LARGE HAWT WAKE MEASUREMENT AND ANALYSIS

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ABSTRACT

From the theoretical fluid dynamics point of view, the wake region of a large horizontal-axis wind turbine has been defined and described, and numerical models of wake behavior have been developed. Wind tunnel studies of single turbine wakes and turbine array wakes have been used to verify the theory and further refine the numerical models. However, the effects of scaling, rotor solidity, and topography on wake behavior are questions that remain unanswered.

In the wind tunnel studies, turbines were represented by anything from scaled models to tea strainers or wire mesh disks whose solidity was equivalent to that of a typical wind turbine. The scale factor compensation for the difference in Reynolds number between the scale model and an actual turbine is complex, and not typically accounted for. Though it is wise to study the simpler case of wakes in flat topography, which can be easily duplicated in the wind tunnel, current indications are that wind turbine farm development is actually occurring in somewhat more complex terrain.

Empirical wake studies using large horizontal-axis wind turbines have not been thoroughly composited, and, therefore, the results have not been applied to the well-developed theory of wake structure. The measurement programs have made use of both in situ sensor systems, such as instrumented towers, and remote sensors, such as kites and tethered, balloon-borne anemometers.

We present a concise overview of the work that has been performed, including our own, which is based on the philosophy that the MOD-2 turbines are probably their own best detector of both the momentum deficit and the induced turbulence effect downwind. Only the momentum deficit aspects of the wake/machine inter-actions have been addressed. Both turbine power out-put deficits and wind energy deficits as measured by the onsite meteorological towers have been analyzed from a composite data set. The analysis has also evi-denced certain topographic influences on the operation of spatially diverse wind turbines.

INTRODUCTION

For wind turbines to make up a significant part of the world's energy generation capability, large clusters of turbines will have to be installed. Since the land area available for such installation is limited, not necessarily by the availability of wind but rather by physical, social, economic and operational constraints, future wind turbine clusters will have to be sited so that maximum utilization of the available land is achieved. The distances between turbines will be governed by factors that include the complexity and geomorphology of the local terrain and the relation-ship of this to the prevailing energy-producing wind. In a steep-sided valley through which the wind blows practically unidirectionally, rows of turbines normal

to the prevailing wind may be erected with lateral separations of only a few diameters. Longitudinally, however, there will be many more rigorous constraints. The second echelon of turbines must be placed suffi-ciently downstream so that wake effects are minimized. Wakes have two effects on turbine operation. First, the wake created by an upwind turbine manifests itself as a momentum deficit to downwind turbines, thereby affecting the apparent energy capture of the downwind turbines. Second, the induced turbulence created by the upwind turbine may have a significant effect on the long-term structural and aerodynamic loads at down-wind turbines and hence increase maintenance or reduce turbine life.

Previous wind turbine wake studies have concentrated on case studies where the field program is specifi-cally set up to make measurements during relatively short periods of time. These measurements actually provide only a quick snapshot of the wake. A tech-nique of data analysis referred to as "binning" was applied to the Goodnoe Hills test site data. In the meteorological community, the process is called compositing where all the appropriate cases are binned according to a (or several) dependent parameters.

CURRENT STUDIES

Data collection at the Goodnoe Hills Candidate Site began long before the actual installation of the MOD-2 turbines. Since then, the PNL Distributed Data System (DDS), a minicomputer-based data acquisition system, was developed and has evolved and routinely collects meteorological data and turbine operating data. Table 1 presents a list of the parameters for which data have been collected. In the current con-figuration, the system is limited to collecting a maximum of eight turbine parameters from each turbine. (This capability is soon to be expanded to 64 parame-ters.) These data and their standard deviations are collected at a rate of once every 2 minutes. The standard deviation is based on 120 one-second samples. The DDS is capable of sampling data from all these channels at a rate of several samples per second if needed.

The Goodnoe Hills test site is located adjacent to the Columbia River gorge on the south-central border of Washington State. The site elevation is about 2600 ft MSL. In general terms the site appears to be on a broad, gently rolling plane. Figure 1 is a computer-generated, three-dimensional, isometric plot of the site topography looking from aloft to the northeast. As can be seen, the site terrain is actually far from simple. Figure 2 shows the site in plan view and on a much smaller scale. The site was laid out with the turbines placed in an array with separation distances of 5, 7 and 10 diameters. The axis between any pair of turbines was determined to be a climatologically high wind azimuth so that there would intentionally be some possibility of the wake

from one of the turbines impacting one of the others. Historically, significant periods of strong winds occur on azimuths of about 200°, 255° and 280°.

