18C

PNL-4572

UC-60

Wake Structure Measurements at the Mod-2 Cluster Test Facility at Goodnoe Hills

P. B. S. Lissaman
T. G. Zambrano
G. W. Gyatt

March 1983

Prepared for
Pacific Northwest Laboratory
under Subcontract B-D5788-A-N

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-4572

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PNL-4572
UC-60

WAKE STRUCTURE MEASUREMENTS AT THE MOD-2 CLUSTER TEST FACILITY AT GOODNOE HILLS

P. B. S. Lissaman
T. G. Zambrano
G. W. Gyatt

AeroVironment Inc.
Pasadena, California 91107

March 1983

Prepared for
Pacific Northwest Laboratory
under Subcontract B-D5788-A-N

Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGEMENTS

AeroVironment Inc. acknowledges Simpson Weather Associates of Charlottesville, Virginia, for their assistance in performing the wake measurements at Goodnoe Hills. We also acknowledge Boeing Engineering and Construction Company and the Bonneville Power Administration for their support and use of their on-site facilities and Battelle Pacific Northwest Laboratory for help in providing free stream data.

SUMMARY

A field measurement program was carried out at the cluster of three MOD-2 wind turbines located at Goodnoe Hills, Washington, to determine the rate of decay of wake velocity deficit with downwind distance in various meteorological conditions. Measurements were taken at hub height (200 ft) between July 12 and August 1, 1982. During this period, winds of significant energy were westerly. Wind turbine No. 3 was selected as the test unit, with free stream reference data provided by the nearby meteorological tower No. 2. Wake wind speeds were measured using a radiosonde suspended from a tethered balloon, its position being determined from a grid of ground stakes. Instantaneous readings were recorded by each system every 2 seconds and averaged over 10-minute periods. As a control experiment, the sonde was also operated next to the meteorological tower to calibrate the instrumentation. Measurements were also made downwind of Unit 3 with the turbine off to determine the magnitude of terrain-induced variations in wind speed.

The balloon system used to measure downstream wind data proved to be reliable and convenient. A total of 21 hours of simultaneous balloon and free stream data were obtained. Downstream distances of 900, 1500, 2100, and 2700 ft from the turbine, corresponding to 3, 5, 7, and 9 rotor diameters (D) were investigated. Differences between the instrumentation systems required that corrections be made to the data. After correction, averaged terrain-induced wind speed variations were regarded as insignificant (<3%). There was considerable scatter in the observed 10-minute average downstream to free stream velocity ratios. Turbine-on velocity ratios showed even greater scatter, suggesting that only some measurements were, in fact, representative of wake centerline velocities, and that others were made off centerline due to wake meander or wind shift. Isolation of the high wind speed (30 to 45 mph) velocity ratios, however, revealed velocity deficits of up to about 50% at 3D and 5% at 5D downstream. Measurements at greater downstream distances showed no wake deficit within the limits of resolution of the experiment, indicating that the wake had recovered to free stream conditions. Comparison with the AeroVironment wake model using common values for rotor drag coefficient and turbulence showed similar trends. A quantitative comparison was not justified due to the data scatter.

CONTENTS

INTRODUCTION

BACKGROUND

The MOD-2 wind turbine project is the first in the Federal Wind Energy Program to be dedicated to the design, installation and testing of large-scale wind turbine systems. The three 2.5-megawatt machines clustered at a single site near Goldendale, Washington, provide a unique opportunity for investigating the interactive effects of large-scale machines integrated into a utility network.

Within the U.S. Department of Energy Federal Wind Energy Program, Pacific Northwest Laboratory (PNL) is responsible for determining the performance of a turbine operating in the wake of an upwind machine. PNL contracted AeroVironment Inc. (AV) to design and implement field experiments to assist PNL in collecting and analyzing data on the structure of the MOD-2 wake. Measurements taken during this program are the first of their kind at the Goodnoe Hills test facility.

PRESENT RESEARCH PROBLEM

Wind turbines create wakes of low energy air with characteristics dependent upon turbine, wind, and site parameters. In turbine arrays, the downwind units experience this wake velocity deficit, resulting in loss of power. This degradation in performance is of importance to the array efficiency. Because the region of primary interest for placement of downstream units begins five rotor diameters downstream, wake structure studies must concentrate on defining the wake in this region.

Over the past five years, the array problem has been extensively studied analytically and in wind tunnel tests. Data from full-scale turbines operating in the atmosphere that could be compared with these models are quite limited, and this program therefore presents a valuable opportunity for providing these data. The most recent technical report on this topic (Lissaman et al., 1982) establishes that the wake has an approximately Gaussian velocity deficit profile and that the magnitude of the centerline deficit is a function of the free stream turbulence, the turbine drag coefficient, and the downstream distance. The objective of the field measurements in this project was to obtain experimental data on the sensitivity of the wake structure to these parameters.

