The effects of selected atmospheric variables on the power output of a DOE Mod-2 horizontal-axis wind turbine are studied. Particular attention is focused on unsteady, nonuniform flow conditions within the rotor disc as represented by vertical profiles measured at adjacent meteorological towers. Primary variables are wind speed, wind direction and turbulence intensity. A classification on the basis of velocity profiles is found to be useful in conducting basic statistical analysis and in isolating performance anomalies.

Power fluctuation is found to depend primarily on two variables, turbulence intensity and directional shear; the magnitudes of their effects being comparable for the data studied. Increasing turbulence
intensity is associated with increased power while increasing directional shear is associated with decreased power. Under very turbulent conditions the power is adversely affected by relatively large yaw angles associated with high values of the lateral turbulence intensity component.
Effects of Selected Atmospheric Variables
On the Power Output of a
DOE Mod-2 Wind Turbine

by

Alan Clifford Germain

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed June 25, 1984
Commencement June 1985
APPROVED:

Redacted for privacy

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Date thesis is presented       June 25, 1984

Typed by Dee Dee Reynolds for    Alan Clifford Germain
I wish to express my sincere appreciation to the Bonneville Power Administration (BPA) for their interest and monetary support in undertaking this project. In particular, I would like to thank Nicholas G. Butler, Contract Monitor, for his thorough review and helpful comments.

Thanks to Dr. Robert E. Wilson, Department of Mechanical Engineering, for his advice and guidance throughout.

Special thanks to Mr. Robert W. Baker, Research Assistant in the Department of Atmospheric Sciences, for his role in enlisting the support of BPA and in providing logistical support and encouragement whenever needed.

I would also like to acknowledge the conscientious efforts of Ms. Dee Dee Reynolds in preparing draft and final copy of this thesis.
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EFFECTS OF SELECTED ATMOSPHERIC VARIABLES ON THE POWER OUTPUT
OF A DOE MOD-2 WIND TURBINE

I. INTRODUCTION

The Mod-2 wind turbine program is funded by the U.S. Department of Energy with technical management by NASA Lewis Research Center. The development contract was awarded to Boeing Engineering and Construction Company. The data for this study are from the Goodnoe Hills cluster (3 turbines) which is operated by the Bonneville Power Administration (BPA). BPA has also funded this particular research effort.

The objective of this study is to determine which flow parameters have the strongest influence on power output. If flow through the rotor swept area were steady and uniform the only variables affecting power would be wind speed and air density. The real wind is neither steady nor uniform, and the real data have considerable scatter (std. dev. of 20 minute averages on the order of 100 kW). The task is to measure the unsteady, nonuniform wind characteristics and investigate the effects on power output.

The physical size of the Mod-2 machine puts special emphasis on the nonuniform aspects. All machines are subject to unsteady effects but small machines experience much less of the spatial variability. It is expected that this work and other similar studies will put the importance of detailed flow conditions into perspective. The perspective will improve performance prediction
by identifying the most important parameters to be measured for siting of future installations. Information of the kind provided may also be used to identify operating conditions under which a change in the control system may improve performance of existing machines.

Boundary Layer Structure

The Atmospheric or Planetary Boundary Layer (PBL) is a zone of transition from the ground or sea surface to the 'free atmosphere' above. Descriptions of the structure of the PBL are a mixture of observational and theoretical results. Early work is summarized in a review paper by Counihan (1975) on adiabatic atmospheric boundary layers. The most successful equations for the speed profile have been the logarithmic law and the power law. The log law may be derived from dimensional scaling arguments (Plate, 1982) and has been preferred in the meteorological community. The power law is empirical but more easily manipulated, and has been favored in engineering practice. The theoretical change in direction with height under neutral conditions is described by the well-known Eckman spiral solution (Holton, 1979) and predicts that in the northern hemisphere the velocity vector will rotate clockwise with height.

As atmospheric conditions are rarely exactly neutral modifications to the theory for neutral conditions are required to make the results generally useful. The similarity theory of Monin
and Obukhov (1971) is used extensively to augment the log law while other studies provide corrections to be applied to the power law (Spera & Richards, 1979). Observational studies (Clarke, 1970) and development of additional similarity theories leads to the identification of stability regimes (Plate, 1982). Studies from fixed towers (Crawford & Hudson, 1973) and numerical modeling (Deardorff, 1972) add much more detailed knowledge and establish the dominant role of the diurnal heating cycle. The strength and sign of the surface heat flux determines not only conditions within the boundary layer but also the actual height of the PBL, which may vary from tens of meters to several kilometers (Deardorff, 1978). An especially interesting feature is the low level jet associated with the nocturnal boundary layer. With strong radiative cooling a zone of supergeostrophic winds may develop above the top of the newly formed surface inversion. Blackadar (1957) and Thorpe (1977) show that this phenomenon may be explained theoretically in terms of an inertial oscillation.

Turbulence is described most readily by the variance of the velocity components (Frost, 1978), but more completely in the spectral representation (Davenport, 1961). A compromise for applications is based on gust events (Powell, 1979). The importance of the turbulence energy budget, namely the extraction of mean flow kinetic energy and subsequent turbulent dissipation, is outlined in Tennekes and Lumley (1972).
Wind Turbine Applications

Frost et al. (1978) summarize the relations of importance to wind turbine development in an engineering handbook. Siting of large turbines has been studied and the results are compiled in another handbook by Heister and Pennell (1981). Much of the observational and modeling work has been carried out over flat terrain, yet the best sites for wind turbines are often found on ridge tops or in mountain passes. These considerations are addressed by Bouwmeester et al. (1978). Turbulence is also affected by topography and Dutton et al. (1979) give the results of their studies of normalized turbulence spectra over complex terrain.

Performance Measurement

There are two basic types of performance evaluation. If simultaneous observations of power and wind speed are collected, a power curve may be generated. Here performance is defined as the electrical output in relation to the wind input. Efficiency is described by the power coefficient (Cp), expressing the ratio of power to the available kinetic energy flux. Power curves are commonly obtained by the method of bins, first outlined by Akins (1978). Guidelines and accepted standards for performance evaluation may be found in Bergey (1979) or Frandsen et al.

A second approach involves time integration of power to obtain energy capture. When applied to longer data sets, a more direct assessment of economic performance is possible. The cost of energy (COE), defined as the cost of acquisition, operation, and maintenance divided by the quantity of energy produced, is the overall measure of effectiveness of a particular design at a particular site.

It is usually required to estimate the COE before construction. The average power production is estimated by the convolution of power and wind speed probability over speed (summing over all speeds power at a given speed times the probability of observing the speed). Multiplication by the appropriate time interval then gives energy production (Frandsen et al., 1983). The accuracy of this estimate thus depends on both the power curve and the input wind distribution. Wilson and Lissaman (1974) discuss aerodynamic theory for wind machines and give a computer code for computation of rotor power. Wind inputs are obtained from site surveys (Lissaman et al., 1980) or extrapolated from regional resource evaluations (Barchet and Elliott, 1979). This estimate is improved if actual data are available for the turbine and the proposed site. Pennell and Miller (1982) point out that control system features, especially start up cycle lags and yaw tracking delays, are likely to detract from the actual performance of large turbines.
and propose the use of an 'operating strategy' model. Thresher (1979) presents an interesting analysis of the cost of energy in relation to wind speed, siting and turbine parameters.

Performance Analysis

Anderson et al. (1982) compare results from theory, wind tunnel and field testing for a 3 meter horizontal axis machine. They concentrate on detailed flow measurements, validation of tip and hub loss models and yaw effects. Glasgow et al. (1980) look at a wide range of yaw angles on the Mod-0 machine (100 kW). Frandsen and Christensen (1980) consider coherence between wind speed and power on the Gedser machine as well as the statistical aspects of sampling technique. Sundar and Sullivan (1983) investigate the turbulence spectrum as seen by a rotating blade element for different size rotors reaching conclusions similar to those of Thresher et al. (1983). Hansen (1980) theorizes that power output will increase in turbulence due to the cubic dependence of power on wind speed in the power equation. Kirchhoff (1979) uses similar logic to establish a maximum ratio of power in turbulence to power in steady state and then compares turbine response characteristics to conclude that for the machine studied, approximately 70% of the turbulence energy may be captured. However, these papers do not account for varying power coefficient, nor do they discuss the implications of the linear ramp shape common to most power curves. Wasynczuk et al. (1981) discuss a dynamic model for the Mod-2 drive
train identifying resonances and transfer characteristics.

Hillesland et al. (1983) detail their experiences with pitch schedule and control system modifications on a Mod-2 design. Specifications and early test results for the Mod-2 are given in the Mod-2 Final Report (DOE, 1982). An overview of the status of current megawatt-scale projects is presented by Vachon and Schiff (1983).
Turbine Description

The Mod-2 is driven by a 300 foot (91.5m) diameter two-bladed horizontal-axis rotor sitting atop a 200 foot (61m) tower. The rotor is tip controlled, features a teetering hub and operates at a constant speed in an upwind configuration. Pitch and yaw control systems are microprocessor-based active hydraulic systems. Power is transferred through a planetary gearbox to a synchronous generator rated at 2.5 megawatts (Figure 2.1).

Tower/Yaw

The nacelle and rotor assemblies are supported by the yaw bearing on top of a hollow 10 foot diameter steel tower. The tower has a conical base section which flares toward the bottom to a 21 foot diameter. The base bolts to a concrete foundation pad which in turn is fastened to bedrock with rock anchors. The yaw bearing is a three-row roller type in a 10 foot diameter ring, and has a fixed internal ring gear on the tower race. The meshing pinion is driven by a hydraulic motor mounted in the nacelle. The control system utilizes a pair of wind sensors mounted on the nacelle roof to gauge the yaw error. Three checks are performed. If the average yaw error over a 6 minute period exceeds 7 degrees, or if the average over 26 seconds exceeds 20 degrees then a yaw maneuver
FIGURE 2.1: MOD-2 WIND TURBINE

MAJOR DIMENSIONS AND CONFIGURATION
is initiated at the rate of one-quarter degree per second. If the average error remains over 20 degrees for more than 2 minutes than yaw is stopped and the turbine shut down. When not being yawed a set of brakes prevents rotation of the yaw bearing.

Drive Train/Generator

The drive train and generator are located within the nacelle housing. The low speed shaft rotates at 17.55 rpm. The shaft assembly has two main parts; the outer, or low speed shaft, and an inner, or quill shaft. The quill shaft transmits rotor torque and is a 'soft' shaft intended to absorb torque fluctuations thereby reducing power variation. The quill shaft drives an epicyclic gearbox with a 103:1 step-up to an 1800 rpm high speed shaft. This shaft is connected through a flex-disc coupler to the generator. The generator is a synchronous three-phase machine rated at 2.5 megawatts with a 0.8 power factor. The output voltage is 4.16 kV which is stepped-up in two stages; first two 12 kV at each tower base and then to 69 kV at the on-site substation.

Rotor

The rotor is made of steel and consists of 5 sections. The single hub section has an oval cross-section and is 60 feet (18.3m) long. The working section of each blade has a 45 foot (13.7m) controllable tip and a 75 foot (22.9m) midsection. The airfoil
shape changes from NACA 23012 at the tip to NACA 23028 at the in-
board end of the midsection. The teetering hub feature is intended
to isolate the drive train from blade bending moments and to reduce
cyclic loads within the blades due to wind speed shear or yaw
error. This is accomplished by using an elastomeric bearing com-
posed of alternating concentric layers of steel and rubber. A
typical cyclic teeter angle is 2 to 4 degrees with fixed stops
provided to limit travel to 6.5 degrees.

Pitch control of the tip sections is via hydraulic cylinders
mounted at the tip spindle. Pitch rates are normally less than 1
degree per second, while rates up to 8 degrees per second are
possible in the event of critical system faults. Between cut-in
and rated wind speed pitch is fixed and rotor speed is controlled
by varying the generator load. Above rated wind speed the genera-
tor output is held steady and excess power is 'spilled' by feather-
ing the blade tips. Above the cut-out speed or below cut-in the
tips are completely feathered to 90 degrees pitch.

Operational Parameters

Operational stability, power fluctuation and the magnitude of
cyclic loading are all influenced by control strategy. Efforts to
improve overall performance have included changes in pitch sche-
dule, changes in signal filters and the installation of vortex
generators along the blade midsection. The data used in this study
were taken under the following conditions: fixed 5 degree pitch
schedule, no vortex generators, and control system notch filters at 0.36 Hz and 1.7 Hz, which are, respectively, the tower first mode and the 2P frequency (twice per revolution).

Site Description

The Mod-2 wind turbine site is located along the Columbia River in south-central Washington State, about 15 miles (24 km) east of Goldendale in Klickitat County. Being east of the Cascade mountain range, the climate of the area is a dry, continental type. Vegetation is sparse; mostly grasses and low growing brush with scattered pockets of scrub oak or juniper.