TABLE 1. Data Parameters Collected at the Goodnoe Hills Test Site

PNL Tower:

1) wind direction at 33 ft
2) wind direction at 50 ft
3) wind direction at 200 ft
4) wind direction at 350 ft
5) wind speed at 33 ft
6) wind speed at 50 ft
7) wind speed at 200 ft
8) wind speed at 350 ft
9) temperature at 33 ft
10) temperature difference between 350 ft and 33 ft
11) air flow at 33 ft
12) air flow at 350 ft
13) pressure at 200 ft
14) u-component at 200 ft
15) v-component at 200 ft
16) w-component at 200 ft

BPA Tower:

1) wind speed at 50 ft
2) wind direction at 50 ft
3) wind speed at 195 ft
4) wind direction at 195 ft
5) temperature at 50 ft
6) pressure at ground
7) ice detector
8) u-component at 200 ft
9) v-component at 200 ft
10) w-component at 200 ft

Turbine #1, #2, #3:

1) field current
2) generator power
3) utility power
4) generator voltage
5) rotor speed
6) blade #1 pitch
7) yaw error
8) nacelle position

Figure 2--Large-scale map of the Goodnoe Hills test site with 50-ft contours shown

Turbulence at the site has been qualitatively characterized as moderate to strong when the wind is from any one of the prevailing wind directions. As a more quantitative measure, a quantity known as the turbulence intensity was calculated using an entire year's site data. Plots of the resulting analyses are given in Figures 3 and 4. For this analysis the data were not stratified by atmospheric stability. The authors recognize that such a stratification would provide useful information. However, since the analysis was based on the equivalent of 1-s data, the results should evidence worst-case conditions. All the data in each of 72 5°-bins were averaged individually. The turbulence intensity, I, is equal to the RMS of the eddy velocities divided by the mean wind speed:

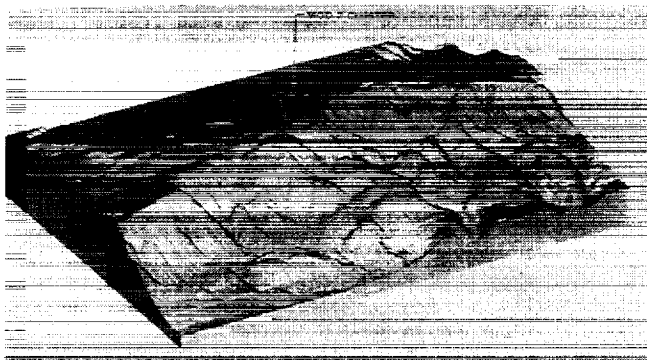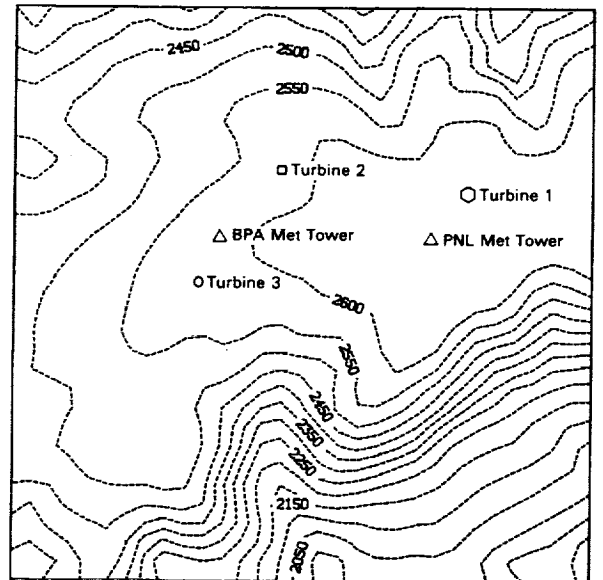$$I = \frac{\sqrt{\overline{u'^2}}}{\overline{U}}$$ (1)

Figure 1--Computer-generated view of the topography at the Goodnoe Hills test site showing the locations of the three turbines. Base dimensions of the map are 4 by 5.5 miles.
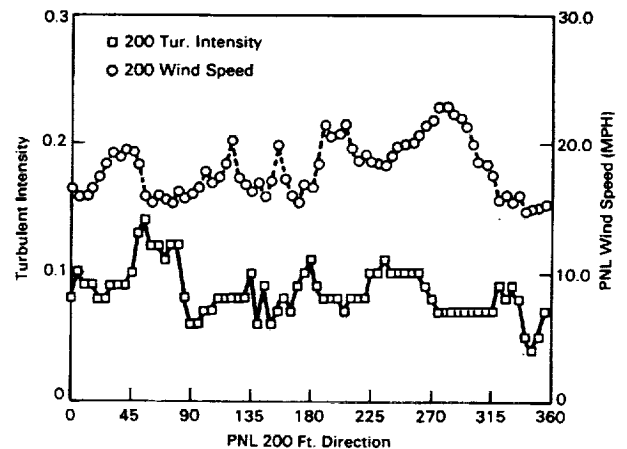