OBJECTIVE OF THE RESEARCH

The main purpose of the field tests was to measure the centerline velocity deficit and determine its downstream development as a function of ambient turbulence and turbine drag coefficient.

As will be shown later, the wake deficits represent small perturbations upon what is already a temporally and spatially varying flow field. In this first program, it was therefore considered too ambitious to attempt to measure detailed wake structure in the field. This decision was justified by the rather extensive scatter of the experimental data obtained in this test.

TECHNICAL APPROACH

PARAMETERS THAT DETERMINE WAKE STRUCTURE

The wake of a wind turbine is the volume of air extending downstream from the rotor disk that has been slowed relative to the free stream by the process of energy extraction. This slower moving air is gradually re-energized by the surrounding air through turbulent mixing so that, far downstream, the effect of the turbine on the flow field cannot be detected. The rate of re-energization and, hence, the recovery rate of wind speed with downstream distance, are the subjects of this study. Several numerical models have been developed to simulate the wake of wind turbines. For this study, the approaches of Lissaman and Bate (1977) and Lissaman et al. (1982) were used to identify the parameters that determine the wake structure; these are discussed below.

Turbine Drag Coefficient

The initial condition of the wake can be taken as a uniform jet of slow-moving fluid, the velocity of this jet being determined by the turbine drag coefficient (C_D). Figure 1 shows the variation of the MOD-2 drag coefficient as a function of wind speed as predicted by NASA. The test schedule was planned to cover a variety of wind speed conditions so that the effect of the turbine drag coefficient on wake structure could be determined.

Ambient Turbulence

From its initial condition as a uniform jet, the wake begins to expand due to turbulent mixing with the surrounding free stream air. Since the growth of the wake is in a radial direction as it progresses downstream, it is the transverse or crosswind turbulence level that determines the wake growth rate. Two distinct length scales of turbulence need to be distinguished. Eddies smaller than the wake diameter produce the mixing of wake and free stream air that causes wake growth. Eddies larger than the wake, however, cannot do this and merely cause the wake to meander. A sketch distinguishing these two effects is shown in Figure 2. The velocity deficit profile in the wake can be expected to be approximately Gaussian; since the total wake momentum deficit is constant, the magnitude of the wake centerline velocity deficit is a function of the wake radius.

