120 WRITE #1, S%
130 PRINT: GOTO 100
```

```
10 REM  COMPUTER PROGRAM #3
20 REM
30 REM  DETERMINES THE AVERAGE WIND SPEED DURING A MONTH
40 REM  USING THE SEQUENTIAL WIND SPEED DATA FILE CREATED
50 REM  IN COMPUTER PROGRAM #1.
60 REM
70  DIM SPEED(30,7)
80  L%=0: J%=0: K!=O
90  OPEN "SPEEDJAN" FOR INPUT AS #1
100 FOR DAY=0 TO 30
110 FOR HOUR=0 TO 7
120 INPUT #1, SPEED(DAY,HOUR)
130 J%=J% + SPEED(DAY,HOUR)
140 L%=L% + 1
150 NEXT HOUR
160 PRINT USING "\##\";SPEED(DAY,0);SPEED(DAY,1);
    SPEED(DAY,2);SPEED(DAY,3);SPEED(DAY,4);SPEED(DAY,5);
    SPEED(DAY,6);SPEED(DAY,7)
170 NEXT DAY
180 K!=(J%*1.15)/L%
190 PRINT "AVERAGE WIND SPEED FOR JANUARY= " K! "mph"
200 PRINT "J%="J%,"L%="L%
```

```
10 REM  COMPUTER PROGRAM #4
20 REM
30 REM  DETERMINES THE AVERAGE WIND POWER BY MONTH IN WATTS
40 REM  PER SQUARE FOOT.  INPUT WIND SPEED IN KNOTS AND THE
50 REM  MONTHLY AVERAGE ATMOSPHERIC DENSITY IN lbm/ft^3.
60 REM  WIND SPEED DATA FROM COMPUTER PROGRAM #1 IS USED.
70 REM
80  DIM SPEED(30,7)
90  J!=0: L%=0: POWER!=0: K!=O
100 RHO!=.0794
110 OPEN "SPEEDJAN" FOR INPUT AS #1
120 FOR DAY=0 TO 30
130 FOR HOUR=0 TO 7
140 INPUT #1, SPEED(DAY,HOUR)
150 J!=.10102*RHO!*SPEED(DAY,HOUR)^3
160 POWER!=POWER!+J!
170 L%=L%+1
180 NEXT HOUR
190 NEXT DAY
200 K!=POWER!/L%
210 LPRINT "AVE. WIND POWER DENSITY FOR JANUARY="K!"W/FT^2"
220 LPRINT "J!="J!, "POWER!="POWER!, "L%="L%
```

```
10 REM  COMPUTER PROGRAM #5
20 REM
30 REM  DETERMINES THE DIURNAL WIND SPEED AVERAGE BY MONTH.
40 REM  WIND SPEED DATA FROM COMPUTER PROGRAM #1 IS USED.
50 REM
60  DIM SPEED(30,7)
70  OPEN "SPEEDJAN" FOR INPUT AS #1
80  FOR DAY=0 TO 30
90  FOR HOUR=0 TO 7
100 INPUT #1, SPEED(DAY,HOUR)
110 NEXT HOUR, DAY
120 LPRINT "JANUARY"
130 FOR H=0 TO 7
140 DIURNAL%=0
150 FOR D=0 TO 30
160 DIURNAL%=DIURNAL% + SPEED(D,H)
170 NEXT D
180 DIURNALAVE!= (DIURNAL%*1.15)/31
190 LPRINT "DIURNAL WIND SPEED FOR"H"="DIURNALAVE!"MPH"
200 NEXT H
210 LPRINT "FINISHED"
```

```
10 REM  COMPUTER PROGRAM #6
20 REM
30 REM  DETERMINES THE DIURNAL WIND POWER AVERAGE BY MONTH
40 REM  IN WATTS PER SQUARE FOOT.  WIND SPEED DATA FROM
50 REM  COMPUTER PROGRAM #1 IS USED.
60 REM
70  DIM SPEED(30,7)
80  RHO!=.0794
90  OPEN "SPEEDJAN" FOR INPUT AS #1
100 FOR DAY=0 TO 30
110 FOR HOUR=0 TO 7
120 INPUT #1, SPEED(DAY,HOUR)
130 NEXT HOUR, DAY
140 LPRINT "JANUARY"
150 FOR H=0 TO 7
160 DIURNAL!=0
170 FOR D=0 TO 30
180 DIURNAL!=DIURNAL! + .10102*RHO!*SPEED(D,H)^3
190 NEXT D
200 DIURNALAVE!= DIURNAL!/31
210 LPRINT "DIURNAL WIND POWER FOR"H"="DIURNALAVE!"W/FT^2"
220 NEXT H
230 LPRINT "FINISHED"
```