Figure 3--Long-term turbulence intensity versus wind direction measured at the 200-ft level on the PNL meteorological tower
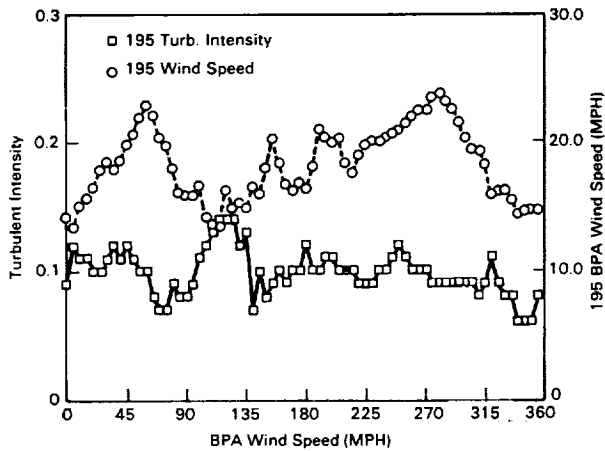
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Figure 4--Same as Figure 3 but from the 195-ft
level at the BPA tower

Interpretation of Figures 3 and 4 should be approached
with caution. The increased turbulence intensity at
the PNL tower between 45° and 90° and the marked reduc-
tion in wind speed are artifacts associated with the
wind shadow cast by the tower. Similarly, in Figure 4,
the increased turbulence intensity and reduced wind
speed at about 110° show the same effect at the BPA
tower, which was installed with a different rotation
than the PNL tower. Figure 5 illustrates the effect
of tower shadow on the measurement of wind speed. In
the quadrant between approximately 45° and 135°, any
comparison of the winds at the two towers should be
viewed with caution. The first major dip in the data
is the effect of the PNL tower shadow on its anemom-
eter while the large peak following represents the
effect of the BPA tower shadow on its anemometer.
Regardless of these discrepancies, the reader can
easily see that for either tower, the average turbu-
lence intensity at hub height is on the order of 0.1.
The climatological mean wind speed at the site is
15.3 mph. The Z_0 is roughly 0.05 m, which is expected
in open, rolling, brushy or crop land. The turbulence
intensity is an indication of a physical phenomenon
that plays an important role in the lateral reentrain-
ment of momentum as well as the spread of a turbine
wake.

Data collected by the DDS in the period from August
through mid-November 1982 were used in this study.
The period was restricted because multiple turbine
data as well as meteorological data were not available
until then. Turbine #2 parameters were not connected
until mid-October. The data were cleaned up and
screened and a special data set was created specifi-
cally for this wake study. In screening the data
three criteria were used to qualify the data for inclu-
sion. First, at least one turbine had to be running.
This was determined by discriminating on the basis of
rotor rpm, nacelle direction and power out. Second,
the wind, as measured at the PNL tower, had to be from
a direction that would cause the turbine wake to fall
on either another turbine or one of the meteorological
towers. Data from each azimuth angle from one turbine
to each of the others or the towers ±30° were incorpo-
rated. Third, single values that were judged to be
noise rather than data and periods that escaped ear-
lier detection but were actually times when the tur-
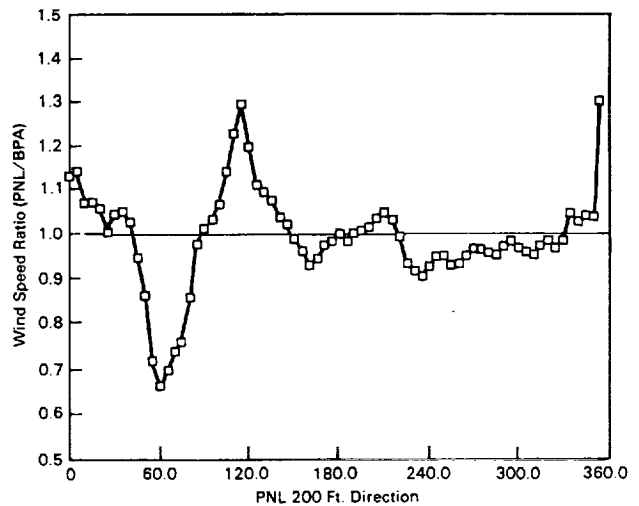bine parameter sensors were being calibrated were
eliminated.