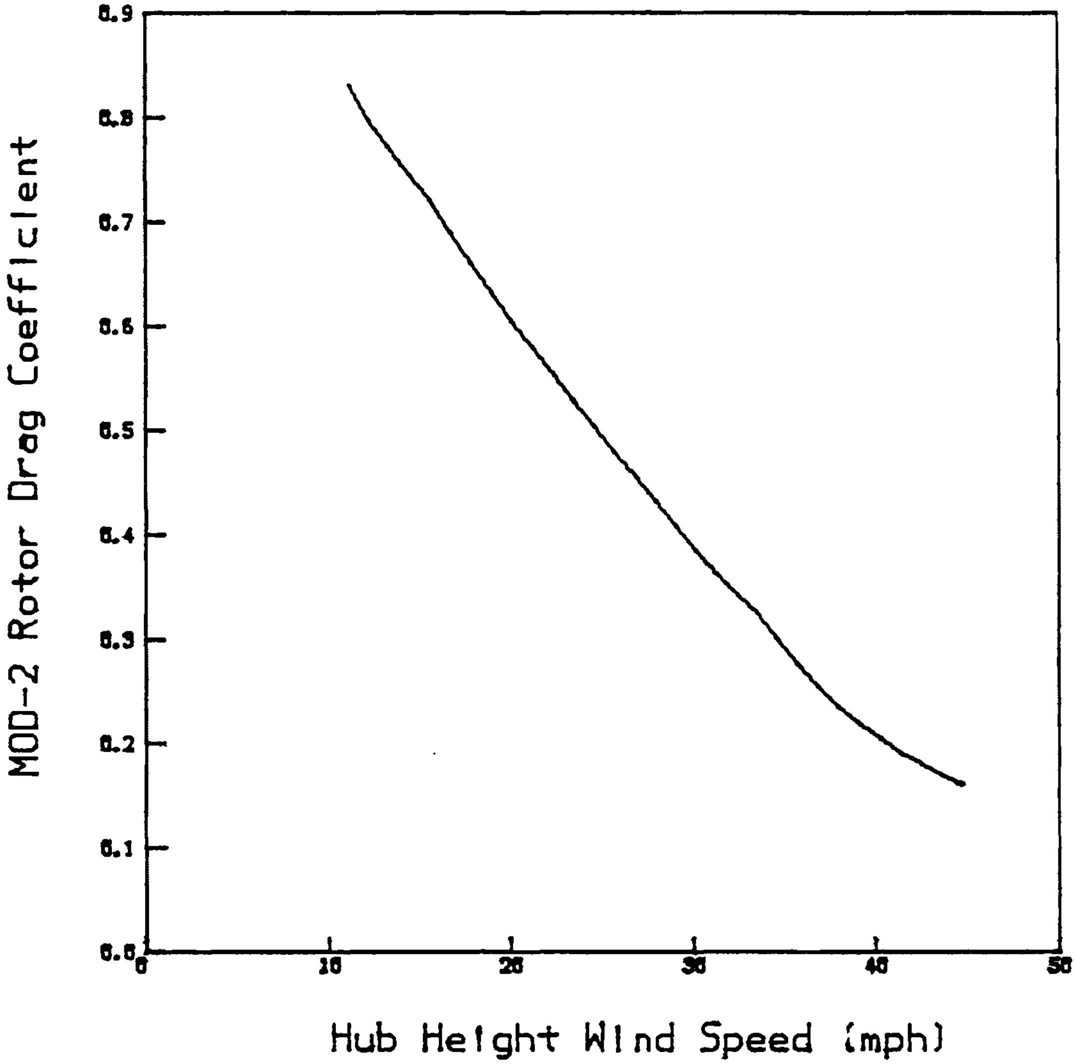

FIGURE 1. Variation of MOD-2 Drag Coefficient with Wind Speed

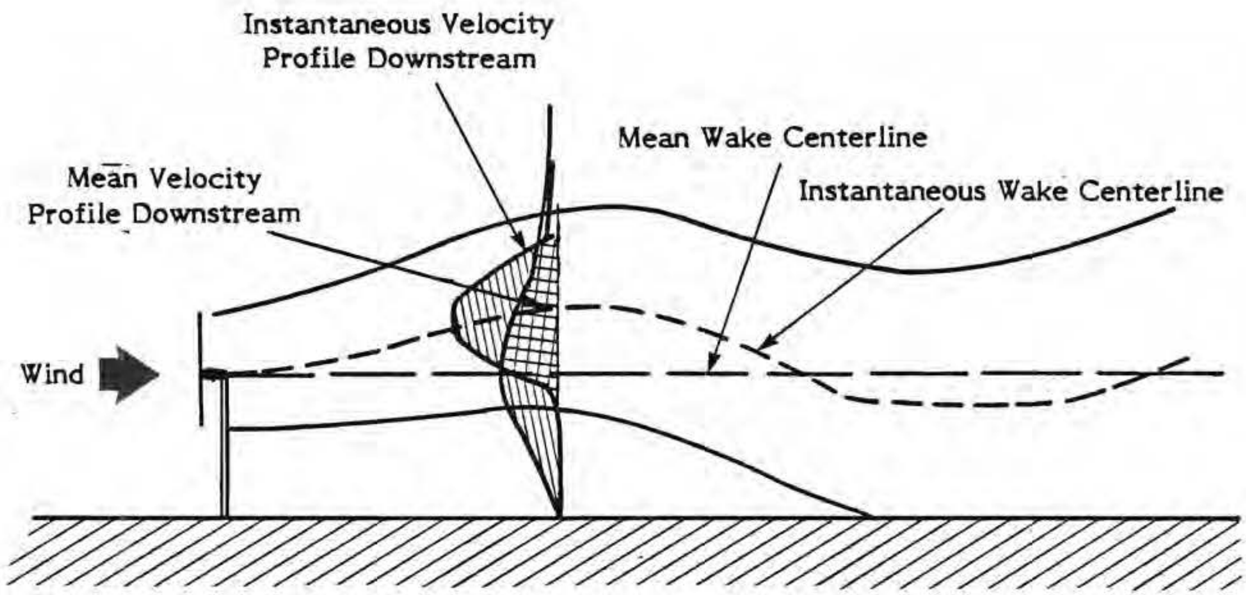

FIGURE 2. Effect of Turbulence Scale On a Wind Turbine Wake

In the field program, measurements were taken during both day- and nighttime conditions in order to determine the rate of recovery of wake velocity as a function of turbulence.

Downstream Distance

The primary region of interest in a wake measurement program, from the point of view of wind farm design, is approximately five rotor diameters downstream. In this region, the wake centerline velocity deficit is not expected to exceed about 20% of the free stream speed.