```
10 REM  COMPUTER PROGRAM #7
20 REM
30 REM  CALCULATE THE PERCENTAGE OF TIME THE WIND BLOWS
40 REM  FROM EACH DIRECTION.  DIRECTIONS ARE ROUNDED TO
50 REM  THE NEAREST 10 DEGREES.  WIND DIRECTION DATA FROM
60 REM  COMPUTER PROGRAM #2 IS USED.
70 REM
80  DIM DIR(30,7)
90  LPRINT "JANUARY"
100 OPEN "DIRJAN" FOR INPUT AS #1
110 FOR DAY=0 TO 30
120 FOR HOUR=0 TO 7
130 INPUT #1, DIR(DAY,HOUR)
140 NEXT HOUR, DAY
150 FOR DIRECTION=0 TO 36
160 L%=0
170 FOR DAY=0 TO 30
180 FOR HOUR=O TO 7
190 IF DIR(DAY,HOUR)<>DIRECTION THEN 210
200 L%=L% + 1: J%=J% + 1
210 NEXT HOUR, DAY
220 LPRINT "NUMBER OF READINGS FROM" DIRECTION "= " L%
230 NEXT DIRECTION
240 LPRINT "TOTAL NUMBER OF READINGS = " J%
```

```
10 REM  COMPUTER PROGRAM #8
20 REM
30 REM  DETERMINES THE AVERAGE WIND SPEED FROM EACH
40 REM  DIRECTION FOR A ONE MONTH PERIOD.  DIRECTIONS
50 REM  ARE ROUNDED TO THE NEAREST 10 DEGREES.  WIND
60 REM  SPEED DATA FROM COMPUTER PROGRAM #1 AND WIND
70 REM  DIRECTION DATA FROM COMPUTER PROGRAM #2 ARE USED.
80 REM
90  LPRINT "JANUARY"
100 LPRINT "DIRECTION   AVE. SPEED   NO. READINGS   TOTAL"
110 DIM DIR(30,7): DIM SPEED(30,7): N%=0
120 OPEN "DIRJAN" FOR INPUT AS #1
130 FOR DAY=0 TO 30
140 FOR HOUR=0 TO 7
150 INPUT #1, DIR(DAY,HOUR)
160 NEXT HOUR, DAY
170 OPEN "SPEEDJAN" FOR INPUT AS #2
180 FOR DAY=0 TO 30
190 FOR HOUR=0 TO 7
200 INPUT #2, SPEED(DAY,HOUR)
210 NEXT HOUR, DAY
220 FOR DIRECTION=0 TO 36
230 L%=0: J!=0
240 FOR DAY=0 TO 30
250 FOR HOUR=0 TO 7
260 IF DIR(DAY,HOUR)<>DIRECTION THEN 290
270 L%=L% + 1: N%=N% + 1
280 J!=J! + SPEED(DAY,HOUR)*1.15
290 NEXT HOUR, DAY
300 K!=J!/L%
310 LPRINT USING "#####     ":DIRECTION,K!,L%,J!
320 NEXT DIRECTION
330 LPRINT "TOTAL NO. READINGS= " N%
```

```
10 REM  COMPUTER PROGRAM #9
20 REM
30 REM  DETERMINES THE NUMBER OF TIMES THE WIND BLOWS FROM
40 REM  EACH DIRECTION (EACH TIME IS EQUIVALENT TO A THREE
50 REM  HOUR PERIOD), THE AVERAGE AND TOTAL WIND POWER
60 REM  FROM EACH DIRECTION, AND TOTAL WIND POWER PASSING
70 REM  THE WIND SENSOR.  DIRECTIONS ARE ROUNDED TO THE
80 REM  NEAREST 10 DEGREES.  CALCULATIONS ARE MADE FOR A
90 REM  ONE MONTH PERIOD USING THE WIND SPEED AND DIRECTION
100 REM DATA OF COMPUTER PROGRAMS #1 AND #2, RESPECTIVELY.
110 REM
120 LPRINT "DIRECTION  AVE.POWER  NO.READINGS  TOTAL POWER"
130 DIM DIR(30,7):DIM SPEED(30,7)
140 FOR DIRECTION=0 TO 36
150 L%=0: J!=0
160 OPEN "DIRJAN" FOR INPUT AS #1
170 FOR DAY=0 TO 30
180 FOR HOUR=0 TO 7
190 INPUT #1, DIR(DAY,HOUR)
200 NEXT HOUR, DAY
210 OPEN "SPEEDJAN" FOR INPUT AS #2
220 FOR DAY=0 TO 30
230 FOR HOUR=0 TO 7
240 INPUT #2, SPEED(DAY,HOUR)
250 NEXT HOUR, DAY
260 FOR DAY=0 TO 30
270 FOR HOUR=0 TO 7
280 IF DIR(DAY,HOUR)<>DIRECTION THEN 320
290 L%=L% + 1: N%=N% + 1
300 RHO!=.0794
310 J!=J!+ (.10102*RHO!*SPEED(DAY,HOUR)^3)*3
320 NEXT HOUR, DAY
330 CLOSE #1, #2
340 K!=J!/L%: JJ!=JJ!+J!
350 LPRINT USING "########     ";DIRECTION,K!,L%,J!
360 NEXT DIRECTION
370 LPRINT "TOTAL NO. READINGS= " N%
380 LPRINT "TOTAL POWER = " JJ!
```