The wind regime of the area is strongly influenced by the proximity of the Columbia River Gorge. From the turbine site the Columbia River flows west through the Cascade mountain range. Typical pass elevations in the Cascades are four to five thousand feet (1500m), while the river cuts through at 72 feet (22m). The Columbia Gorge is the most significant mountain gap between the Fraser River in southern British Columbia and the San Francisco Bay area. In a broad sense this gap is a connection between the contrasting conditions of the ocean and the interior plateaus. Thus prevailing westerlies are often reinforced by a large-scale thermal circulation set up by surface heating on the plateaus of eastern Oregon and Washington, the strongest winds being observed in association with favorable surface pressure gradients during frontal passage. Conversely, during periods with established high
pressure to the east and relatively cold air on the plateaus a
drainage flow results in strong easterly winds out through the
Gorge. The west winds are strongest at the eastern end of the
Gorge, while east winds are strongest at the west end of the Gorge.

Topographically the wind turbine site is located in an area of
considerable variability (Figure 2.2). The site has an elevation
of 2600 feet (800m) and sits on top of an east-west ridge which is
part of a larger ridge feature extending to the west-southwest and
east-northeast. These ridges, which overlook the Columbia River,
slope steeply to the south to meet the river at 265 feet (80m)
elevation. Across the river on the Oregon side a broad, rather
flat plateau stretches out at 1200 to 1500 feet (360-460m). About
5 miles (8 km) east of the site the main ridge is interrupted by a
deep ravine running from the north into the Columbia. To the west
and north the slopes are gentler out into the Klickitat Valley
which has a typical elevation of 2000 feet (600m).

From the standpoint of meteorology the terrain is complex. It
will be difficult to generalize results obtained in this setting to
other sites.

There are three Mod-2 wind turbines installed at the Goodnoe
Hills test facility. A designated priority of the overall test
plan is to assess the effects of turbine wake interference (Hadley
and Renné, 1983), so the turbines are set in a triangular pattern
with legs of 5, 7 and 10 rotor diameters as shown in Figure 2.3.
Meteorological data are collected at two towers, one maintained by
Bonneville Power Administration (BPA) and the other by Battelle
FIGURE 2.2: TOPOGRAPHY OF THE GOODNOE HILLS AREA.
FIGURE 2.3: GOODNOE HILLS TEST SITE ARRANGEMENT

Elevations in feet above mean sea level

1 TURBINE DIAMETER = 1000 FEET
Pacific Northwest Laboratories (PNL). The towers are less than 2500 feet (750m) apart but the measured wind velocities at a given height will not necessarily be the same. The difference may be ascribed to alteration of the flow pattern by terrain features. The wind at turbine 1 is best represented by the PNL tower while turbine 3 is closer to the BPA tower. Measured wind may also be influenced by the turbine wakes. Under westerly flow the wake of turbine 3 is likely to influence both turbine 1 and the PNL tower. Further information on the nature and effects of these wakes can be found in a study by Baker and Walker (1982). Thus care must be exercised in using data from these towers. The available power data were from turbine 1 and turbine 3, while the wind directions were predominantly west (220°-300°) and east (50°-120°). Due to the uncertainties introduced by the wake effects the present analysis is restricted to turbine 3 under west wind conditions, specifically to directions greater than 235 degrees true.

Instrumentation

Table 2.1 gives a summary of the sampled meteorological and turbine parameters. The BPA tower is 195 feet (60m) tall and has two levels of instrumentation. The PNL tower is 350 feet (110m) tall with instruments at four levels during the period the test data were taken. Wind sensors are the propeller type (Aerovane) on the BPA tower and cup type (Climatronics) on the PNL tower. The meteorological towers have an open-lattice construction with
<table>
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<th>TABLE 2.1: SUMMARY OF SAMPLED PARAMETERS</th>
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</thead>
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<tr>
<td>BPA Tower:</td>
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<tr>
<td>Temperature: 50'</td>
</tr>
<tr>
<td>Barometric Pressure: Surface</td>
</tr>
<tr>
<td>PNL Tower:</td>
</tr>
<tr>
<td>Wind Speed and Direction: 33', 50', 200', 350'</td>
</tr>
<tr>
<td>Temperature: 33', 350'</td>
</tr>
<tr>
<td>Barometric Pressure: 200'</td>
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</tr>
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</tr>
<tr>
<td>Generator Power</td>
</tr>
<tr>
<td>Utility Power</td>
</tr>
<tr>
<td>Generator Voltage</td>
</tr>
<tr>
<td>Rotor Speed</td>
</tr>
<tr>
<td>Yaw Error</td>
</tr>
<tr>
<td>Nacelle Azimuth</td>
</tr>
<tr>
<td>Data Format:</td>
</tr>
<tr>
<td>Two minute averages and standard deviations of one second instantaneous</td>
</tr>
<tr>
<td>FORTRAN F7.2</td>
</tr>
</tbody>
</table>
standoff booms mounted at the various levels. The wind instruments
are mounted on the outboard end giving approximately 6 feet (2m)
clearance from the tower. This arrangement reduces tower interfer-
ence but cannot eliminate the 'tower shadow'. The booms are
oriented to the west to prevent problems during west winds which
are much more common at the site.

Data from the towers are fed to a central collection system at
the standard rate of one sample per second. The average and
standard deviation are calculated every two minutes for storage on
computer disc. The data were provided by PNL on magnetic tape.

Calibration

Calibration of the tower sensors is carried out by personnel
from BPA or PNL on the respective towers. PNL recommended a 7%
reduction of the 200' level wind speed based on wind tunnel testing
of their sensors. Comparison of the corrected tower data showed
fair agreement with the exception of the hub height wind direction.

Directions at the PNL tower are measured at four levels, and
the averaged data show a linear change in direction with height.
Furthermore, the 50' wind directions from the two towers were in
close agreement. This leads to the conclusion that a correction
should be applied to the 195' BPA tower direction.

The method chosen to determine the amount of correction is
based on the assumption that the difference in direction between
two heights will be the same under well-mixed daytime conditions.
The results indicate that a correction of plus 10.86 degrees should be applied to the BPA 195' value. Figure 2.4 shows a diurnal plot of the corrected directional shift between 50' and 200' for the two towers. The lower values observed at the PNL tower may be due in part to mixing by the wake of turbine 3. Further comparison of the two towers is found in Appendix B.

Data Editing

The raw data set includes 640 hours of observations (30 two minute averages per hour) from the time period October 6, 1982 to November 12, 1982. However, for much of this time wind speeds were below the turbine cut-in speed. In addition, there were times when the turbine was inoperative due to scheduled maintenance. Daily log sheets were obtained from NASA Lewis Research Center which allowed down time to be screened out. For preliminary analysis two data sets were identified. One set contained only 'selected runs', defined as continuous runs of at least two hours in length while the second set, referred to as 'all data', included all times for which the turbine was available for operation. For turbine number 3, from the original 640 hours of data there were 160 hours of 'selected runs' and 222 hours of 'all data' above 12.5 mph.
FIGURE 2.4: DIURNAL PLOT OF DIRECTIONAL SHIFT BETWEEN 50' and 200' FOR THE BPA AND PNL TOWERS

(BPA 200' CORRECTED BY ADDING 10.86 DEGREES)
Density Correction

It is recommended practice in wind turbine performance analysis (Frandsen et al., 1983) to correct measured power values to standard sea level conditions, that is, to calculate the power which would have been obtained in a flow of the same wind speed but with standard air density (1.225 kg/m$^3$). Correcting for density facilitates comparison of data from various sites by removing a known source of variability in power output. A look at the power equation shows that power is directly proportional to density, which suggests a ratio form for the correction.

$$P = \frac{1}{2} \rho A C_p V^3$$

where

- $\rho$ = atmospheric density
- $A$ = rotor swept area
- $C_p$ = power coefficient
- $V$ = wind speed

The method of correction used in this analysis is an extension of the generally accepted ratio technique. For either method air density may be calculated using the Ideal Gas Law, the required inputs being air temperature and barometric pressure. (Air density is also a function of moisture content, however, the difference between saturated and dry air at 20 degrees C is less than one percent and this difference decreases for lower temperatures.) In the simpler method measured power is multiplied by the ratio of
densities to obtain corrected power. In effect this procedure is correcting the power as measured at the generator.

The method chosen for this study uses a drive train loss model to obtain corresponding rotor power before correcting for density. After multiplying by the density ratio the loss model is applied in reverse to convert corrected rotor power to corrected generator power. The details of the loss model and a comparison of correction with and without losses are presented in Appendix A.

Data for the density calculation were taken from the PNL tower. Temperature was linearly interpolated from the temperatures measured at 33 feet and 350 feet to the hub height. Barometric pressure was available directly at the 200 foot level.
III. PRELIMINARY ANALYSIS

The first step in the analysis was to generate output power curves using the method of bins. The method of bins simply involves sorting the data points into 'bins' or equal intervals of wind speed and then averaging the power within each bin. Using narrow bins can result in bins with few points while choice of a wide bin width increases the variability within each bin. A convenient bin width of 1 mile per hour was chosen here. Appendix C contains a discussion of the statistical aspects of the method of bins. See also, Akins (1978), Hausfeld and Hansen (1983) or Frandsen and Christensen (1980). The raw data were in the form of two minute averages. To assess the effect of various averaging periods a series of power curves was obtained. The periods were 2, 4, 8, 16, 30, and 60 minutes. Three representative cases are shown in Figures 3.1 to 3.3 and Figure 3.3a gives tabulated values. Each of these curves was calculated twice; once for 'all data' and once for the 'selected runs' subset.

Averaging Period

Examining the power curves and tabulated information, two features are apparent. First, the bin averages across averaging period do not exhibit any systematic variation. Second, the standard deviation within bins decreases for the longer periods. As pointed out by Hausfeld and Hansen (1983) the standard deviation
FIGURE 3.1: TWO MINUTE AVERAGE POWER CURVE
FIGURE 3.2: SIXTEEN MINUTE AVERAGE POWER CURVE
TURBINE NO. 3
HOURLY AVERAGES - ALL DATA
ERROR BARS ± 1 STD DEV

REFERENCE CONDITIONS:
ELEVATION: SEA LEVEL
DENSITY: 1.225 kg/m³

FIGURE 3.3: HOURLY AVERAGE POWER CURVE
<table>
<thead>
<tr>
<th>WIND SPEED</th>
<th>2 MINUTES</th>
<th>16 MINUTES</th>
<th>60 MINUTES</th>
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</thead>
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<tr>
<td></td>
<td>ALL</td>
<td>SD</td>
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<td>0</td>
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<td>2.530</td>
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<td>-</td>
</tr>
</tbody>
</table>

FIGURE 3.3a: TABULATED POWER CURVES.
of power observations can be used as an indicator of the correlation between wind conditions at the measurement station and the turbine. Figure 3.4 shows a plot of standard deviation of power versus averaging period. The plotted value was obtained by taking a sample-weighted average of the 20 to 30 mph bin values. This curve indicates that an averaging period of 10 or 20 minutes would be a good compromise giving higher correlation while retaining as many samples as possible. It is worth noting that this result is directly related to the separation distance of the instrument and tower, hence the physical size of the turbine. A similar curve obtained by Hausfeld and Hansen for a rotor diameter of 33 feet had a knee at 2 minutes.

All Data vs. Selected Runs

Reference to the data in Figure 3.3a shows that the difference between selected runs and all data is at the low end of the power curve. The selected runs contain fewer observations and average much more power at the low wind speeds, while the curves are identical elsewhere. This is a result of the criteria used in separating the selected runs. Selected runs do not contain data from times when the turbine was going through start up or shut down cycles. The selected runs are more appropriate for comparison to performance models while using the entire data set is the better representation for energy capture estimation. To illustrate the importance of this consideration a comparison of estimated energy
FIGURE 3.4: STANDARD DEVIATION VERSUS AVERAGING PERIOD

- SELECTED RUNS
- ALL DATA
production is made. Using a Rayleigh distribution with an average wind speed of 16 mph two separate estimates are formed. The results indicate that using 'selected run' type data overestimates the energy by 5 percent. A comparison is also made between the 2 and 60 minute averaging periods. The results differ by less than 1% and indicate that energy estimates based on longer averaging periods are as accurate as shorter ones provided the reference power curve is of the 'all data' type.

**Power Curve Shape**

The shape of the Mod-2 power curve is typical of many pitch-controlled designs. The design point for maximum power coefficient is normally chosen near the peak in the design wind speed distribution, in this case, 20 mph (Mod-2 Final Report). Below this speed the power coefficient is constant or a gradually increasing function of speed. The curvature in this portion of the power curve is a reflection of the cubic dependence of power on wind speed as expressed in the power equation. Above the design point the power coefficient decreases due to less than optimal blade tip to wind speed ratios for the rotor. This factor offsets the cubic speed relation and in this case results in a nearly linear curve between 20 and 30 mph. As the curve approaches rated power the effects of the control system become evident. Observations significantly above the associated bin average may be limited by control action while those below are not. This selective process tends to
depress the bin averages. Above a certain speed none of the observations fall below rated power and the curve becomes horizontal.