FIELD MEASUREMENT PLAN

Freestream Data

Measurement of free stream wind speed and crosswind turbulence was required. Analysis of wind records from previous years suggested that the energetic winds of interest to this study would all be from the west unless a storm condition were to occur. West winds would leave the Bonneville Power Administration (BPA) tower (No. 2) clear of any turbine wake interference effects. Figure 3 shows the layout of machines and towers at the Goodnoe Hills site. A UVW propeller anemometer, with the capability of measuring all three components of wind speed, was mounted at the 195-ft (turbine hub height) level of the BPA meteorological tower. The single propeller anemometer already installed at the 195-ft level was kept operating to act as a backup in the event of a failure in the UVW system.

Downstream Data

A radiosonde suspended from a tethered balloon was used to measure downstream conditions. The radiosonde transmitted data to a ground station where it was decoded and recorded on magnetic tape. This method provided a portable platform for making hub-height wind speed measurements. Figures 4 and 5 show the balloon and radiosonde.

Sampling Rate

As explained earlier, it is the eddies of length scale smaller than the wake diameter that cause wake growth. The sampling rate of the UVW anemometer therefore had to be

UNIT	#1	#2	#3	BPA TWR #2	PNL TWR #1	Base Elev Above Sea Level
#1	-	2014	3046	2693	645	2622
#2	2014	-	1505	991	1726	2574
#3	3046	1505	-	523	2504	2568
BPA TWR	2693	991	523	-	2213	2577
PNL TWR	645	1726	2504	2213	-	2624

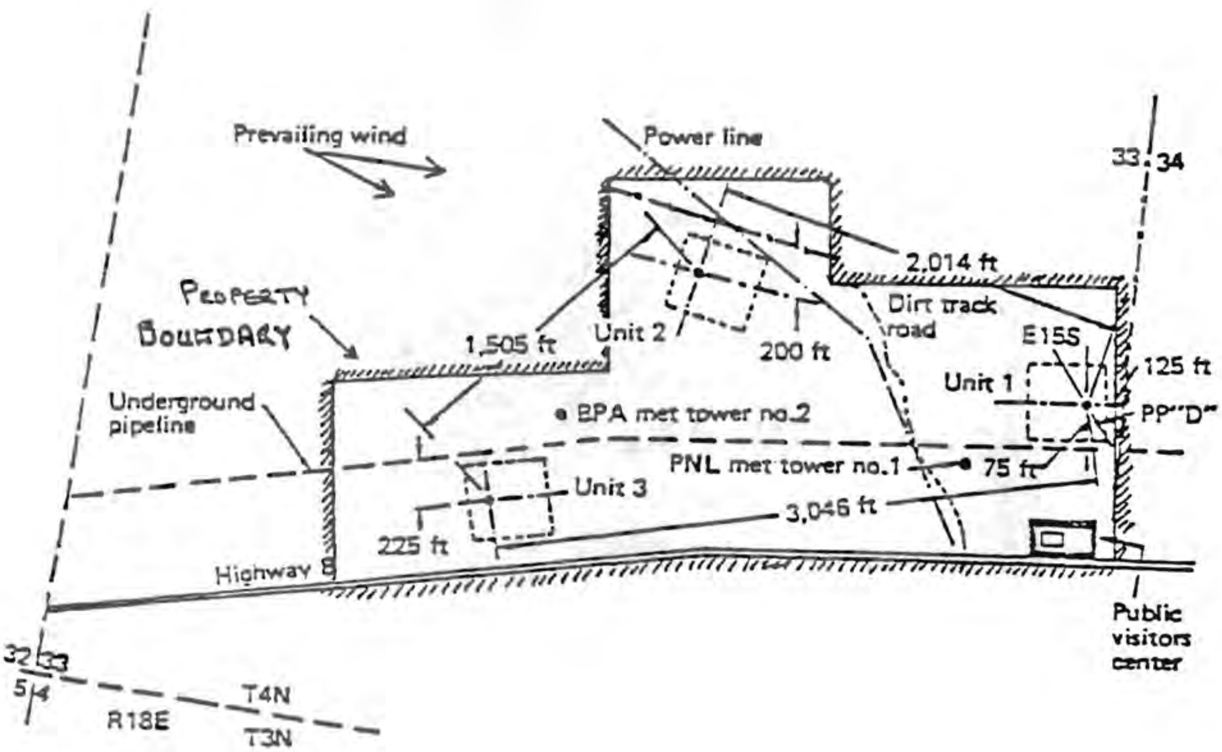

FIGURE 3. Goodnoe Hills Site Layout and Distances Between Major Features (feet)