```
10 REM  COMPUTER PROGRAM #10
20 REM
30 REM  DETERMINES THE FREQUENCY IN PERCENT THAT THE WIND
40 REM  BLOWS AT EACH SPEED DURING A ONE MONTH PERIOD.
50 REM  WIND SPEED DATA FROM COMPUTER PROGRAM #1 IS USED.
60 REM
70  LPRINT "WIND SPEED    NO. READINGS    PERCENT OF TIME"
80  DIM SPEED(30,7)
90  FOR WINDSPD=0 TO 44
100 L%=0: PERCENT!=0
110 OPEN "SPEEDJAN" FOR INPUT AS #1
120 FOR DAY=0 TO 30
130 FOR HOUR=0 TO 7
140 INPUT #1, SPEED(DAY,HOUR)
150 IF SPEED(DAY,HOUR)<>WINDSPD THEN 170
160 L%=L%+1: N%=N%+1
170 NEXT HOUR, DAY
180 CLOSE #1
190 PERCENT!=(L%/248)*100
200 LPRINT USING "    ##.#       ";WINDSPD,L%,PERCENT!
210 NEXT WINDSPD
220 LPRINT "TOTAL NO. READINGS= " N%
```

```
10 REM  COMPUTER PROGRAM #11
20 REM
30 REM  DETERMINES THE WIND ENERGY AVAILABLE IN
40 REM  KILOWATT HOURS PER SQUARE FOOT AT EACH WIND
50 REM  SPEED DURING A ONE MONTH PERIOD.  WIND SPEED
60 REM  DATA FROM COMPUTER PROGRAM #1 IS USED.  THIS
70 REM  IS TOTAL ENERGY AVAILABLE MEANING IT HAS NOT
80 REM  BEEN REDUCED BY THE BETZ COEFFICIENT.
90 REM
100 LPRINT "WIND SPEED    NO. READINGS    ANNUAL ENERGY"
110 DIM SPEED(30,7)
120 TOTAL!=0:N%=0
130 FOR WINDSPD=0 TO 36
140 L%=0: ENERGY!=0
150 OPEN "SPEEDJAN" FOR INPUT AS #1
160 FOR DAY=0 TO 30
170 FOR HOUR=0 TO 7
180 INPUT #1, SPEED(DAY,HOUR)
190 IF SPEED(DAY,HOUR)<>WINDSPD THEN 230
200 RHO!=.0794
210 ENERGY!=ENERGY!+ (.0010102*RHO!*SPEED(DAY,HOUR)^3)*3
220 L%=L%+1: N%=N%+1
230 NEXT HOUR, DAY
240 CLOSE #1
250 TOTAL!=TOTAL!+ENERGY!
260 LPRINT USING "    ###.#      ";WINDSPD,L%,ENERGY!
270 NEXT WINDSPD
280 LPRINT "TOTAL NO. READINGS= " N%
290 LPRINT "TOTAL ENERGY = " TOTAL!
```

```
10 REM  COMPUTER PROGRAM #12
20 REM
30 REM  DETERMINES THE NUMBER OF HOURS THE WIND BLOWS AT
40 REM  EACH WIND SPEED DURING A MONTH.  IN THE ANALYSIS
50 REM  IT WAS EXPANDED TO COVER A ONE YEAR BLOCK OF WIND
60 REM  SPEED DATA.  THIS INFORMATION WAS ENTERED INTO A
70 REM  SEQUENTIAL ACCESS FILE USING COMPUTER PROGRAM #13
80 REM  AND THEN USED IN COMPUTER PROGRAM #15.
90 REM
100 PRINT "WIND SPEED       TIME IN"
110 PRINT "  KNOTS           HOURS"
120 DIM SPEED(30,7)
130 TOTAL%=0
140 FOR WINDSPD = 0 TO 44
150 TIME%=0
160 OPEN "SPEEDJAN" FOR INPUT AS #1
170 FOR DAY = 0 TO 30
180 FOR HOUR = 0 TO 7
190 INPUT #1, SPEED(DAY,HOUR)
200 IF SPEED(DAY,HOUR)<>WINDSPD THEN 220
210 TIME%=TIME%+3
220 NEXT HOUR,DAY
230 CLOSE #1
240 PRINT USING "    ####    ";WINDSPD,TIME%
250 TOTAL%=TOTAL%+TIME%
260 NEXT WINDSPD
270 PRINT "TOTAL HOURS= ";TOTAL%
```