Standard Deviation of Power Observations

The effects of averaging time on standard deviation have been discussed above, but it is also of interest to note that for any given curve the standard deviation appears to be independent of speed through the midrange of the curve. This suggests that the variation is more closely related to variables normalized by speed.
IV. VARIABLES FOR ANALYSIS

The focus of the remainder of this work is on the effects and relative importance of atmospheric parameters on power output. The question is asked: given a fixed hub height wind speed, is the observed power under one set of conditions different from the power under another set of conditions? To answer this question variables must be chosen using both physical insight and evidence from the data as guides.

Power

Referring back to the preliminary analysis curves it is seen that most of the variability in output can be directly explained by wind speed alone. The first step then is to segregate the remaining unexplained variability. In the context of regression analysis the average power curves obtained by the method of bins represent a fit through the data using hub height wind speed as the 'regressed' variable, although no specific functional form has been used. Following this line of reasoning a polynomial involving powers of wind speed could be fit to the data using a least squares technique. A third order polynomial is the minimum required to reproduce the 's' shaped power curve, yet the accuracy of the result remains an open question as the polynomial represents a serious constraint on the form of the curve. Accuracy can be improved by limiting the range of application and checked by
comparing to bin averages. Now, the individual data points may be considered in relation to the fitted curve and analyzed as residuals of the regression.

This viewpoint has been taken here with the following considerations. Observations near cut-in or rated power are subject to control system effects. Therefore, only data from the midrange (17-29 mph) of wind speeds have been used in analysis. This decreases the number of samples but has the advantage of improving the accuracy of the fitted curve. Figure 4.1 shows a method of bins power curve and the corresponding fitted cubic curve. The fitted curve is seen to represent a smoothed mean power curve within the range of application.

With the fitted curve as a reference, the difference between observed and expected power for each observation is now defined as the power offset. Thus, the transformed data have zero mean power offset. It is important to note that the fitted cubic curve defines average power continuously so the offset is not biased by a discreet bin approach.

One question regarding the interpretation of the power offset remains. Can offsets from different speeds be compared without adjustment? Figure 4.2 shows a plot of offset power and its standard deviation versus wind speed bin. This demonstrates that the power variability is not a function of wind speed. Power offsets from within the speed band may be compared directly.
FIGURE 4.1: TWENTY MINUTE AVERAGE POWER CURVE AND CUBIC FIT
### 20 MINUTE AVERAGE POWER CURVE AND LEAST SQUARES CUBIC FIT

<table>
<thead>
<tr>
<th>WIND SPEED</th>
<th># OF OBS.</th>
<th>BIN AVERAGE</th>
<th>STD DEV</th>
<th>CURVE FIT</th>
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</table>

**FIGURE 4.1a. DATA FOR FIGURE 4.1.**
FIGURE 4.2: MIDRANGE POWER OFFSET AND STANDARD DEVIATION BY BIN
Speed

Hub height speed is a secondary variable in the power offset context. The important condition to be specified is the change of speed with height through the rotor disc. This is often loosely referred to as velocity shear but a distinction is made here between speed shear and direction shear. For convenience the speeds at 50 feet and 350 feet are expressed as ratios of the 200 foot speed. It is anticipated that the presence of speed shear will have two main effects. First, the rate of kinetic energy flux through the rotor swept area is proportional to the cubic weighted average wind speed over the disc. It is reasonable to expect that some measure of disc average speed should be considered. A simple method using a linear average and assuming equal aerodynamic contribution from the entire rotor disc was used. This choice is made considering the essentially linear character of the power curve. The power curve shape is determined by the interplay of wind speed and Cp, the power coefficient, and it is not known whether Cp will vary in the nonuniform rotational environment in the same manner as it would in steady conditions. Since elemental blade torque is proportional to velocity squared (Wilson and Lissaman, 1974), an alternative disc average is calculated using a squared-weighted disc average. Details of the method are found in Appendix D. Second, the rotor blades must travel through the shear layer. Thus a measure of the magnitude of shear is of interest. The total shear is expressed as a normalized speed shear factor.
defined as the difference between the upper and lower speed ratios. The dimensional form of average shear may be recovered by multiplying the shear factor by hub height speed and then dividing by the height difference.

**Direction**

Direction of the wind is always an important variable. Depending on the particular site, different flow directions may be associated with distinct air mass types or be affected by local terrain features. It is hoped that specifying flow conditions in detail will account for these differences and allow samples from different wind directions to be compared directly. As mentioned in the site description the wind direction for the test data is restricted to west winds greater than 235 degrees.

Within the rotor disc, the difference in direction between two heights, called the directional shear factor, is selected as a variable. (Directional shear has units of radians per length rather than degrees, thus the term directional shear factor.) The majority of velocity profiles veer with increasing height (clockwise rotation) and subtracting the lower level from the upper will normally give a positive result. This convention will be used throughout.

Since the upper level (350') wind direction is an estimated quantity (Appendix B) the variable for analysis will be the lower directional shear factor, that is, the difference between hub
height direction and the 50' direction. The total directional shear factor (350'-50') is approximately twice the lower value.

Turbulence

Turbulence intensity, defined as the standard deviation of a particular speed component divided by the average speed, is used as the turbulence indicator. Both longitudinal and lateral turbulence are considered. The longitudinal value is available directly from the standard deviation of measured speed, while the lateral value is obtained by converting the standard deviation of direction to radians. As described in the section on site wind characteristics, the turbulence changes rapidly with height. However, the hub height value seems to be representative, that is, using an area weighted averaged of the three levels did not alter the results significantly.

No attempt is made here to describe the spectral content of the turbulence, but an assumption regarding separation of time scales is employed. Slowly varying winds will be followed coherently by the turbine (Frandsen and Christensen, 1980) and are not considered as turbulence in the present context. Therefore, the turbulence intensity is based on an average of 2 minute intensities, which is equivalent to a high pass filter having a characteristic time of 2 minutes.
Gradient Richardson Number

The Richardson Number is a nondimensional parameter related to the local stability of the flow. In equation form,

\[
RI = \frac{\text{Buoyancy}}{\text{Shear Gradient}} = \frac{(g/T_0)(\gamma_D - \gamma)}{(\Delta u/\Delta z)^2}
\]

where

- \( g = \text{gravitational constant} \)
- \( T_0 = \text{reference absolute temp} \)
- \( \gamma_D = \text{dry adiabatic lapse rate} \)
- \( \gamma = \text{local lapse rate} \)
- \( \Delta u = \text{change in mean wind speed} \)
- \( \Delta z = \text{change in height} \)

The Richardson Number measures the relative contributions to turbulence energy of buoyancy generation and shear generation. Shear generation is always positive while the buoyancy term may have either sign depending on the lapse rate. Negative Richardson Numbers result from lapse rates greater than the dry adiabatic rate, favoring convective overturning. Positive values indicate stable stratification. Small velocity gradients (shear generation term) allow the more distinct stable or unstable regimes to develop and numerically are associated with larger absolute values of the Richardson Number.

The gradient Richardson Number is a point measure of stability and ideally would be calculated as a function of height, however, this would require a series of temperature and wind speed measurements through the layers of interest. Using the available
data an average or bulk Richardson Number has been calculated for the turbine layer. The lapse rate is estimated by the temperature difference between the 50 and 350 foot levels while the shear gradient was computed between 50 and 200 feet to avoid numerical problems with small shears occurring during jet flow.

Yaw

Yaw is used here to denote the horizontal angle between the wind direction and the turbine nacelle orientation. The yaw angle is not, of course, a wind characteristic but rather an indirect indicator of the ability of the control system to maintain alignment.

Yaw data was available in two forms. The first is based on a comparison of nacelle position (azimuth) and the tower wind direction. In preliminary analysis this data did not appear to be useful since even hourly average yaw values were large, suggesting a calibration problem. The second source for yaw information is the nacelle sensor system, which serves as the monitor for the turbine control system. The nacelle sensors are located very close behind the rotor and would not be expected to have the same magnitude of response as a tower mounted sensor which is outside the zone of influence of the turbine. Nevertheless, the nacelle wind sensor data appear reasonable and have been selected to represent the yaw angle.
The variable used here is the cosine of the two minute averaged yaw angle, subsequently averaged over the twenty minute periods. Using the cosine avoids the problem of positive and negative yaw angles cancelling each other within averaging periods. Appendix E gives some results based on the signed yaw angle.

**Standard Deviation of Power**

The standard deviation of power output is another indirect indicator of turbine conditions. Under more turbulent flow the power fluctuations increase and it is of interest whether these fluctuations are detrimental to power output. As with turbulence intensity the 20 minute value is obtained by averaging a series of 2 minute standard deviations.
V. SITE WIND CHARACTERISTICS

Site winds during the test period (Oct. 1-Nov. 8, 1982) exhibit a distinct bimodal character. Figure 5.1 is a wind rose for the period while Figure 5.2 gives the wind speed, direction and diurnal frequency distributions for the test data. The wind direction is predominantly west-southwest to west-northwest with a good representation through the speed range utilized for analysis. The only other important winds were the weaker nighttime winds out of the east and northeast. Figure 5.3 gives ground surface profiles for the most common directions.

The strength of winds during this period was somewhat less than the annual expectation which is in accord with reported seasonal trends. Hadley and Renne (1983) describe the seasonal cycle of wind strength as having a maximum in late spring and early summer while the minimum is midwinter. He also reports that on an annual basis "maximum speeds are typically from the northwest and occur in the late afternoon and early evening hours reaching a peak at approximately 10 p.m., but continuing strong most of the night. Minimum speeds occur in the late morning and early afternoon hours." Comparing to the frequency distributions for the test period a general agreement is seen. The northwest winds are somewhat stronger and tend to occur more during the night. The morning winds are lighter and often have a southerly component suggesting an influence from morning upslope flow on the slopes immediately to the south.
FIGURE 5.1: WIND ROSE for the TEST PERIOD
(BY 30 DEGREE SECTORS)
FIGURE 5.2: FREQUENCY DISTRIBUTIONS of the TEST DATA
Figure 5.3: Ground Surface Profiles

DISTANCE FROM TURBINE (FEET)
Figures 5.4 - 5.7 are plots of the diurnal variation of speed, direction and turbulence in the rotor disc layer. These plots show that the influence of the diurnal cycle is not overshadowed by synoptic scale features. (Note that hours 25-30 are a repeat of 1-6.) In particular, the increased mixing during midday hours is seen to influence all three primary variables. Speed ratios are closer to unity indicating rather flat profile shapes during the day while nighttime values are more extreme due to strongly sheared profiles. The drop in upper speed ratio after midnight is associated with the jet profile (upper speed ratio less than 1). A similar effect may be noted from the directional shear factor plot. As expected, daytime mixing moderates the directional shear through the disc.

The diurnal turbulence curves have a more dramatic shape. Turbulence intensity increases rapidly in the morning hours and decreases nearly as rapidly in the afternoon with a very sharp drop one or two hours before sunset. The lowest level is the most turbulent and shows the smallest diurnal cycle, indicating the increased relative importance of mechanical turbulence production near the surface. While the lateral and longitudinal components exhibit similar trends, the ratio of these components has a cycle of its own. Figure 5.8 shows that relatively high values of this ratio are found during the daytime and that the cycle is stronger at the upper levels.

The Richardson Number (RI) plot has a strong cycle and an interesting shelf during the first half of the night (Figure
FIGURE 5.4: DIURNAL SPEED AND SPEED RATIOS
<table>
<thead>
<tr>
<th>HOUR</th>
<th>DIURNAL DATA</th>
<th>SPEED AND SPEED RATIOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200' WIND SPEED</td>
<td>LOWER SPEED RATIO (50/200)</td>
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</tr>
<tr>
<td>2</td>
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<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>20.6</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>22.2</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>22.2</td>
<td>0.70</td>
</tr>
<tr>
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<td>23.0</td>
<td>0.69</td>
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<td>0.75</td>
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<tr>
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<td>23.8</td>
<td>0.69</td>
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<tr>
<td>Night</td>
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</tr>
</tbody>
</table>

* Estimated values... see Appendix B.