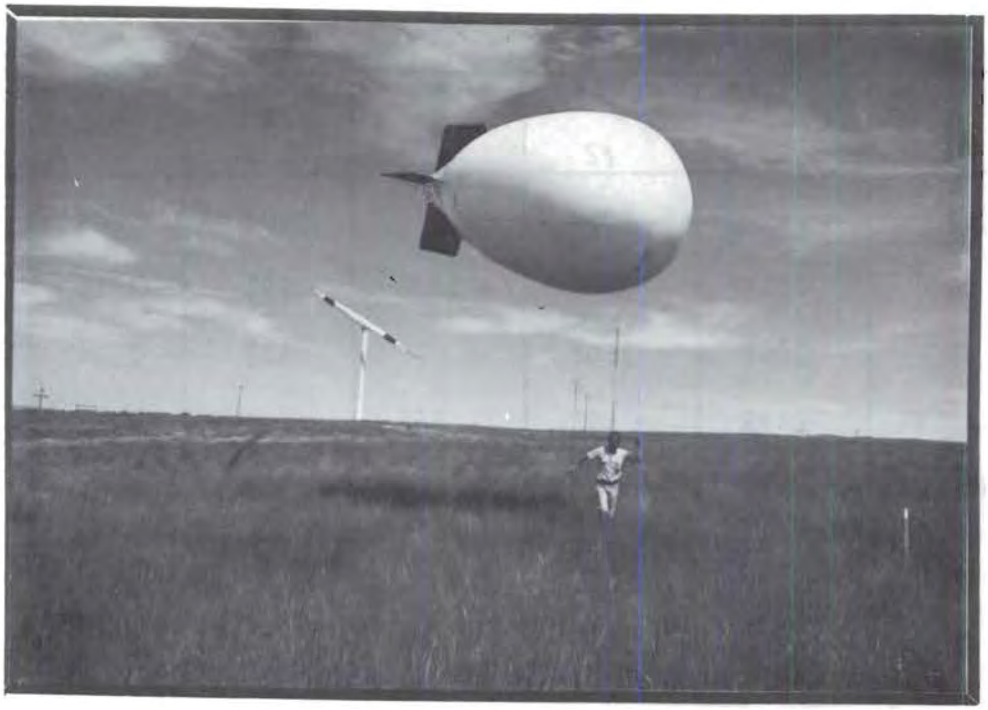

FIGURE 4. Balloon and Operator

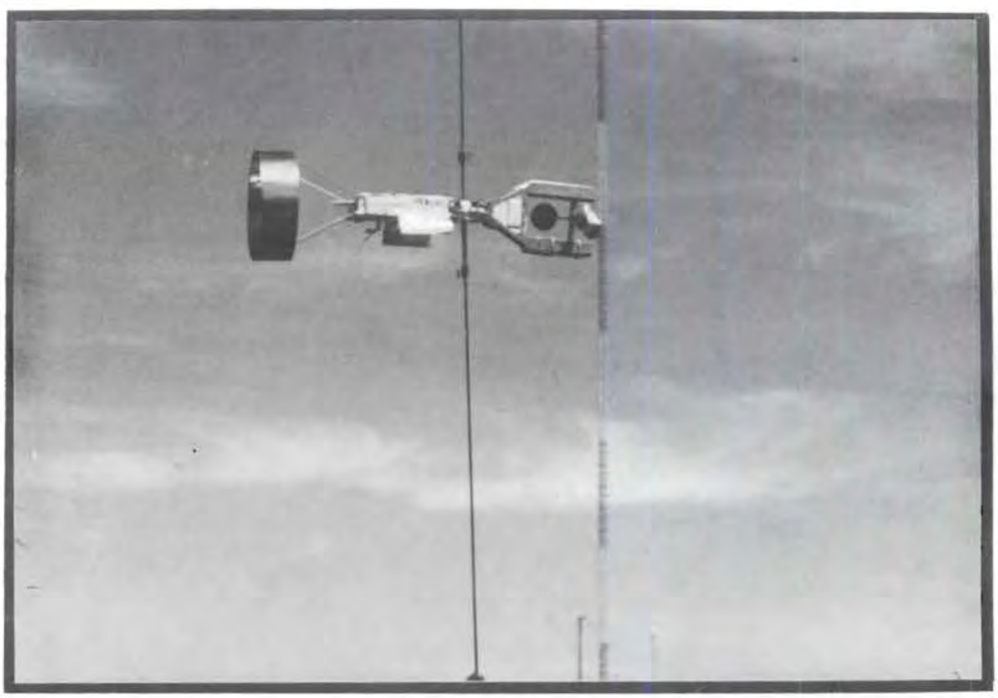

FIGURE 5. Radiosonde Attached to Tether Line

high enough to resolve such small scale turbulence. A sampling rate of 0.5 Hz was the maximum available. At this rate, eddies of length scale down to about 30 ft could be resolved. Since the wake would be at least 300 ft in diameter, this sampling rate was considered sufficient to provide turbulence data representative of wake growth rate. This sampling rate was also used for the sonde.