Figure 5--Time-consistent plot of the wind speed
ratios measured at the two towers clearly
showing the effects of tower shadow on
wind speed

Since the MOD-2 turbines are actually huge anemometers
in themselves, our concept was to use the turbines as
the primary sensors. To check that the transfer func-
tions of wind speed to power were the same for both
turbines, all turbine power-out data from both
turbines #1 and #3 were binned into 50 power classes
for comparison to the wind speeds measured simulta-
neously at each tower. Figures 6 and 7 show the
results of that exercise. In both cases, turbine #1
appears to out-produce turbine #3 at up to about
design speed. Then, the reverse occurs. Whether this
phenomenon is real or whether it is a calibration
error has yet to be determined. In analyzing the com-
posite data, power ratios were the calculated indica-
tor of the sought-after wake effects. The turbine
power transfer function cross-over at about design
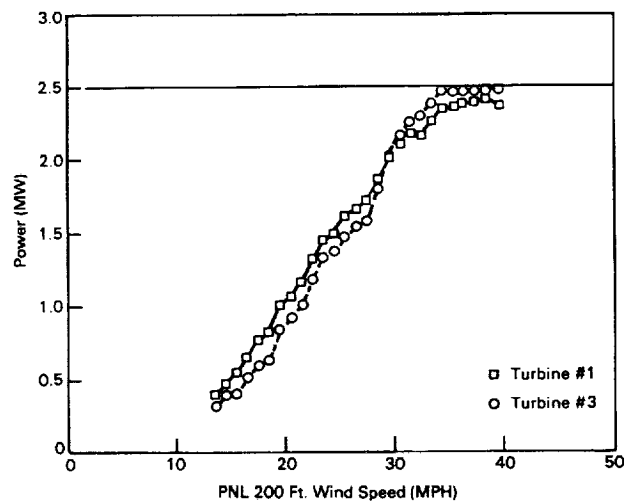speed may consequently be the cause of some of

Figure 6--MOD-2 #1 and #3 wind speed to power
transfer function using the wind
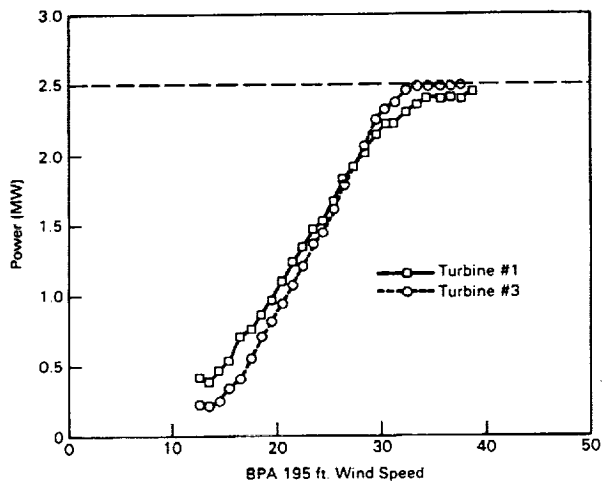speed measured at the PNL tower

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Figure 7--Same as Figure 6 except using the wind
speeds measured at the BPA tower

the variance noticed in the various cases. Further
analyses based on stability, wind direction, etc. is
currently being pursued and the results will soon be
available.

RESULTS

When the first graphs of the screened data were plot-
ted, the result we had anticipated was not realized.
Figure 8 shows the individual data points for the
power ratio of upwind turbine power to downwind tur-
bine power versus azimuth angle. Although there is a
moderate hint of an effect, no firm conclusion could
be drawn. These data were then subjected to further
averaging, or binning, by azimuth angle. That is,
they were averaged by 1° azimuth bins with the result
shown in Figure 9. The individual data points in this
plot are now the average of the data shown in Figure 8.
The curved-fit line is a cubic spline fit to the data.
It will be noticed that the minimum in the power is
both above the power ratio = 1 line and offset to the
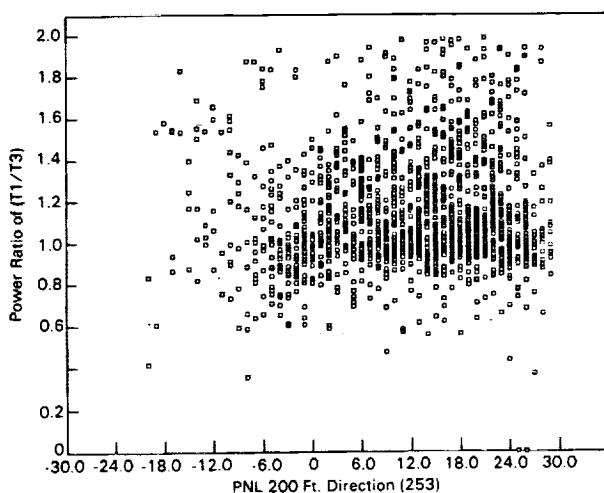left. The vertical offset simply implies that for an