FIGURE 5.4a. BPA TOWER DIURNAL SPEEDS AND SPEED RATIOS.
FIGURE 5.5: DIURNAL DIRECTION and DIRECTIONAL SHEAR FACTORS (in degrees)
<table>
<thead>
<tr>
<th>HOUR</th>
<th>200' WIND DIRECTION</th>
<th>LOWER DIRECTIONAL SHEAR FACTOR (200'-50')</th>
<th>TOTAL DIRECTIONAL SHEAR FACTOR (350'-50')</th>
</tr>
</thead>
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<td>9.1</td>
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<tr>
<td>Day</td>
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<tr>
<td>Night</td>
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<td>7.8</td>
<td>14.3</td>
</tr>
</tbody>
</table>

* Estimated values.... see Appendix B

FIGURE 5.5a. BPA TOWER DIURNAL DIRECTION AND DIRECTIONAL SHEAR FACTOR.
FIGURE 5.6: DIURNAL LONGITUDINAL TURBULENCE INTENSITY
<table>
<thead>
<tr>
<th>HOUR</th>
<th>DIURNAL DATA 50'</th>
<th>LONGITUDINAL TURBULENCE INTENSITY 200'</th>
<th>350' *</th>
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<td>0.042</td>
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<td>0.050</td>
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<td>0.035</td>
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<td>0.064</td>
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<td>0.105</td>
<td>0.070</td>
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<td>0.108</td>
<td>0.067</td>
</tr>
<tr>
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<td>0.151</td>
<td>0.103</td>
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</tr>
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<tr>
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<td>0.053</td>
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<tr>
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<td>0.055</td>
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<td>0.027</td>
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<td>0.040</td>
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<tr>
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</table>

* Estimated values... see Appendix B

**FIGURE 5.6a.** BPA TOWER DIURNAL LONGITUDINAL TURBULENCE INTENSITY.
FIGURE 5.7: DIURNAL LATERAL TURBULENCE INTENSITY
<table>
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<th>LATERAL TURBULENCE INTENSITY</th>
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<td>0.065</td>
</tr>
<tr>
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<td>0.074</td>
</tr>
<tr>
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<td>0.060</td>
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<tr>
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* Estimated values... see Appendix B

FIGURE 5.7a. BPA TOWER DIURNAL LATERAL TURBULENCE INTENSITY.
FIGURE 5.8: DIURNAL TURBULENCE INTENSITY RATIOS
<table>
<thead>
<tr>
<th>HOUR</th>
<th>DIURNAL DATA (50')</th>
<th>TURBULENCE RATIOS (LAT./LONG.)</th>
<th>200'</th>
<th>350' *</th>
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<tbody>
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<td>0.769</td>
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<td>0.876</td>
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<td>0.896</td>
<td>0.810</td>
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</table>

* Estimated values... see Appendix B

**FIGURE 5.8a.** BPA TOWER DIURNAL TURBULENCE INTENSITY RATIOS (LATERAL/LONGITUDINAL).
5.9). It is tempting to interpret RI as a general indicator for the other variables, that is to associate negative RI with a combination of high turbulence and lower shears and positive RI with a combination of low turbulence and higher shears. If the data could be organized in this manner the number of variables could be reduced, and yet this would prevent one from distinguishing between the individual effects of each variable. The indications from the data are mixed. Turbulence and shear levels are normally strongly correlated but may be uncorrelated or even negatively correlated at times. A clue to this behavior is found in Figure 5.10 in which turbulence intensity, speed shear factor and directional shear factor are plotted (note inverted scale for turbulence). It appears that wind speed profiles respond quickly to turbulent mixing while the directional shear exhibits a phase lag, especially noticeable comparing the daytime minimums. The decrease in the shear factor during the night is due to the influence of jet profile shapes.

Using near-neutral data the roughness length (Zo) is estimated at 0.5 to 0.65 feet (0.15-0.20m). Insufficient data were available to determine roughness as a function of direction.
FIGURE 5.9: DIURNAL RICHARDSON NUMBER and SPEED SHEAR FACTOR
<table>
<thead>
<tr>
<th>HOUR</th>
<th>RICHARDSON NUMBER</th>
<th>SPEED SHEAR FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.07</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
<td>0.33</td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.38</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>0.37</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>0.41</td>
</tr>
<tr>
<td>7</td>
<td>0.08</td>
<td>0.45</td>
</tr>
<tr>
<td>8</td>
<td>0.10</td>
<td>0.26</td>
</tr>
<tr>
<td>9</td>
<td>0.04</td>
<td>0.32</td>
</tr>
<tr>
<td>10</td>
<td>-0.09</td>
<td>0.22</td>
</tr>
<tr>
<td>11</td>
<td>-0.05</td>
<td>0.19</td>
</tr>
<tr>
<td>12</td>
<td>-0.13</td>
<td>0.19</td>
</tr>
<tr>
<td>13</td>
<td>-0.06</td>
<td>0.23</td>
</tr>
<tr>
<td>14</td>
<td>-0.02</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>-0.04</td>
<td>0.29</td>
</tr>
<tr>
<td>16</td>
<td>-0.01</td>
<td>0.34</td>
</tr>
<tr>
<td>17</td>
<td>0.03</td>
<td>0.34</td>
</tr>
<tr>
<td>18</td>
<td>0.06</td>
<td>0.41</td>
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<tr>
<td>19</td>
<td>0.08</td>
<td>0.40</td>
</tr>
<tr>
<td>20</td>
<td>0.07</td>
<td>0.40</td>
</tr>
<tr>
<td>21</td>
<td>0.08</td>
<td>0.42</td>
</tr>
<tr>
<td>22</td>
<td>0.08</td>
<td>0.40</td>
</tr>
<tr>
<td>23</td>
<td>0.06</td>
<td>0.38</td>
</tr>
<tr>
<td>24</td>
<td>0.06</td>
<td>0.36</td>
</tr>
<tr>
<td>Day</td>
<td>-0.01</td>
<td>0.29</td>
</tr>
<tr>
<td>Night</td>
<td>0.09</td>
<td>0.38</td>
</tr>
</tbody>
</table>

* Estimated values... see Appendix B

FIGURE 5.9a. BPA TOWER DIURNAL RICHARDSON NUMBER AND SPEED SHEAR FACTOR.
FIGURE 5.10: DIURNAL PHASE COMPARISON
VI. METHODOLOGY

Factor analysis is the most straightforward way of detecting dependence among variables. One variable at a time is chosen, and the data are separated according to levels of the variable. The number of levels will depend on the number of samples and the complexity of the association. Consideration of one variable at a time does not yield information concerning interaction effects. An improvement is obtained by running two factor studies. The two factor comparisons gave confusing results but did establish that the variables are not independent. Experience gained with this analysis led to a new approach involving velocity profile classification.

Motivation for a separation on the basis of velocity profile shapes stems from the realization that the complexity of variable interactions may preclude meaningful results under simple analysis. The alternative approach involves separation into distinct classes containing specific combinations of variables. Averaging variables within each class identifies these combinations as a composite profile. Using the composite values as an indicator of central tendency, criteria for the classes may be formulated.

After working with various numbers of classes a decision to identify seven velocity profile types was made. Three of the profiles have fewer observations and represent the extremes of observed conditions. They are designated as auxiliary profile classes. Basic criteria are degree of speed shear, turbulence
intensity and directional shear. (Appendix F gives details of the separation.) Although not used in the separation, the Richardson Number helps in organizing the classes. Figure 6.1 shows a plot of average Richardson Number versus the average speed shear factor. The basic trend is toward increasing speed shear factor with increasing stability, yet classes 1A and 3A reverse this trend. Referring to Figure 6.2, showing composite speed ratios, it may be seen that the second trend is associated with the low level jet phenomenon. In cases where the jet maximum is below 350 feet profile 1A or 3A will result. For a jet maximum above the turbine layer profile 4 will be observed. Setting aside the jet profile, the remaining six classes may be conveniently visualized in a 2x3 matrix pattern (Figure 6.1). Three of the classes are characterized by higher turbulence with lower directional shear while the remaining three have lower turbulence and higher directional shear. Going the other way across the matrix we are looking at speed shear. Two of the profiles are quite flat (upper speed ratio near 1), two are average and two represent large speed shear factors. Tables 6.1 through 6.7 give the variable means, standard deviation and number of observations within each class. Figure 6.3 illustrates the diurnal distribution data.

Class 1 contains the largest number of observations and is distributed throughout the day and night. Turbulence is relatively high, directional shear factor low and speed shear factor moderate. The composite Richardson Number is 0.02 suggesting near neutral stability.
FIGURE 6.1: ORGANIZATION OF VELOCITY PROFILE CLASSES
HORIZONTAL AXIS:
Wind Speed Ratio
(hub height equals unity)

VERTICAL AXIS:
Height above ground
(50', 200', 350')

FIGURE 6.2: COMPOSITE SPEED RATIOS OF VELOCITY PROFILE CLASSES
<table>
<thead>
<tr>
<th>Class Number 1A</th>
<th>Number of Observations 19</th>
<th>Class Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (mph):</td>
<td></td>
<td>20.1</td>
<td>2.45</td>
</tr>
<tr>
<td>Lower Speed Ratio</td>
<td></td>
<td>0.63</td>
<td>0.029</td>
</tr>
<tr>
<td>Upper Speed Ratio *</td>
<td></td>
<td>0.84</td>
<td>0.067</td>
</tr>
<tr>
<td>Speed Shear Factor</td>
<td></td>
<td>0.202</td>
<td>0.088</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
<td>277.8</td>
<td>5.83</td>
</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td></td>
<td>10.3</td>
<td>2.56</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td></td>
<td>17.3</td>
<td>3.14</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>0.142</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>200'</td>
<td>0.025</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>350' *</td>
<td>0.028</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>0.118</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>200'</td>
<td>0.018</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>350' *</td>
<td>0.024</td>
<td>0.017</td>
<td></td>
</tr>
<tr>
<td>Richardson Number</td>
<td></td>
<td>+0.13</td>
<td>0.047</td>
</tr>
<tr>
<td>Linear Disc Average Ratio</td>
<td></td>
<td>0.921</td>
<td>0.010</td>
</tr>
<tr>
<td>Yaw Angle (cosine)</td>
<td></td>
<td>0.990</td>
<td>0.011</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
<td></td>
<td>0.049</td>
<td>0.014</td>
</tr>
</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
<table>
<thead>
<tr>
<th></th>
<th>Class Number 2A</th>
<th>Number of Observations 21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class Mean</td>
<td>Std. Dev.</td>
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<td>Speed (mph):</td>
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<td>2.81</td>
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</tr>
<tr>
<td>Upper Speed Ratio *</td>
<td>0.98</td>
<td>0.019</td>
</tr>
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<td>Speed Shear Factor</td>
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<td>0.044</td>
</tr>
<tr>
<td>Direction:</td>
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<td>10.3</td>
</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td>5.08</td>
<td>1.72</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td>10.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td>50'</td>
<td>0.147</td>
</tr>
<tr>
<td>200'</td>
<td>0.109</td>
<td>0.009</td>
</tr>
<tr>
<td>350' *</td>
<td>0.086</td>
<td>0.014</td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td>50'</td>
<td>0.138</td>
</tr>
<tr>
<td>200'</td>
<td>0.111</td>
<td>0.015</td>
</tr>
<tr>
<td>350' *</td>
<td>0.103</td>
<td>0.020</td>
</tr>
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<td>Richardson Number</td>
<td>-0.06</td>
<td>0.063</td>
</tr>
<tr>
<td>Linear Disc Average Ratio</td>
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<td>0.005</td>
</tr>
<tr>
<td>Yaw Angle (cosine)</td>
<td>0.984</td>
<td>0.009</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
<td>0.203</td>
<td>0.029</td>
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</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
<table>
<thead>
<tr>
<th>Class Number 3A</th>
<th>Number of Observations 17</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Class Mean</td>
</tr>
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<td>Speed (mph):</td>
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<tr>
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</tr>
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<td>Upper Speed Ratio</td>
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</tr>
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</tr>
<tr>
<td>Total Directional Shear Factor</td>
<td>15.4</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Richardson Number</td>
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<tr>
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</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
TABLE 6.4: COMPOSITE VELOCITY PROFILE

<table>
<thead>
<tr>
<th>Class Number 1</th>
<th>Number of Observations 87</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class Mean</td>
</tr>
<tr>
<td>Speed (mph):</td>
<td></td>
</tr>
<tr>
<td>Lower Speed Ratio</td>
<td>0.76</td>
</tr>
<tr>
<td>Upper Speed Ratio *</td>
<td>1.05</td>
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<tr>
<td>Speed Shear Factor</td>
<td>0.297</td>
</tr>
<tr>
<td>Direction:</td>
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</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td>5.2</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td>10.9</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>0.150</td>
</tr>
<tr>
<td>200'</td>
<td>0.104</td>
</tr>
<tr>
<td>350' *</td>
<td>0.066</td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>0.134</td>
</tr>
<tr>
<td>200'</td>
<td>0.097</td>
</tr>
<tr>
<td>350' *</td>
<td>0.055</td>
</tr>
<tr>
<td>Richardson Number</td>
<td>+0.02</td>
</tr>
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<td>Linear Disc Average Ratio</td>
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</tr>
<tr>
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<td>0.992</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
<td>0.175</td>
</tr>
</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
TABLE 6.5: COMPOSITE VELOCITY PROFILE