Sampling Period

A sampling period was required that would provide a sufficient number of data points for determining average wind speed and variance with a low uncertainty due to random effects. A long sampling period was also desirable to achieve good correlation between the two anemometer stations, which are separated by up to one-half mile. However, in conflict with these requirements was the need for a short enough sampling period to ensure a reasonably stationary mean value. A period of 10 minutes (300 data points per period) was chosen as a first and lower bound estimate of the optimum time.

QUALITY ASSURANCE

A detailed quality assurance report on the sonde system is described by Zambrano and Gyatt (1982) and includes discussion of wind tunnel calibration, data transmission and reduction and error detection. Freestream reference data were provided by PNL.

As a control experiment, the balloon was flown over the BPA tower to position the sonde next to (within about 100 ft) the UVW anemometer. Simultaneous 10-minute average measurements of wind speed were recorded to compare the readings provided by the two systems. The results of these comparison runs for both the UVW and propeller anemometer systems on the BPA tower are given in Appendix A.

WAKE MEASUREMENTS

Locating the Sonde

At all times during data recording it was necessary to know the position of the sonde relative to the test turbine, No. 3 (WTG-3). Energetic winds were expected from the west or west-southwest. A grid of stakes was therefore set up to the east of WTG-3 every 5° at 3, 5, 7 and 9 rotor diameters downstream. This angular interval was considered small enough to allow determination of the sonde position to within 1^o. As an example, at a turbulence level of 10% and a free stream wind speed of 22 mph, the AV model predicts a wake radius of 660 ft at 7 diameters downstream. The velocity profile in the wake can be modeled by the equation

$$\frac{\Delta u}{\Delta u_m} = \left[1 - \left(\frac{r}{R_w}\right)^{1.5}\right]^2 ,$$

where R_w is the wake radius, Δu is the velocity deficit at distance r from the wake centerline, and is Δu_m the centerline velocity deficit.

At 7D, a 1^o angle at the turbine subtends an arc of 37 ft. If, therefore, the balloon was off centerline by 1^o, the measurement of local wake deficit would be only about 3% lower than the centerline wake deficit.

Locating the Wake Centerline

Estimating the angular position of the wake centerline to 1^o was not possible because of the low resolution in wind turbine yaw angle measurement (recorded on-site by strip chart) and the inconsistency of yaw angle compared to wind direction measured at the reference tower. It was discovered in the field, however, that the nacelle angle could be determined by visual observations from the grid of stakes to within about 3^o. This visual method was used to estimate the location of the wake centerline.

Background (Turbine-Off) Measurements

Figure 6 shows a contour map of the Goodnoe Hills site. It can be seen that the terrain slopes gently upwards from west to east and there is a steep gully in the northwest that may have a significant influence on the wind field both in terms of speed and direction. Measurements were therefore made at various downstream distances with the turbine off in order to determine orographic (terrain-induced) speed changes.

Wake Measurement Strategy

The test schedule planned for wake measurements was based on site wind data from previous years, which suggested that mornings could be expected to be calm while