Figure 8--Turbine #1 and turbine #3 power ratio for
all cases when the axis of the wake of
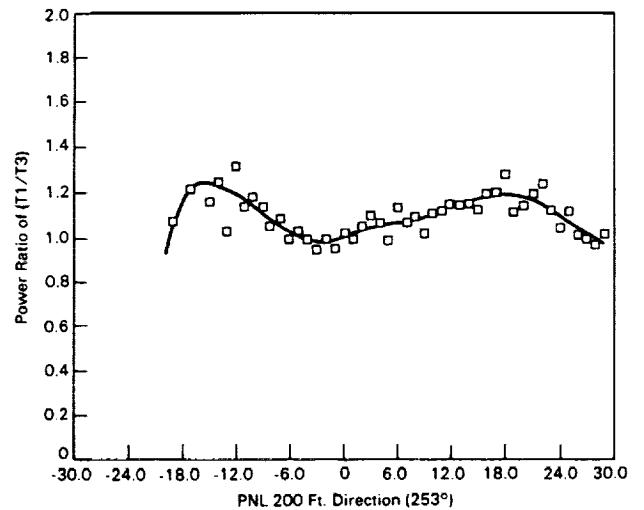turbine #3 was in line with turbine #1

Figure 9--Same as Figure 8 but with all data in each
1° bin averaged. The solid line is a cubic
spline fit to the data.

assumed uniform wind field over the entire test site,
turbine #1 was out-producing turbine #3. The 200-ft
or hub-height wind at the PNL tower was the reference
wind in these studies. Since there is no stratifica-
tion based on power classes, the offset implies that
the baseline should be near the turbine power ratio
of 1.2 rather than 1. The horizontal offset to the
left might be taken lightly as the actual true angle
between turbines #1 and #3 was not accurately measured
before the analysis. We will discuss this further
later. Thinking that the scatter of the data about
the cubic spline fit might be explained if the data
were stratified by power class, we subdivided the data
into as many 500-kW bins as was practical and per-
formed further analyses. Figures 10 through 13 show
the results of that stratification. It should be
pointed out that the data were screened further for
these analyses and the minimum acceptable power was
500 kW.

Figure 10 is the same as Figure 9 but with the 500-kW
cutoff and some other identified spurious data removed.
Left of the -10° point on the graph, the data repre-
sent the average of less than 10 data points and might
thereby be discounted. On the right-hand side of the
graph, the data are all averages of more than ten
values and frequently the average of 40 to 50 2-min
average data. The result reinforces the point that
at 10 diameters an average 15% power deficit can be
expected.

Figure 11 is the composite or average data for all
cases in the wake data set when the power out of
turbine #3 was between 500 kW and 1 MW. Significantly
more scatter is evident in the data but is attribut-
able primarily primarily to fewer primary data points.
In only one 1° data bin were there more than 10 data
points to be averaged. This suggests that the promi-
nent dip of the spline fit line out at -8° to -10° is,
in fact, artificial and that the real wake deficit may
be exemplified by the adjacent plateau to the right
of the null. Based on the number of data points aver-
aged, the baseline power ratio for this power class
might best be assigned to about 1.27, or turbine #1
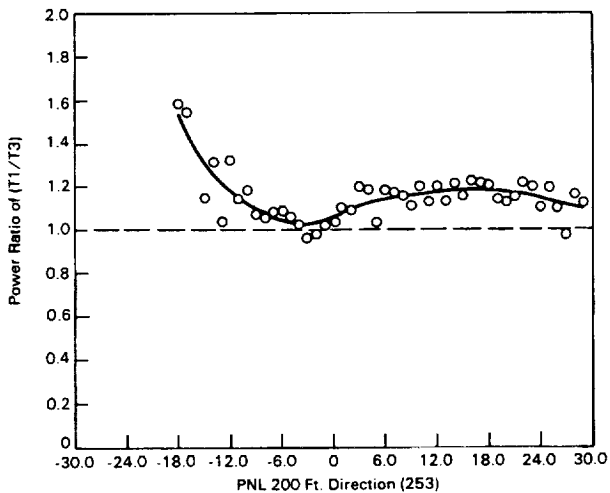producing about 20% more power than turbine #3.

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Figure 10--Same as Figure 9 with the minimum
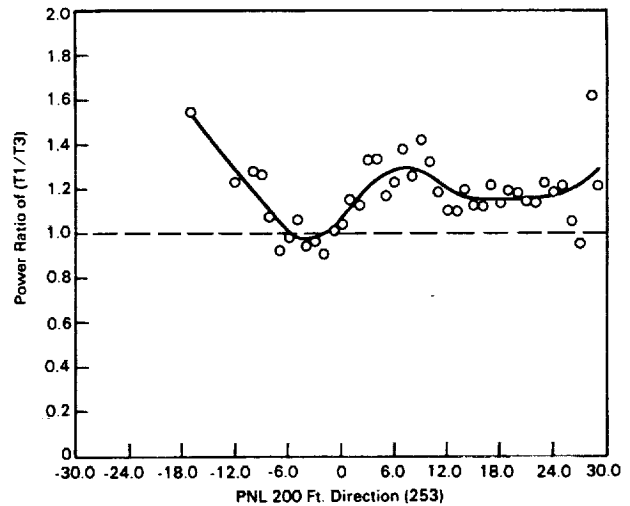power set to 0.5 MW