<table>
<thead>
<tr>
<th>Class Number 2</th>
<th>Number of Observations 74</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class Mean</td>
</tr>
<tr>
<td>Speed (mph):</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.9</td>
</tr>
<tr>
<td>Lower Speed Ratio</td>
<td>0.69</td>
</tr>
<tr>
<td>Upper Speed Ratio *</td>
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</tr>
<tr>
<td>Speed Shear Factor</td>
<td>0.408</td>
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<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>271.9</td>
</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td>6.8</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td>13.3</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Richardson Number</td>
<td>+0.07</td>
</tr>
<tr>
<td>Linear Disc Average Ratio</td>
<td>0.976</td>
</tr>
<tr>
<td>Yaw Angle (cosine)</td>
<td>0.993</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
<td>0.109</td>
</tr>
</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
# TABLE 6.6: COMPOSITE VELOCITY PROFILE

<table>
<thead>
<tr>
<th>Class Number 3</th>
<th>Number of Observations 26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Class Mean</td>
</tr>
<tr>
<td>Speed (mph):</td>
<td></td>
</tr>
<tr>
<td>Lower Speed Ratio</td>
<td>0.69</td>
</tr>
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<td>Upper Speed Ratio *</td>
<td>1.15</td>
</tr>
<tr>
<td>Speed Shear Factor</td>
<td>0.454</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td>4.6</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td>10.3</td>
</tr>
<tr>
<td>Longitudinal Turbulence</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Lateral Turbulence</td>
<td>50'</td>
</tr>
<tr>
<td></td>
<td>200'</td>
</tr>
<tr>
<td></td>
<td>350' *</td>
</tr>
<tr>
<td>Richardson Number</td>
<td>+0.05</td>
</tr>
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<td>0.986</td>
</tr>
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<td>Yaw Angle (cosine)</td>
<td>0.992</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
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</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
### TABLE 6.7: COMPOSITE VELOCITY PROFILE

<table>
<thead>
<tr>
<th>Class Number 4</th>
<th>Number of Observations 40</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Class Mean</td>
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<tr>
<td>Speed (mph):</td>
<td></td>
</tr>
<tr>
<td>Lower Speed Ratio</td>
<td>0.64</td>
</tr>
<tr>
<td>Upper Speed Ratio</td>
<td>1.11</td>
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<td>Speed Shear Factor</td>
<td>0.475</td>
</tr>
<tr>
<td>Direction:</td>
<td></td>
</tr>
<tr>
<td>Lower Directional Shear Factor</td>
<td>9.7</td>
</tr>
<tr>
<td>Total Directional Shear Factor *</td>
<td>16.6</td>
</tr>
<tr>
<td>Longitudinal Turbulence Intensity</td>
<td></td>
</tr>
<tr>
<td>50'</td>
<td>0.134</td>
</tr>
<tr>
<td>200'</td>
<td>0.045</td>
</tr>
<tr>
<td>350' *</td>
<td>0.022</td>
</tr>
<tr>
<td>Lateral Turbulence Intensity</td>
<td></td>
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<tr>
<td>50'</td>
<td>0.111</td>
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<tr>
<td>200'</td>
<td>0.038</td>
</tr>
<tr>
<td>350' *</td>
<td>0.018</td>
</tr>
<tr>
<td>Richardson Number</td>
<td>+0.09</td>
</tr>
<tr>
<td>Linear Disc Average Ratio</td>
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</tr>
<tr>
<td>Yaw Angle (cosine)</td>
<td>0.993</td>
</tr>
<tr>
<td>Standard Deviation of Power</td>
<td>0.065</td>
</tr>
</tbody>
</table>

* These numbers are based on estimated data (see Appendix B)
FIGURE 6.3: DIURNAL DISTRIBUTION of VELOCITY PROFILE CLASSES
Diurnal Distribution of Velocity Profile Classes

<table>
<thead>
<tr>
<th>Hour</th>
<th>1A</th>
<th>2A</th>
<th>3A</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
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<td>3</td>
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<td>0</td>
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<td>19</td>
<td>3</td>
<td>0</td>
<td>0</td>
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<td>10</td>
<td>2</td>
<td>4</td>
</tr>
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<td>20</td>
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<td>1</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
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<td>21</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>7</td>
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<td>22</td>
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<td>3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Day  | 3  | 21 | 3  | 50 | 20 | 8  | 6  |
Night| 16 | 0  | 14 | 37 | 54 | 18 | 34 |
Total| 19 | 21 | 17 | 87 | 74 | 26 | 40 |

FIGURE 6.3a: DATA FOR FIGURE 6.3.
The two most distinctive classes are numbers 1A and 2A. Class 1A exhibits the nocturnal jet behavior with an average upper speed ratio of 0.84. Turbulence intensity is low, directional shear factor relatively high and the Richardson Number is well up into the stable range. Associated with the low speed ratios is the lowest disc average of any class. Velocity profile number 2A is nearly the inverse. Observations are confined to daytime hours, turbulence is high, directional and speed shear factors low while the Richardson Number indicates unstable conditions (convective mixing). This profile has the flattest shape, the upper level speed averaging only one percent above hub height speed and the lower ratio being 0.80.

Class 3A is transitional between the stable jet class (1A) and the more usual combination of stability and large speed shear factor. Aside from the upper speed ratio and higher disc average the conditions are similar to 1A.

The remaining stable classes, 2 and 4, are also primarily nocturnal. Class 4 has the highest average speed shear factor, low turbulence intensity and high directional shear factor. Richardson Number is not quite as high as in the previous cases and the disc average is slightly above the mean. Class 2 is similar but closer to the norms.

Class 3 is somewhat anomalous in that the speed shear factor is unusually large for the indicated turbulence levels. The directional shear factor is relatively low while the disc averages
run high. This profile class seems to be associated with the transition periods between nighttime and daytime regimes.

It is interesting to compare the average directions for each of the classes. Referring to the organization of Figure 6.1 and the composite data of Tables 6.1 and 6.7 it may be noted that the least stable class (2A) has the most southerly direction. Proceeding through classes 1, 3, 2 and 4, then 3A and 1A; the increase in stability is accompanied by an increase in direction. This observation points again to the high degree of interaction among the variables.
VII. RESULTS

The test data upon which the results are based consist of 20 minute averages from selected runs having wind speeds between 17.5 and 29.5 mph and wind directions between 235 and 300 degrees true.

The results of single and two factor analysis of the test data were disappointing. Weak and variable trends were observed for the parameters tested. Separation into categories of speed and direction resulted in smaller numbers of samples per bin and did not improve the situation. The velocity profile classification technique has worked well in clarifying these patterns.

Figure 7.1 gives the mean power offsets and 95% confidence intervals. Recalling from Figure 6.1 which classes are turbulent, it is seen that the offsets in classes 1 and 3 are above average but class 2A is quite low. The stable profiles are mostly close to zero, class 4 being the exception with a mean offset of -38 killowatts. Using the confidence intervals as a guide one may conclude that classes 3 and 4 have significantly different means as well as classes 1 and 2 or 3A and 2A while classes 1 and 3 or 1A, 3A, 2 and 4 are fairly comparable.

A somewhat different pattern is obtained by using the calculated disc average wind speed as the reference speed (Figure 7.2). The jet profile (class 1A) and profile 3A have low disc averages, thus when referenced to the disc average speed they show increased power relative to other classes. Conversely class 3, with a high disc average, is seen to decrease on the new basis.
TURBINE NO. 3
WIND SPEED REFERENCE: HUB HEIGHT

FIGURE 7.1: MEAN POWER OFFSETS BY CLASS, HUB HEIGHT REFERENCE
Confidence Intervals for Mean Power Offset by Class
Hub Height Reference

<table>
<thead>
<tr>
<th>Class</th>
<th>$\bar{X}$</th>
<th>$\sigma$</th>
<th>n</th>
<th>t</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>-.009</td>
<td>.058</td>
<td>19</td>
<td>2.10</td>
<td>-.37, .019</td>
</tr>
<tr>
<td>2A</td>
<td>-.098</td>
<td>.117</td>
<td>21</td>
<td>2.08</td>
<td>-.151, -.045</td>
</tr>
<tr>
<td>3A</td>
<td>-.019</td>
<td>.076</td>
<td>17</td>
<td>2.12</td>
<td>-.058, .020</td>
</tr>
<tr>
<td>1</td>
<td>+.029</td>
<td>.097</td>
<td>87</td>
<td>1.99</td>
<td>.008, .050</td>
</tr>
<tr>
<td>2</td>
<td>-.005</td>
<td>.073</td>
<td>74</td>
<td>1.99</td>
<td>-.022, .012</td>
</tr>
<tr>
<td>3</td>
<td>+.068</td>
<td>.094</td>
<td>26</td>
<td>2.06</td>
<td>.030, .106</td>
</tr>
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<td>4</td>
<td>-.030</td>
<td>.057</td>
<td>40</td>
<td>2.02</td>
<td>-.048, -.012</td>
</tr>
</tbody>
</table>

Based on Student's t-distribution with n-1 degrees of freedom

FIGURE 7.1a: DATA FOR FIGURE 7.1.
FIGURE 7.2: MEAN POWER OFFSETS BY CLASS, DISC AVERAGE REFERENCE
Confidence Intervals for Mean Power Offset by Class
Linear Disc Average Reference

<table>
<thead>
<tr>
<th>Class</th>
<th>$\bar{X}$</th>
<th>$\sigma$</th>
<th>n</th>
<th>t</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
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<td>.049</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.115</td>
</tr>
<tr>
<td>2A</td>
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<td>21</td>
<td>2.08</td>
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<td></td>
<td>-.038</td>
</tr>
<tr>
<td>3A</td>
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<td>.076</td>
<td>17</td>
<td>2.12</td>
<td>-.013</td>
</tr>
<tr>
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<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>.038</td>
</tr>
<tr>
<td>2</td>
<td>-.013</td>
<td>.079</td>
<td>74</td>
<td>1.99</td>
<td>-.031</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
<td>.005</td>
</tr>
<tr>
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<td>+.031</td>
<td>.091</td>
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<td>-.006</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td>.068</td>
</tr>
<tr>
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<td>.060</td>
<td>40</td>
<td>2.02</td>
<td>-.052</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-.014</td>
</tr>
</tbody>
</table>

Based on Student's $t$-distribution with $n-1$ degrees of freedom

FIGURE 7.2a: DATA FOR FIGURE 7.2.
Classes 1 and 2 are not as distinctly separated on this basis but classes 3 and 4 maintain their separation. It is not known whether the simple method of compensation based on linear averaging is valid. Using sum of squares of residuals from the cubic curve fit as a criterion, no significant improvement was found using either the linear disc average or the squared-weighted disc average. Thus the idea of using the disc average to remove a known source of variability is not pursued further. It is still surprising that the power outputs of classes 1A and 3A are not lower than that of class 2. Likewise the low power observed in class 2A is unexpected. These results explain in part the lack of success in analyzing the unclassified data as a whole.

Further consideration of the three auxiliary classes will be postponed until the four main classes have been discussed. Table 7.1 shows the four main classes organized as a 2x2 factor study. The reference power curve is recalculated using only data from the main classes and a slight shift in the power offsets may be noted. The new groupings, 5, 6, 7 and 8, are the row and column sums respectively. Comparing the variables and offsets, the following general trends may be observed:

- increasing speed shear factor .............. decreasing power
- increasing directional shear factor .......... decreasing power
- increasing long. turbulence intensity ....... increasing power
| Classes | 5, 6 and 7, 8 are the row and column sums respectively |
increasing standard deviation of power ........ increasing power cosine of the yaw angle ..................... no trend

These general trends may be investigated further by considering the product moment correlation coefficient between each of the variables and power.

Calculated correlation coefficients were tested for significance under the null hypothesis that the coefficient was zero (Snedecor and Cochran, 1978). Table 7.3 shows the critical values for each class at the 90% confidence level. Table 7.2 gives coefficients for the same groupings as in Table 7.1. Coefficients which are significantly different from zero are marked to the right with the appropriate sign.

The speed shear factor has no significant correlation to power within the four main classes. Indications in groups 5 and 6 are contradictory and weak.

Directional shear factor shows negative correlation in three of the main classes and is significant in all of the summed groups.

Longitudinal turbulence shows some positive correlation in class 1 and group 5 but none in classes 2 and 4 or group 6. Groups 7 and 8 both indicate positive correlation.

Lateral turbulence is similar to longitudinal but the correlation is weaker.

The linear disc average has no significant correlation within the main classes, but some positive indication in groups 5 and 8.