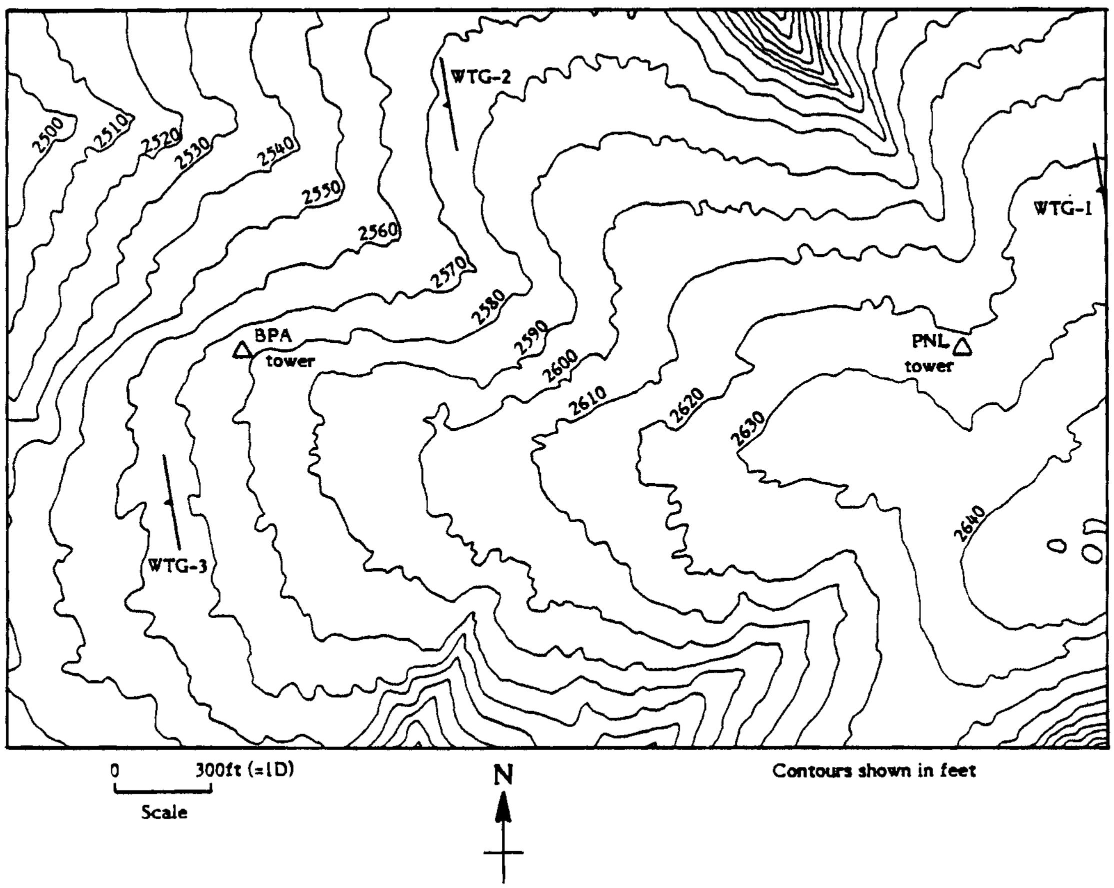

FIGURE 6. Topography of the Goodnoe Hills Site

evenings would probably be the period of the most energetic winds. The schedule was designed to cover a full range of meteorological conditions (wind speed and turbulence).

With the turbine on line, the balloon was positioned on the estimated wake centerline at the selected downstream distance. Sonde data were then recorded for at least 30 minutes before a re-evaluation of the wake centerline position was made. If a significant shift in wind direction ($\geq 5^{o}$) had occurred, the balloon would be moved to the new centerline and data recording would restart. Using this approach, a compromise was made between taking data off centerline and continually repositioning the balloon to follow every shift in wind direction.

RESULTS

DATA RECOVERY

Sonde Data Recovery

During the two-week test period, almost 30 hours of useful data were obtained from the sonde, representing a data recovery of over 95% with respect to measurements attempted. Any data loss was a result of normal transmission and reception difficulties between the balloon and ground station rather than hardware failures.

Freestream Data Recovery

Freestream data were recovered for 70% (~21 hrs) of the time that the sonde was operating. The main cause of the data loss was hardware problems during the first part of the field program involving the data recording equipment for the UVW anemometer. Because of this, a backup cassette system was installed to supply 10-second average UVW data. There were also problems with the UVW recorder during the second part of the experiment; two-minute average wind speed and direction data measured by the propeller anemometer were used to cover these periods. Of the 21 hours of free stream data, 24% (~5 hr) were the preferred UVW component data measured every two seconds, 50% (~10 hr) were 10-second average UVW data, and the remaining 26% (~5 hr) were two-minute average propeller anemometer wind speed and direction data. The latter two types, representing 76% of the free stream data, were not suitable for determining turbulence intensity since they were average values and of too low a resolution to record eddies of a size which would cause wake growth.

Distribution Summary of Collected Data

The 21 hours of simultaneous balloon and free stream data recovered can be divided into three types: 27% comparing the sonde and tower readings, 23% taken with the turbine off to investigate background or terrain-induced effects, and 50% dedicated to turbine-on wake measurements. Figure 7 shows the number of 10-minute periods recorded at each downstream distance and the stake positions at which the sonde was operated. Although the objective of the program was to concentrate on the region from 5