Figure 12--Same as Figure 9 but for those cases
when the power out of turbine #3 was
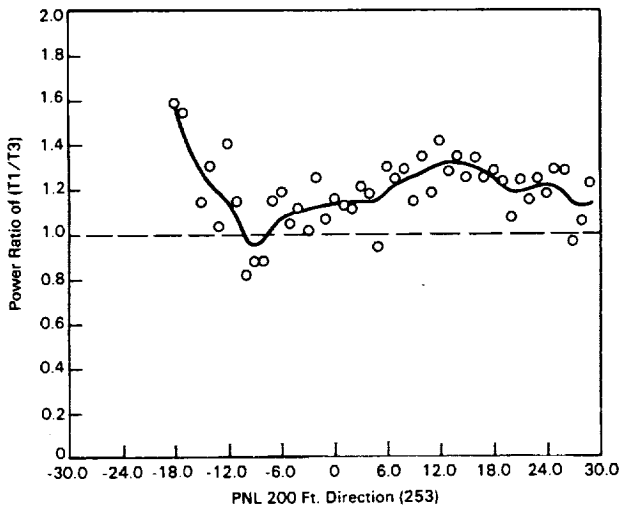between 1.0 and 1.5 MW

Figure 11--Same as Figure 9 but only for time when
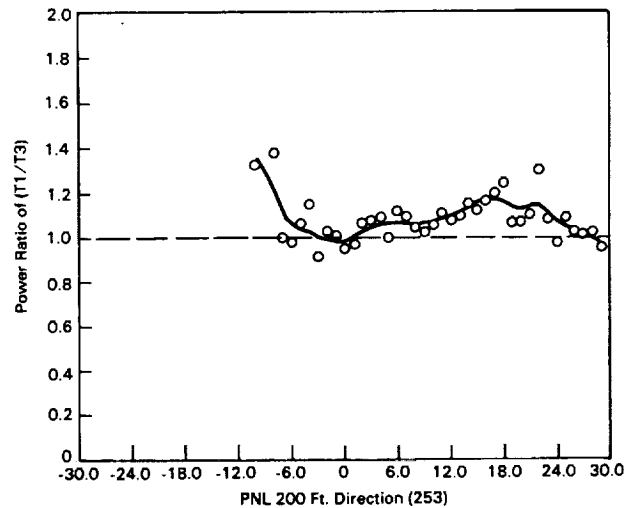the power out of turbine #3 was between
0.5 and 1.0 MW

Figure 13--Same as Figure 9 except the power out
of turbine #3 was anything greater than
1.5 MW

Figure 12 is the result for the data in the power
class 1.0 to 1.5 MW. In this case there were about
25% more data for the entire set and for the most part
there were more data in the bins of most importance.
The nearly straight line in the 15° to 24° area on the
right side of the graph is probably a reasonable
approximation of the baseline for comparison. If this
is so, then the deficit at the center is close to 20%.
The large increase in the power ratio immediately to
the right of the wake centerline is not felt to be the
result of lateral reentrainment of momentum but rather
a decrease in the number of data points averaged
(higher variance).

The final power class had to include data from 1.5 to
2.5 MW to provide sufficient data for meaningful analy-
sis. Figure 13 shows this data. In this power class
we estimate the power ratio baseline to be about 1.1
and, therefore, the wake deficit for this high power
class has been reduced to 11 or 12%. If Figures 10
through 13 were superimposed, one would observe an

interesting, and at this point unexplained, shift or
migration of the region of maximum wake deficit to the
right or northward, nearer the assumed centerline
azimuth. Similarly, with increased power out the
effect of the wake is apparently reduced. The lateral
migration may be caused by the flow separating from
the surface boundary layer at the higher wind speeds,
and thereby reducing the ground effect or surface
stress.

Although the evidence for a power reduction of the
order of 15 to 25% at turbine separation distances of
10 diameters is shown by Figures 9 through 13, one
must keep in mind Figure 8, which showed that the
standard deviation about that average was very high
indeed and that such a deficit is not constant by any
means.