Standard deviation of power is positively correlated in class 4 and groups 7 and 8.
TABLE 7.2: CORRELATION COEFFICIENTS FOR MAIN CLASSES (VARIABLES VS. POWER OFFSET).

<table>
<thead>
<tr>
<th>1</th>
<th>+19</th>
<th>3</th>
<th>+58</th>
<th>5</th>
<th>+28</th>
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<tr>
<td>0.101</td>
<td>0</td>
<td>-0.138</td>
<td>0</td>
<td>0.164</td>
<td>+</td>
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<td>-</td>
<td>-0.378</td>
<td>-</td>
<td>-0.246</td>
<td>-</td>
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<td>0.176</td>
<td>0</td>
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<td>0</td>
<td>0.165</td>
<td>+</td>
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<tr>
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<td>0</td>
<td>0.186</td>
<td>0</td>
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<tr>
<td>0.156</td>
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<td>0</td>
<td>0.112</td>
<td>0</td>
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<tr>
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<td>0</td>
<td>0.027</td>
<td>0</td>
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<tr>
<td>87</td>
<td>26</td>
<td></td>
<td></td>
<td>113</td>
<td></td>
</tr>
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<table>
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<th>-23</th>
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<td>0</td>
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<td>-</td>
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<td>-0.209</td>
<td>0</td>
<td>-0.266</td>
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<td>0.106</td>
<td>0</td>
<td>0.065</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>0.048</td>
<td>0</td>
<td>0.051</td>
<td>0</td>
</tr>
<tr>
<td>-0.068</td>
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<td>0.115</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>0.011</td>
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<td>+</td>
<td>0.132</td>
<td>0</td>
</tr>
<tr>
<td>-0.102</td>
<td>0</td>
<td>0.192</td>
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<td>-0.011</td>
<td>0</td>
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<td>74</td>
<td>40</td>
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<td></td>
<td>114</td>
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</table>

<table>
<thead>
<tr>
<th>7</th>
<th>+4</th>
<th>8</th>
<th>00</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.129</td>
<td>0</td>
<td>-0.221</td>
<td>-</td>
<td>Speed Shear Factor</td>
<td></td>
</tr>
<tr>
<td>-0.248</td>
<td>-</td>
<td>-0.546</td>
<td>-</td>
<td>Directional Shear</td>
<td></td>
</tr>
<tr>
<td>0.180</td>
<td>+</td>
<td>0.518</td>
<td>+</td>
<td>Long. Turb. Inten.</td>
<td></td>
</tr>
<tr>
<td>0.120</td>
<td>0</td>
<td>0.502</td>
<td>+</td>
<td>Lat. Turb. Inten.</td>
<td></td>
</tr>
<tr>
<td>0.053</td>
<td>0</td>
<td>0.382</td>
<td>+</td>
<td>Disc Average</td>
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</tr>
<tr>
<td>0.201</td>
<td>+</td>
<td>0.557</td>
<td>+</td>
<td>Power Std. Dev.</td>
<td></td>
</tr>
<tr>
<td>-0.040</td>
<td>0</td>
<td>0.059</td>
<td>0</td>
<td>Cos of Yaw Angle</td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>66</td>
<td></td>
<td></td>
<td># of Observations</td>
<td></td>
</tr>
</tbody>
</table>

Classes 5, 6 and 7, 8 are the row and column sums respectively. 0, +, - indicate significance of correlation coefficient as determined from the data of Table 7.3.
TABLE 7.3: CRITICAL CORRELATION COEFFICIENTS FOR FIRST CLASS DIVISION.

Test $H_0$: $\rho = 0$

Reject $H_0$ for $\left| \frac{\sqrt{n-2} \cdot r}{\sqrt{1-r^2}} \right| > t_{\alpha/2}$

Where $t$ is Student's t-distribution for level of confidence $1-\alpha$.

$\alpha = 0.10$

<table>
<thead>
<tr>
<th>Class</th>
<th>n</th>
<th>t</th>
<th>$r_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>19</td>
<td>1.74</td>
<td>.389</td>
</tr>
<tr>
<td>2A</td>
<td>21</td>
<td>1.73</td>
<td>.369</td>
</tr>
<tr>
<td>3A</td>
<td>17</td>
<td>1.75</td>
<td>.412</td>
</tr>
<tr>
<td>1</td>
<td>87</td>
<td>1.66</td>
<td>.177</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>1.67</td>
<td>.193</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>1.70</td>
<td>.328</td>
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<td>40</td>
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<td>.155</td>
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<tr>
<td>7</td>
<td>161</td>
<td>1.65</td>
<td>.130</td>
</tr>
<tr>
<td>8</td>
<td>66</td>
<td>1.67</td>
<td>.204</td>
</tr>
</tbody>
</table>
The yaw angle has no significant correlation to power offset in these classes.

These results suggest that the speed shear factor does not have a significant effect on power output within the range of the test data. Also the effects of disc average are not as important as the other variables.

Thus two variables of primary importance have emerged; directional shear and turbulence. In order to explore the effects of these two variables further a new classification of the data excluding the three auxiliary classes is made. Table 7.4 shows the results obtained by redefining the four main classes on the basis of turbulence intensity and directional shear factor alone. These classes are designated as:

1B high turbulence intensity, low directional shear
2B low turbulence intensity, low directional shear
3B high turbulence intensity, high directional shear
4B low turbulence intensity, high directional shear.

Comparing groups 5B and 6B it is seen that turbulence intensity is positively associated with power as before. Comparing groups 7B and 8B a negative correlation of power and directional shear is found, again consistent with previous results. The magnitudes of the effects of the two variables appear to be comparable.

Correlation of the variables versus power offset for the new "B" classes is given in Table 7.5.
TABLE 7.4: VARIABLE MEANS FOR "B" CLASSES

<table>
<thead>
<tr>
<th>Class</th>
<th>Offset(kW)</th>
<th>1B</th>
<th>3B</th>
<th>5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>5B</td>
<td>+29</td>
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<td></td>
</tr>
<tr>
<td>6B</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7B</td>
<td>+23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td>-20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Classes 5B, 6B and 7B, 8B are the row and column sums respectively</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>0.343</td>
<td>0.347</td>
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</tr>
<tr>
<td>3B</td>
<td>-3</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
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<td>7.5</td>
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<td>0.106</td>
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<td>0.096</td>
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<td>0.979</td>
<td>0.982</td>
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<td>59</td>
<td>119</td>
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</tbody>
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<table>
<thead>
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<th>Mean</th>
<th>Standard Deviation</th>
<th>Classes 5B, 6B and 7B, 8B are the row and column sums respectively</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-41</td>
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<td>10.5</td>
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<td>0.973</td>
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<table>
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<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Classes 5B, 6B and 7B, 8B are the row and column sums respectively</th>
</tr>
</thead>
<tbody>
<tr>
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<td>+23</td>
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<td>8B</td>
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<td>0.376</td>
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<td>0.079</td>
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<td>4.2</td>
<td>8.9</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>0.085</td>
<td>0.079</td>
<td>0.978</td>
<td></td>
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<tr>
<td>0.074</td>
<td>0.073</td>
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<td></td>
</tr>
<tr>
<td>0.976</td>
<td>0.978</td>
<td>0.992</td>
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</tr>
<tr>
<td>0.133</td>
<td>0.129</td>
<td>0.133</td>
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</tr>
<tr>
<td>0.993</td>
<td>0.993</td>
<td>0.993</td>
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</tr>
<tr>
<td>119</td>
<td>109</td>
<td># of Observations</td>
<td></td>
</tr>
</tbody>
</table>

**KEY**
- **Class Offset(kW)**
- **Speed Shear Factor**
- **Directional Shear**
- **Long. Turb. Inten.**
- **Lat. Turb. Inten.**
- **Disc Average**
- **Power Std. Dev.**
- **Cos of Yaw Angle**

Classes 5B, 6B and 7B, 8B are the row and column sums respectively.
TABLE 7.5: CORRELATION COEFFICIENTS FOR "B" CLASSES (VARIABLES VS. POWER OFFSET).

<table>
<thead>
<tr>
<th></th>
<th>3B</th>
<th>5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B + 60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>0.162</td>
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<td></td>
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<td></td>
<td>0.335</td>
<td>-0.070</td>
</tr>
<tr>
<td></td>
<td>0.311</td>
<td>-0.025</td>
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<tr>
<td></td>
<td>0.212</td>
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<tr>
<td></td>
<td>0.135</td>
<td>0.114</td>
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<tr>
<td></td>
<td>-0.264</td>
<td>0.113</td>
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<td></td>
<td></td>
<td>0.263</td>
</tr>
<tr>
<td>59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6B - 27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B - 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>-0.048</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-0.158</td>
<td>-0.033</td>
</tr>
<tr>
<td></td>
<td>-0.118</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>-0.086</td>
<td>0.169</td>
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<tr>
<td></td>
<td>0.110</td>
<td>-0.276</td>
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<td></td>
<td>0.008</td>
<td>0.038</td>
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<tr>
<td></td>
<td>0.001</td>
<td>0.035</td>
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<tr>
<td></td>
<td></td>
<td>0.050</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7B + 23</td>
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<td></td>
</tr>
<tr>
<td>7B</td>
<td>-0.094</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-0.336</td>
<td>-0.100</td>
</tr>
<tr>
<td></td>
<td>0.338</td>
<td>-0.178</td>
</tr>
<tr>
<td></td>
<td>0.381</td>
<td>0.170</td>
</tr>
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<td></td>
<td>0.266</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>0.334</td>
<td>0.148</td>
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<tr>
<td></td>
<td>-0.164</td>
<td>0.226</td>
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<td></td>
<td></td>
<td>0.131</td>
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<tr>
<td>109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8B - 20</td>
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</tr>
<tr>
<td>8B</td>
<td></td>
<td></td>
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<tr>
<td>8B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>109</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

KEY

Class Offset(kW)

- Speed Shear Factor
- Directional Shear
- Lat. Turb. Inten.
- Disc Average
- Power Std. Dev.
- Cos of Yaw Angle

Classes 5B, 6B and 7B, 8B are the row and column sums respectively 0, +, - indicate significance of correlation coefficient as determined from the data of Table 7.6.
TABLE 7.6: CRITICAL CORRELATION COEFFICIENTS FOR SECOND CLASS DIVISION-"B" CLASSES.

Test $H_0$: $\rho = 0$

Reject $H_0$ for $\left| \frac{\sqrt{n-2} r}{\sqrt{1-r^2}} \right| > t_{\alpha/2}$

Where $t$ is Student's t-distribution for level of confidence $1-\alpha$.

$\alpha = 0.10$

<table>
<thead>
<tr>
<th>Class</th>
<th>$n$</th>
<th>$t$</th>
<th>$r_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>60</td>
<td>1.67</td>
<td>.209</td>
</tr>
<tr>
<td>2B</td>
<td>59</td>
<td>1.67</td>
<td>.216</td>
</tr>
<tr>
<td>3B</td>
<td>59</td>
<td>1.67</td>
<td>.214</td>
</tr>
<tr>
<td>4B</td>
<td>50</td>
<td>1.68</td>
<td>.234</td>
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<td>5B</td>
<td>119</td>
<td>1.66</td>
<td>.149</td>
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<tr>
<td>6B</td>
<td>109</td>
<td>1.66</td>
<td>.158</td>
</tr>
<tr>
<td>7B</td>
<td>119</td>
<td>1.66</td>
<td>.150</td>
</tr>
<tr>
<td>8B</td>
<td>109</td>
<td>1.66</td>
<td>.158</td>
</tr>
</tbody>
</table>
As before, the speed shear factor is not significantly correlated with power.

The directional shear factor correlation is weak within the classes but consistent in the marginal groupings.

The two components of turbulence intensity exhibit similar behavior. In general, turbulence intensity is positively correlated with the power offset, but it is interesting to note the negative correlation for the lateral component in class 4B.

The disc average is positively correlated in class 1B and group 7B, but not strongly.

The standard deviation of power shows some positive trend in groups 7B and 8B.

The cosine of the yaw angle is contradictory in 1B and 3B and insignificant elsewhere.

These data suggest that different mechanisms may be operating under the various flow conditions. Discussion of this point will be continued later in regard to the auxiliary classes.

The magnitude of power fluctuation excluding auxiliary classes may be summarized as follows: 50% of the data (classes 2B and 3B) represent average power output. 25% of the data (class 1B; low directional shear, high turbulence) are approximately 50 kW above average and 25% of the data (class 4B; high directional shear, low turbulence) are approximately 50 kW below the average.

To put this in perspective energy production is estimated using a Rayleigh distribution with a 16 mph mean wind speed. The energy using the reference power curve is compared to the energy
using a power curve which is 50 kW higher between cut in and rated wind speeds but identical above rated power. This comparison results in a 4.3% increase in estimated energy production. An additional comparison may be made by using different mean wind speeds in the frequency distribution. Changing the mean wind speed from 16 to 17 mph results in a 13.2% increase in estimated energy. Thus a site with wind characteristics more typical of class 4B would be expected to produce less energy, yet if that site had a mean wind speed one-third to one-half mile per hour higher the losses due to flow conditions would be compensated for.