```
10 REM  COMPUTER PROGRAM #13
20 REM
30 REM  ALLOWS THE DATA CONCERNING THE NUMBER OF HOURS THE
40 REM  WIND BLOWS AT EACH SPEED DURING A YEAR TO BE
50 REM  TRANSFERRED FROM HARDCOPY TO MAGNETIC TAPE SO THAT
60 REM  IT CAN BE PROCESSED BY COMPUTER.  IN THIS CASE WIND
70 REM  SPEED DATA WAS REDUCED IN COMPUTER PROGRAM #12,
80 REM  THE RESULTS ENTERED BY HAND USING THIS PROGRAM, AND
90 REM  THE RESULTS THEN USED BY COMPUTER PROGRAM #15.
100 REM COMPUTER PROGRAM #12 COULD HAVE BEEN WRITTEN SO
110 REM THAT THE RESULTS WERE ENTERED DIRECTLY INTO A
120 REM SEQUENTIAL FILE.
130 REM
140 OPEN "HOURS" FOR OUTPUT AS #1
150 INPUT "NUMBER OF HOURS"; S%
160 IF S%=9999 THEN CLOSE: END
170 WRITE #1, S%
180 PRINT: GOTO 150
```

```
10 REM  COMPUTER PROGRAM #14
20 REM
30 REM  ALLOWS THE DATA CONCERNING THE OUTPUT OF A
40 REM  WIND POWER SYSTEM AT EACH WIND SPEED TO BE
50 REM  TRANSFERRED FROM HARDCOPY TO MAGNETIC TAPE
60 REM  SO THAT IT CAN BE PROCESSED BY COMPUTER.  IN
70 REM  THIS CASE THE OUTPUT IN KILOWATTS AT EACH WIND
80 REM  SPEED WAS ENTERED FOR THE JACOBS MODEL 1023 WIND
90 REM  POWER SYSTEM.  THIS DATA WAS STORED IN A SEQUENTIAL
100 REM FILE AND LATER USED BY COMPUTER PROGRAM #15.
110 REM
120 OPEN "JACOBSOU.T" FOR OUTPUT AS #1
130 INPUT "OUTPUT IN KILOWATTS"; S%
140 IF S%=1000 THEN CLOSE: END
150 WRITE #1, S%
160 PRINT: GOTO 130
```

```
10 REM  COMPUTER PROGRAM #15
20 REM
30 REM  ESTIMATES THE YEARLY OUTPUT OF A WIND POWER SYSTEM
40 REM  (IN KW HRS) AT EACH WIND SPEED AT A PARTICULAR SITE.
50 REM  THIS IS DONE BY MULTIPLING THE NUMBER OF HOURS THE
60 REM  WIND BLOWS AT EACH WIND SPEED AT A SITE BY THE
70 REM  SYSTEM OUTPUT AT EACH WIND SPEED.  THE WIND SPEED
80 REM  DATA INPUT IN COMPUTER PROGRAM #13 AND THE WIND
90 REM  POWER SYSTEM DATA INPUT IN COMPUTER PROGRAM #14
100 REM ARE USED.
110 REM
120 LPRINT "WIND SPEED       OUTPUT IN KW HRS"
130 DIM H(44): DIM O(44)
140 YEAROUT!=0
150 SPDOUT!=0
160 OPEN "HOURS" FOR INPUT AS #1
170 FOR J=0 TO 44
180 INPUT #1, H(J)
190 NEXT J
200 CLOSE #1
210 OPEN "JACOBSOU.T" FOR INPUT AS #1
220 FOR L=0 TO 44
230 INPUT #1, O(L)
240 NEXT L
250 CLOSE #1
260 FOR K=0 TO 44
270 SPDOUT!= H(K) * O(K)
280 YEAROUT!= YEAROUT! + H(K) * O(K)
290 LPRINT USING "     ##       ########  ";K,SPDOUT!
300 NEXT K
310 LPRINT "TOTAL OUTPUT FOR YEAR = "; YEAROUT!
```

The vita has been removed from the scanned document