To illustrate any effect that can be discerned at
closer separations, a small amount of data was

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obtained with turbine #2 running and, ostensibly, producing a wake that was impacting turbine #1. These data were included in the wake data set and were analyzed similar to the previously discussed data. Because there were not enough data points, no power class stratification could be accomplished. The resulting analysis is depicted in Figure 14. In this graph, unlike the others, the centerline was fixed at an arbitrary azimuth that roughly splits the angle between turbine #2 and #3 with the vertex at turbine #1. From this, the baseline power ratio appears to be just below 1.0. In this case a power ratio of less than 1 infers that turbine #2 is producing more power at the reference wind speed than is turbine #1. The data at the right end of the graph (where the 276 is marked on the abscissa) represent the wake deficit of turbine #2 as seen by turbine #3. The magnitude of the deficit is about 11 or 12%, and the distance between the two turbines is 7 diameters.

Figure 15--The ratio of measured wind speeds at the PNL and BPA towers with the PNL tower in the wake of turbine #3
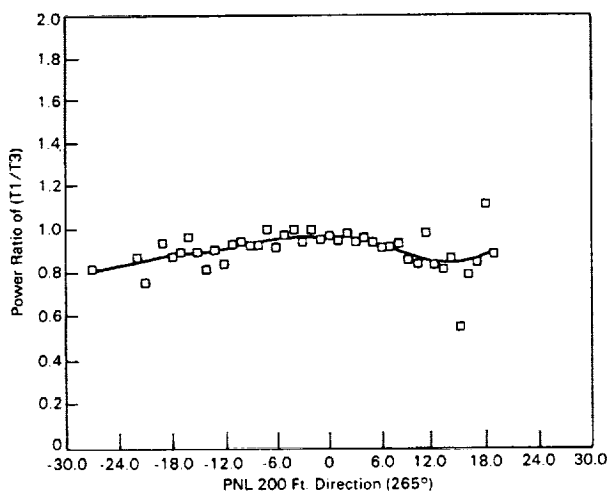

Figure 14--The power ratio of turbines #2 and #1 with the wake of turbine #2 depicted at about 12° to 14°. Some of the data used occurred with all three turbines running and some slight effect of turbine #3's operation can be inferred from the lefthand part of the plot.

Figure 16--Wind speed ratio of the PNL and BPA measured wind speeds during the occurrence of a wake from turbine #1 at the PNL tower

In performing these analyses we have attempted to utilize as much data as possible from the Goodnoe Hills test site. As mentioned earlier, the decision to use the MOD-2 wind turbines as the primary sensors for the wakes analysis does not preclude us from looking at other data. There are periods of time when the turbines were running and producing wakes that impacted the meteorological towers. When the wind blows from the WSW to WNW the wake of turbine #3 should be monitored by the instrumented PNL tower. By screening our data in the appropriate manner, we were able to pick out the wake. Figure 15 is a cubic-spline fit to the bin-averaged wind speed data for periods when turbine #3 was running and the wind was from 260° ±30°. On this graph we have plotted the ratio of the measured wind speeds on the ordinate as opposed to the power ratio. The wind speed deficit at the distance of 8.3 diameters (turbine #3 to the PNL tower) is about 20%.

Figure 16 is another example of a turbine wake inter-acting with the PNL tower. In this instance, the wake-
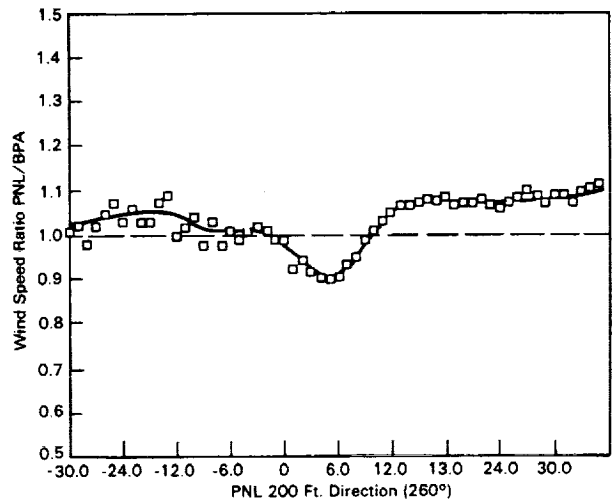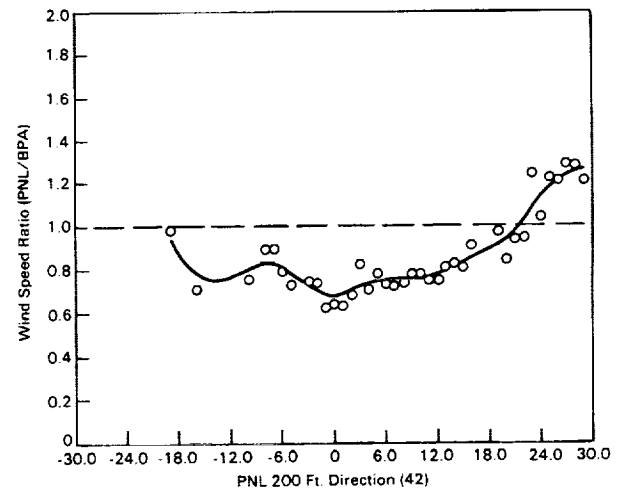
producing turbine is #1 and the separation distance is only 2.2 diameters. The wind speed deficit, again taking into account the difference in measured wind at the two towers, appears to be approximately 45 to 50%.