Returning now to the auxiliary classes, the variable means and correlation coefficients are shown in Table 7.7. Class 3A has relatively large speed shear in the lower disc but a rather flat shape above. This class represents stable flows with low turbulence intensity and high directional shear. The correlation coefficients indicate that turbulence intensity is the most strongly correlated atmospheric parameter. The correlation is negative which is contrary to the general results obtained earlier but in agreement with the trend noticed in class 4B. Class 1A represents stable jet profiles and may be considered as a more extreme form of class 3A. The turbulence intensity is extremely low and the disc average is the lowest of any class. The correlations show only one significant value, that being a positive correlation with directional shear factor.

These results are confusing and offer no clear conclusions. It appears that the effects of turbulence under these conditions
TABLE 7.7: VARIABLE MEANS AND CORRELATION COEFFICIENTS FOR AUXILIARY CLASSES.

Variable Means for Auxiliary Classes

<table>
<thead>
<tr>
<th>1A</th>
<th>- 9</th>
<th>2A</th>
<th>- 98</th>
<th>3A</th>
<th>- 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.202</td>
<td>0.173</td>
<td>0.325</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10.3</td>
<td>5.1</td>
<td>10.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.025</td>
<td>0.109</td>
<td>0.039</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.018</td>
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<td>0.033</td>
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<td></td>
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</tr>
<tr>
<td>0.921</td>
<td>0.969</td>
<td>0.952</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.049</td>
<td>0.203</td>
<td>0.072</td>
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</tr>
<tr>
<td>0.990</td>
<td>0.984</td>
<td>0.992</td>
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</tr>
</tbody>
</table>

Correlation Coefficients for Auxiliary Classes
Variables vs. Power Offset

<table>
<thead>
<tr>
<th>1A</th>
<th>- 9</th>
<th>2A</th>
<th>- 98</th>
<th>3A</th>
<th>- 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.194</td>
<td>0</td>
<td>0.416</td>
<td>+</td>
<td>0.119</td>
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<tr>
<td>0.559</td>
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<td>-0.225</td>
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<td>0</td>
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<tr>
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<td>0</td>
<td>-0.576</td>
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<td>-0.671</td>
<td>-</td>
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<td>0.316</td>
<td>0</td>
<td>-0.125</td>
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<td>+</td>
<td>-0.112</td>
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Key

Class Offset(kW)

Speed Shear Factor
Directional Shear
Long. Turb. Inten.
Lat. Turb. Inten.
Disc Average
Power St. Dev.
Cos of Yaw Angle

# of Observations

0, +, - indicate significance of correlation coefficient as determined from the data of Table 7.3.
are qualitatively different from the effects seen in the main data classes. No explanation is found for the fact that power is not adversely affected by the low disc average values. It would be interesting to look at data for teeter angle to see if these classes are special in that regard.

Class 2A, representing daytime turbulent conditions with extremely flat speed profiles, has very low power output. This reverses the trend of the main data where increasing turbulence intensity is correlated with increasing power. The correlations point to speed shear factor and yaw angle as the important variables. Considering that all of the main classes have mean yaw cosine values of 0.992 or 0.993 whereas class 2A has a mean of 0.984, it seems probable to conclude that the decrease in power is due to increased directional fluctuations. This is supported by the high level of lateral turbulence intensity for this class, but the correlation coefficient is not large enough to be considered significant. Relaxing the strict definition of significance, it is interesting to note that the sign of the longitudinal turbulence component remains positive while the lateral component coefficient has a negative sign.

Insufficient data were available to reach any conclusions regarding the effects of direction on power output. As noted in the section on methodology the wind direction is related to atmospheric stability making it difficult to compare data across direction categories without interference. Another point of concern is the influence of the turbine wake on the tower
measurements. Data having wind directions less than 235 degrees are not used to avoid direct wake interference. It is possible, however, that some region outside the turbine wake may have flow which is accelerated around the turbine/wake obstruction. No documented evidence quantifying this effect was found, and it is assumed here that the effect is minor.
VIII. CONCLUSIONS

Flow conditions vary dramatically on a diurnal basis. Turbulence intensities are greater during daytime hours while the strongest speed and direction shears are observed during the night. A low level (=200') nocturnal jet is present in 10% of the test data. The data are from a relatively short time period (1.5 months) and are not expected to represent the full range of flow conditions at the site.

Average power curves obtained by the method of bins are not sensitive to the selected data averaging period, within the range of 2 minute to hourly data. The standard deviation of power observations within bins is a function of averaging period and may be used as an indicator in selecting an averaging period which minimizes spatial correlation problems while maintaining as many samples as possible. On this basis an averaging period of 20 minutes is chosen for the Mod-2.

For purposes of energy production estimation it is preferable to use data which have not been edited to remove start up and shut down cycles or times of marginal operation. In this analysis use of edited data resulted in an overprediction on the order of 5%. Accuracy in predicting energy capture would require measuring power delivered to the load, which would account for losses due to control system operation and electrical losses beyond the generator terminals. This distinction was not specifically addressed in this
study and all power data presented are measured at the generator output terminals.

Detailed analysis is limited to west winds (>235 degrees) and the midrange of wind speeds (17.5-29.5 mph). Within this range the magnitude of power fluctuation is independent of wind speed. Referring to the seven generic velocity profile classes, 20% of the data are distributed in the three auxiliary classes while the remaining 80% fall into the four main classes.

Within the main classes the two most influential parameters are turbulence intensity and directional shear, the magnitude of their effects being comparable. The evidence in support of turbulence effects is stronger with little practical difference between using the longitudinal or lateral component as the indicator. The power fluctuation may be summarized as follows: 50% of the data are near average, 25% (low directional shear, high turbulence intensity) are 50 kW above average and 25% (high directional shear, low turbulence intensity) are 50 kW below average.

The effects of speed shear on power are negligible for the range of shears observed. This suggests that the teetered hub feature of the Mod-2 is successful in alleviating speed shear effects. The variations of the disc average speed and the cosine of the yaw angle are small in the main classes. It appears that any effects on power from these parameters are overshadowed by other factors. The standard deviation of power is related to the
turbulence intensity and is therefore associated with increased power.

The auxiliary classes show trends which suggest that different mechanisms are operating under the less typical flow situations. No explanation is found for the fact that the two stable auxiliary classes maintain average power output despite relatively high directional shear, low turbulence intensity and low disc average wind speeds. The power output for the unstable auxiliary class appears to be adversely affected by relatively high yaw angles associated with the large values of lateral turbulence intensity. In hindsight the contradictory trends of the auxiliary classes were responsible for frustrating early attempts to analyze the data as a whole.

Insufficient data were available to reach any conclusions concerning the effects of direction on power output. The wind direction is related to atmospheric stability and therefore to both turbulence and shear levels. It was not possible to compare data across direction categories without interference from the other parameters.

Drawing from the results of this study the following recommendations for siting of machines similar to the Mod-2 are made. Wind speed should be measured directly at hub height or extrapolated using a set of diurnally varying speed ratios obtained at the site. Errors introduced in an extrapolation from low level data are likely to be the most serious encountered. At 20 mph a 10% error in estimated wind speed results in a 27% error in
estimated power. The data should be taken as close to the proposed site as possible. In complex terrain, sites separated by as little as 1/2 mile may show mean wind speed differences as large as 1-2 mph at the 200 foot level. Representative data should be obtained to assess the magnitude of the directional shear through the turbine layer and turbulence should be measured at hub height with particular attention to the lateral component during unstable conditions.

The present study represents a brief look at the interaction of flow conditions and power output for a specific site. Much more data from a wider range of conditions will need to be analyzed to fill in the puzzle.
BIBLIOGRAPHY


Bouwmeester, R.J.B., R.N. Meroney, and V.A. Sanborn, 1978: Sites for wind power installations — wind characteristics over ridges. DOE RLO-2438-78/2.


APPENDICES
APPENDIX A
Density Correction

The purpose of density correction is to remove a deterministic source of variability in power measurements. Data from various sites may be compared when observations are reduced to a reference density, usually standard sea level (1.225 kg/m$^3$). The correction is more appropriately applied to power at the rotor rather than to power at the generator or utility grid connection. This is simply a reflection of the fact that drive train losses are a function of power level but unaffected by atmospheric density.

The power data for the present study were measured at the generator, and must be converted to rotor power using an estimate of the drive train losses. Such an estimate for the Mod-2 was provided by Dr. R.E. Wilson as follows:

$$P_{\text{loss}} = 0.1768 + 0.0246 P_{\text{gen}} + 0.0098 P_{\text{gen}}^2$$

(1)

where power is in megawatts.

Now,

$$P_{\text{rotor}} = P_{\text{gen}} + P_{\text{loss}}$$

(2)

so,

$$P_{\text{rotor}} = 0.1768 + 1.0246 P_{\text{gen}} + 0.0098 P_{\text{gen}}^2$$

(3)

Multiplying by the density ratio (sea level/observed), corrected
rotor power is obtained. Using the quadratic formula, sea level generator power may be found from equation 3.

Thus the method is straightforward but does depend on an estimate of drive train losses. The question of whether the extra effort is worthwhile is best answered by comparing results with losses considered to results obtained by a simple ration correlation.

The two methods produce nearly identical amounts of correction at rated power, but somewhat different amounts at lower levels. This is due to the fact that losses are a large fraction of total power at low wind speeds. Table A1 gives the percentage difference in corrected power for various power levels and a comparison for three density ratios; 1.05, 1.087 and 1.15. The site density ratio for Goodnoe Hills is 1.087 while a ratio of 1.15 would be typical for a correction from 5000 feet or 1500 meters elevation to sea level. Thus the difference between the two methods is most pronounced at the low end of the power curve and for large density ratios.

From the viewpoint of energy capture the integrated difference in power would be very small. For purposes of detailed performance analysis the distortion at the low end of the power curve could be quite significant.
TABLE A1: PERCENT DIFFERENCE IN DENSITY CORRECTIONS WITH AND WITHOUT DRIVE TRAIN LOSSES.

<table>
<thead>
<tr>
<th>Site Power (megawatts)</th>
<th>Corrected Power Without Losses</th>
<th>Corrected Power With Losses</th>
<th>% Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density Ratio: 1.05</td>
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<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.105</td>
<td>0.109</td>
<td>3.5</td>
</tr>
<tr>
<td>0.2</td>
<td>0.210</td>
<td>0.214</td>
<td>1.8</td>
</tr>
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<td>0.5</td>
<td>0.525</td>
<td>0.529</td>
<td>0.7</td>
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<tr>
<td>1.0</td>
<td>1.050</td>
<td>1.053</td>
<td>0.3</td>
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<tr>
<td>1.5</td>
<td>1.575</td>
<td>1.580</td>
<td>0.2</td>
</tr>
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<td>2.0</td>
<td>2.100</td>
<td>2.100</td>
<td>0.1</td>
</tr>
<tr>
<td>2.5</td>
<td>2.620</td>
<td>2.620</td>
<td>---</td>
</tr>
<tr>
<td>Density Ratio: 1.087 (Good-noe Hills)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.109</td>
<td>0.115</td>
<td>5.5</td>
</tr>
<tr>
<td>0.2</td>
<td>0.217</td>
<td>0.224</td>
<td>3.2</td>
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<td>0.5</td>
<td>0.544</td>
<td>0.550</td>
<td>1.1</td>
</tr>
<tr>
<td>1.0</td>
<td>1.087</td>
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<td>0.6</td>
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<td>1.631</td>
<td>1.635</td>
<td>0.2</td>
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<td>2.174</td>
<td>2.177</td>
<td>0.1</td>
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<tr>
<td>2.5</td>
<td>2.718</td>
<td>2.718</td>
<td>---</td>
</tr>
<tr>
<td>Density Ratio: 1.15</td>
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<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.115</td>
<td>0.126</td>
<td>8.9</td>
</tr>
<tr>
<td>0.2</td>
<td>0.230</td>
<td>0.241</td>
<td>4.7</td>
</tr>
<tr>
<td>0.5</td>
<td>0.575</td>
<td>0.586</td>
<td>1.8</td>
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<tr>
<td>1.0</td>
<td>1.159</td>
<td>1.159</td>
<td>0.8</td>
</tr>
<tr>
<td>1.5</td>
<td>1.725</td>
<td>1.730</td>
<td>0.4</td>
</tr>
<tr>
<td>2.0</td>
<td>2.300</td>
<td>2.305</td>
<td>0.2</td>
</tr>
<tr>
<td>2.5</td>
<td>2.875</td>
<td>2.875</td>
<td>---</td>
</tr>
</tbody>
</table>

* % difference of corrected power without losses compared to corrected power with losses.
APPENDIX B

Estimation of upper level speed and direction

Turbine 3 was chosen for detailed analysis due to lack of wake interferences and the favorable location of the BPA meteorological tower. However, this tower is 195' tall with instruments at 50' and 195'. Adequate characterization of flow conditions through the rotor disc could not be realized without some idea of speed at the 350' level. There is inherent uncertainty in forming such an estimate but a method was devised which hopefully minimizes the errors. Unfortunately no check can be made on the procedure.