How well do these observations compare with other mea-sured wake data? Several researchers have made wake measurements at the MOD-OA at Clayton, New Mexico. Wind speeds in the wake of the turbine were monitored at a vertical plane array two diameters downwind (1). The array consisted of seven 200-ft towers with 12 fast-response anemometers arranged in a circle whose diameter equalled the turbine rotor diameter. Inside this circle was a horizontal line of 5 additional ane-mometers at hub height. The maximum deficit measured in the case analyzed was 25%. Later, the researchers added a pair of towers to the Clayton site approxi-

mately two diameters away from the MOD-OA on the same azimuth but on the other side of the turbine relative to the seven-tower array (2). Although the authors do not summarize their data, it appears that in the transition region of the wake outside the potential core, the typical deficits that were measured ranged from 25 to 50%, with the greater deficits occurring at the lower mean wind speeds. In identifiable far-wake instances, the deficit measured ranged from 20 to 30%. In these cases also, the larger deficits occurred at the high wind speeds.

SUMMARY AND CONCLUSIONS

Comparison of these study results to current numerical wake models (3,4,5,6) have not been completed. Results are of such a preliminary nature that reporting them here might serve only to do a disservice to both the data analyses and the models. The authors are resolved to complete this work and believe that the data base created will prove to be ultimately useful.

To the best of our knowledge, this is the first opportunity anyone has had to gather, process and analyze wind turbine wake data in this manner. One of this study's major shortcomings is the fact that we currently suffer from a paucity of data when we should have an abundance. This should not be construed as an excuse. The lack of data from a program depending on prototypical equipment (both the data system as well as the turbines) is normal. Since the data would be collected normally, the project becomes time-dependent and in some ways time-intensive but not labor-intensive.

Since the wind is stochastic in nature, attempting to define the structure of a turbine wake with spatially and temporally small samples required by labor-intensive methods is not only tedious but potentially quite inaccurate. The utility of the more labor-intensive methods is potentially in verifying measurements such as we have made at the site. Verification of the possible boundary layer effects on the curvature of the wake as a function of wind speed and/or power extraction would be most difficult and expensive as well as frustrating were it to be attempted with a labor-intensive method.

As mentioned above, the nature of the wind is stochastic in both speed and direction. Many observers or researchers have commented that the wakes and hence the flow at the Goodnoe Hills Test Site do not necessarily go in a straight line. In analyzing the wake data set, indications of this anastomosing phenomenon do not leap out but conversely there are indications of flow veering or backing under some, as yet undefined, circumstances. The wake research program at PNL is part of a larger program involved with atmospheric and topographic influences on wind flow. It is our intention to proceed with both of these research tasks as quickly as possible.

Finally, it would appear from the nature of the data collected at the test site that statistical studies of the power-producing wind speeds and their directions are in order. The three MOD-2s at the test site were laid out such that there was some probability of wake interaction between any pair of the turbines or even all three. If the number of occurrences of wakes impacting downwind turbines as screened by our analysis is any indication, then the impact of wakes may not be significant with proper array design. The per-

cent of time that wakes appeared to impact other turbines was a small percentage of the total time. After making such a statement, we hasten to add that the site is a test site after all. Under those conditions, as opposed to the more typical utility conditions, the opportunity for wake interactions may have been significantly reduced due to human intervention and testing.

This is a preliminary report of ongoing work; considerably more analysis is left to be done. Besides the multivariate analysis that we have outlined here, there is also considerable verification to be done. Some of this can be done relatively soon, some will have to wait for the return to service of the remaining two turbines at Goodnoe Hills. We anticipate that this work will continue for several more years. Although it is tempting to propose that the question of wake momentum deficits could in fact practically be put to rest at this moment, there is some question in our minds if that is so. At the current state-of-the-art of turbine design and construction where large margins are built in for self-protection, the statement that we can calculate wake deficits now may be true if a worst-case condition is all that is desired. Conversely, in the future when designs become more finely tuned and the margins designed and built into turbines are reduced to a bare minimum, we are not comfortable with our current capabilities.

The current state of the wake turbulence-induced stress loads is an unknown. It appears that there is potential for considerable work in this area in the future. Variations of the analyses performed to look at wake deficits using the DDS data may be apropos for turbulence studies; however, the instrumentation and data rate would both have to be supplemented and/or changed.

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