The rationale is as follows: The PNL 350' speed is available but this alone may be a poor estimate. Incorporation of hub height information should improve the results. Three simple predictors are considered in making the estimate and a consensus formed. The first guess is that the speed at the 350' level will be identical at the two locations. The second guess asserts that the ratio of speeds (350/200) is identical while the third guess is obtained by applying the difference in hub height speeds at the two towers to the PNL 350' observation. In equation form,

\[
V_{350}^{\text{BPA}} = \frac{1}{3} \left( V_{350}^{\text{BPA}} + \left( \frac{V_{350}^{\text{PNL}}}{V_{350}^{\text{BPA}}} \right) V_{200}^{\text{BPA}} \right) \\
+ \left( V_{200}^{\text{BPA}} - V_{200}^{\text{PNL}} + V_{350}^{\text{PNL}} \right)
\]
Direction is obtained in a similar way using the average of two predictors. In equation form:

\[ D_{350_{\text{BPA}}} = \frac{1}{2} (D_{350_{\text{PNL}}} + D_{200_{\text{BPA}}} + (D_{350_{\text{PNL}}} - D_{200_{\text{PNL}}}) ) \]

Turbulence intensity is taken to be the same at both towers.

To give an idea of how this estimation works, Table Bl shows average values for the entire data set for both towers and also six examples for hourly data. Estimated values are marked with an asterisk.
### TABLE B1: METEOROLOGICAL TOWER DATA COMPARISON

<table>
<thead>
<tr>
<th>Date/Hour</th>
<th>Wind Speed (mph)</th>
<th>Wind Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50'</td>
<td>200'</td>
</tr>
<tr>
<td>All Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>16.5</td>
<td>22.8</td>
</tr>
<tr>
<td>BPA</td>
<td>16.4</td>
<td>23.2</td>
</tr>
<tr>
<td>275 / 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>14.3</td>
<td>17.7</td>
</tr>
<tr>
<td>BPA</td>
<td>15.6</td>
<td>18.6</td>
</tr>
<tr>
<td>275 / 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>19.3</td>
<td>24.2</td>
</tr>
<tr>
<td>BPA</td>
<td>18.8</td>
<td>24.4</td>
</tr>
<tr>
<td>275 / 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>15.9</td>
<td>21.5</td>
</tr>
<tr>
<td>BPA</td>
<td>14.7</td>
<td>21.3</td>
</tr>
<tr>
<td>275 / 21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>13.1</td>
<td>20.1</td>
</tr>
<tr>
<td>BPA</td>
<td>12.7</td>
<td>20.6</td>
</tr>
<tr>
<td>275 / 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNL</td>
<td>14.1</td>
<td>21.2</td>
</tr>
<tr>
<td>BPA</td>
<td>13.5</td>
<td>20.9</td>
</tr>
<tr>
<td>276 / 3</td>
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<td></td>
</tr>
<tr>
<td>PNL</td>
<td>11.3</td>
<td>18.0</td>
</tr>
<tr>
<td>BPA</td>
<td>11.8</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Asterisks denote estimated values
APPENDIX C

Method of Bins

The statistical aspects of the method of bins have been investigated by several researchers, notably Aikins (1978), Hausfeld and Hansen (1983) and Frandsen and Christensen (1980). Their work points out a statistical bias inherent in the bin sorting process. Simultaneous observations of power and wind speed can be modeled as a bivariate normal random process. Under this assumption each speed bin contains a slice of the bivariate distribution and the points in each of these slices are normally distributed. Therefore, the mean in each bin coincides with the point of tangency to the isoprobability lines (Figure C1). Connecting the points from adjacent bins with a line gives the estimated average curve, line S in the figure. This line would also correspond to the least squares line through the distribution with speed as the independent variable. This implies that the true mean power is underestimated at higher wind speeds while at the low end it is overestimated. However, the magnitude of this effect is related to the degree of noncoherence. That is, the results obtained from a process having a narrower distribution will be nearer the true values (Figure C1). An alternative view is obtained by considering power as the independent variable. The least squares line for speed based on power is labeled P in the figure.
FIGURE CL: BIVARIATE NORMAL PROBABILITY DISTRIBUTIONS
Figure C2 shows two power curves, one from wind speed bins, the other from power bins. If bias is present the two curves should be divergent at the ends. The lack of divergence allows one to conclude that the observed shape of the power curve is due to real effects such as aerodynamics or control system behavior rather than statistical bias.
TURBINE NO. 3
HOURLY AVERAGES - SELECTED DATA

REFERENCE CONDITIONS:
ELEVATION: SEA LEVEL
DENSITY: 1.225 kg/m³

FIGURE C2: COMPARISON OF POWER CURVES USING SPEED BINS AND POWER BINS
Power Curve Data for Statistical Comparison of Speed Bins and Power Bins

<table>
<thead>
<tr>
<th>SPEED BINS</th>
<th>POWER BINS</th>
</tr>
</thead>
<tbody>
<tr>
<td># OBS</td>
<td>WIND SPEED (MPH)</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
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<td>11</td>
<td>23</td>
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<td>7</td>
<td>24</td>
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<td>12</td>
<td>25</td>
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<td>8</td>
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<td>34</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>0</td>
<td>37</td>
</tr>
</tbody>
</table>

Based on hourly averages

FIGURE C2a: DATA FOR FIGURE C2.
Calculation of a disc average velocity is conveniently separated into two parts. The first involves generating a speed for any required height within the disc by means of an interpolation function. The second part consists of integrating the velocity over the entire disc, in this case assuming no horizontal variation of speed and equal aerodynamic contribution from all parts.

The requirements of the interpolation are to fit a smooth curve through the three data points (50', 200', 350') and to avoid introducing any spurious shapes. Linear interpolation between points is a possibility, however, boundary layer theory and observations indicate that a log profile is more appropriate.

\[ V = A \ln \left( \frac{Z}{Z_0} \right) \]  
\[ V = A \ln Z - B \]

where \( A \) is a constant related to surface shear stress and \( Z_0 \) is the roughness length. Relaxing the definitions of the constants, they may be used as parameters to fit the curve. Equation 1 may be rearranged

\[ V = A \ln Z - B \]

where

\[ B = A \ln Z_0 \]
The log fit will work in most cases but there are times when the 350' speed is less than the hub height value, indicating a low level jet. Using a normalized composite jet shape (Mahrt et al., 1979) it was possible to obtain empirically a function which approximated the deviation of the jet from a log profile. This is of the form

\[ V = c \left( \frac{Z/Z_j}{1 + (Z/Z_j)^4} \right) \]

which has a maximum near \( Z/Z_j = 0.75 \). Thus to fit a jet at the 200' level \( Z_j = 265' \). Adding the jet term to the log equation, we have a three parameter model for the speed profile.

\[ V = a \ln Z + b + c \left( \frac{Z'}{1 + Z'}^4 \right) \]

where \( Z' = \frac{Z}{Z_j} = \frac{Z}{265} \).

Figures D1 through D4 show examples of the fit through a range of observed velocity profile shapes.

The numerical integration is carried out by summing contributions from 15 horizontal slabs, each slab having a precalculated weight based on its areal contribution.
FIGURE D1: INTERPOLATION FIT, EXAMPLE 1
FIGURE D2: INTERPOLATION FIT, EXAMPLE 2
FIGURE D3: INTERPOLATION FIT, EXAMPLE 3
FIGURE D4: INTERPOLATION FIT, EXAMPLE 4
APPENDIX E

Yaw Angle

This appendix contains a discussion of the results from a brief analysis of the effect of yaw on power output obtained by treating yaw as the signed angle rather than considering the cosine of the yaw angle. The cosine was used to approximate turbine response and to eliminate cancellation of positive and negative angles within an averaging period. Here, the signed angle is used, in view of the interactive effects between yaw and teeter which suggest that the turbine responses to positive and negative yaw angles are qualitatively different. The sign conventional employed results in positive yaw when the azimuth of the wind direction is greater than the azimuth of the nacelle.

Table E1 gives the average yaw angle and standard deviation for each of the velocity profile classes. The angles are most often positive and the largest values are found in the auxiliary classes. The standard deviations are fairly uniform in the four main classes, lowest for the stable auxiliary classes (1A and 3A) and highest for the unstable auxiliary class (2A). Comparing the yaw data to power offsets no clear trend is visible.

As a further test, the data are sorted into five levels of the yaw angle as shown in Table E2. Again, comparing the power offsets for various ranges of yaw, no trend is apparent.
TABLE E1: AVERAGE AND STANDARD DEVIATION OF THE YAW ANGLE BY CLASS.

<table>
<thead>
<tr>
<th>Class</th>
<th>Number of Observations</th>
<th>Power Offset (kW)</th>
<th>Yaw Angle (Degrees)</th>
<th>Std. Dev. (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>19</td>
<td>-9</td>
<td>5.6</td>
<td>2.7</td>
</tr>
<tr>
<td>2A</td>
<td>20</td>
<td>-101</td>
<td>2.4</td>
<td>8.6</td>
</tr>
<tr>
<td>3A</td>
<td>17</td>
<td>-19</td>
<td>3.7</td>
<td>3.1</td>
</tr>
<tr>
<td>1</td>
<td>87</td>
<td>+29</td>
<td>1.3</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>-5</td>
<td>0.4</td>
<td>4.3</td>
</tr>
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<td>3</td>
<td>26</td>
<td>+68</td>
<td>1.0</td>
<td>4.6</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>-30</td>
<td>-1.1</td>
<td>3.8</td>
</tr>
<tr>
<td>All</td>
<td>283</td>
<td>+1</td>
<td>1.2</td>
<td>4.6</td>
</tr>
</tbody>
</table>

TABLE E2: POWER OFFSET FOR FIVE LEVELS OF YAW ANGLE.

<table>
<thead>
<tr>
<th>Yaw Angle Range</th>
<th>Power Offset (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than -2.7°</td>
<td>-2 kW</td>
</tr>
<tr>
<td>-2.7° to 0.1°</td>
<td>+3 kW</td>
</tr>
<tr>
<td>0.1° to 2.4°</td>
<td>-13 kW</td>
</tr>
<tr>
<td>2.4° to 5.2°</td>
<td>+12 kW</td>
</tr>
<tr>
<td>Greater than 5.2°</td>
<td>+2 kW</td>
</tr>
</tbody>
</table>
Thus the present data indicate that the effects of yaw are either negligible or overshadowed or other variables such as turbulence or directional shear. One exception to this conclusion is noted in the discussion section of the main text in regard to the unstable auxiliary class (2A).
APPENDIX F

Velocity Profile Class Separation

The logic used in partitioning the data into the various profile classes is specific to the data used in this study. The objective of the separation is to form distinct groups representing the range of observed flow conditions. The main variables used as criteria are upper speed ratio, speed shear factor, directional shear factor and lateral turbulence intensity. Tests for the more distinct auxiliary classes are performed first, then classes 3 and 4, and finally classes 1 and 2. Thus classes 1 and 2 are central to the data and consist of samples which do not fit the more exacting requirements of the other classes.

In general, each separation is based on a set of criteria involving speed ratios, turbulence and directional shear. In some cases, when one of the criteria is not satisfied, the other criteria are retested at a more restrictive level. In Figure F1, for example, in order to be assigned to class 2A, the lateral turbulence intensity must be greater than or equal to 0.08, the upper speed ratio must be less than or equal to 1.01 and the directional shear factor should be less than 7 degrees. However, if the directional shear factor is more than 7 degrees, the sample may still be assigned to class 2A provided the turbulence intensity is greater than 0.09. Further velocity profile class separations are given in Figures F2 and F3.
FIGURE F1: VELOCITY PROFILE CLASS SEPARATION, AUXILIARY CLASSES.
FIGURE F2: VELOCITY PROFILE CLASS SEPARATION, CLASS 3,4.
FIGURE F3: VELOCITY PROFILE CLASS SEPARATION, CLASS 1,2.
The particular values used are not very important, as they depend on the range of values observed in a given data set. Many of the criteria are based on whether a particular value is less than or greater than the average of that variable. Development of a classification scheme is a trial and error process. The scheme presented here is preliminary in the sense that primary importance is given to speed ratios whereas subsequent analysis shows that other variables are more important. The primary accomplishment of this separation is the identification of the auxiliary classes which allows the main data to be analyzed separately.