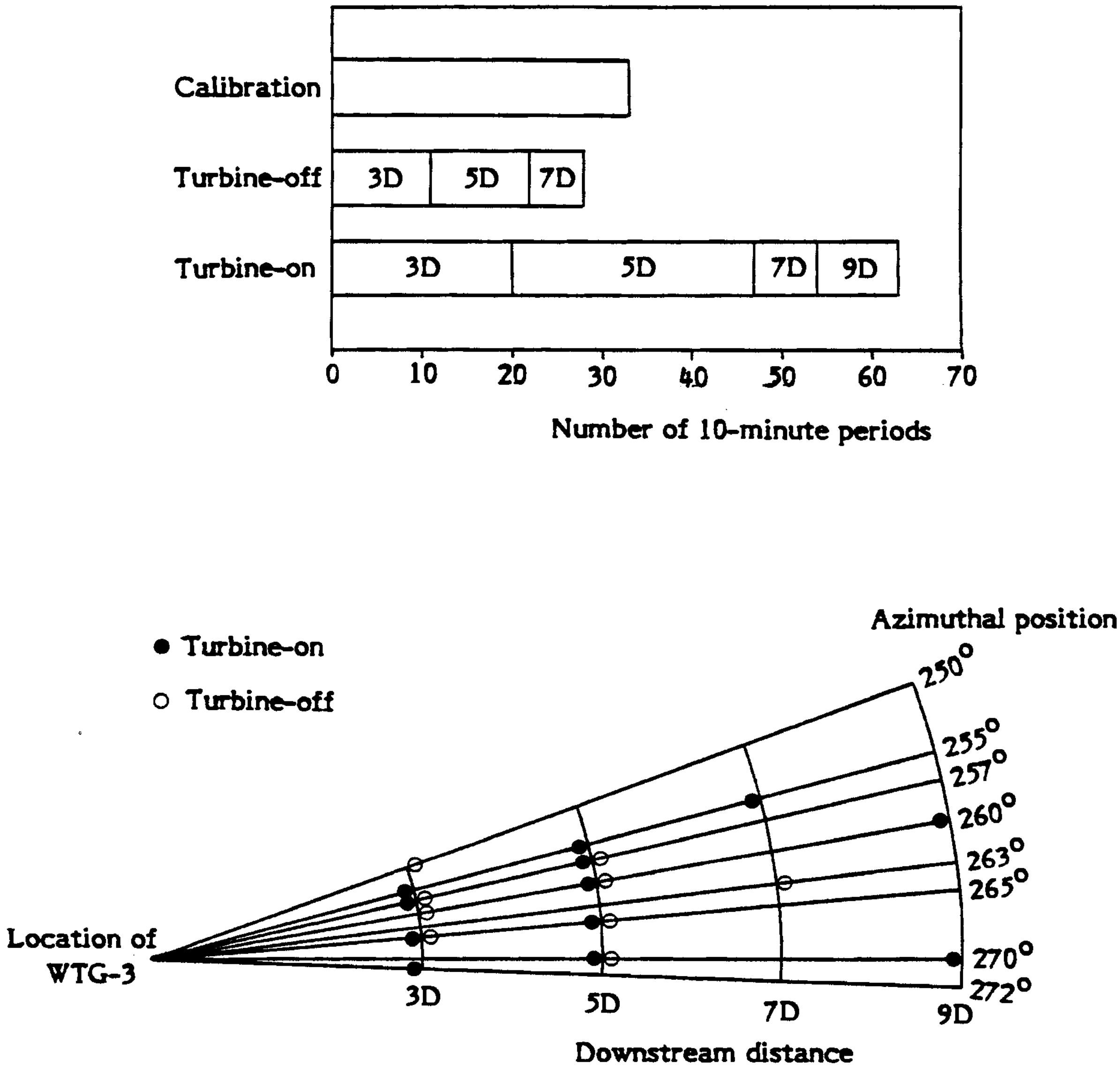

FIGURE 7. Summary of Sonde Positions at Which Measurements Were Taken

rotor diameters downstream, experience in the field suggested measurements at extreme downwind distances might be excessive at this early stage in the development of wake measurement techniques. Expected velocity deficits at 7D and 9D were of the order of only a few percent. Most measurements were therefore taken at 5D but an investigation of the wake at 3D was also made where significant deficits of up to 50% are theoretically possible.

The results of each 10-minute measurement period are given in detail in Appendix A.

BACKGROUND MEASUREMENTS

The background velocity ratios measured with the turbine off are shown in Figure 8. It can be seen that there is considerable scatter in this data. When the measured ratios at each location are averaged, however, it becomes apparent that background effects account for only a few percent change in wind speed. Figure 9 shows these average values together with the associated standard deviations.

WAKE VELOCITY RATIOS

The velocity ratios measured with the turbine on are presented in Figure 10. Again, the scatter is considerable even though each point represents a 10-minute average value. Before further analysis, points with a velocity ratio above 1.3 (one at 5D and one at 9D) were discarded; such points were suspected to be in error due to spurious signals undetected in the quality assurance plan.

As a first attempt at determining gross effects, the remaining data were averaged for each downstream distance. The results of this operation are shown in Figure 11, together with predictions from the AV wake model using common values of turbine drag coefficient and turbulence. While a significant decrease in wind speed at 3D can be seen, results beyond this are inconclusive. Each 10-minute period was therefore scrutinized carefully to determine whether there were grounds to be more selective in the averaging process.

Sorting by turbulence level was not possible due to the relatively short time for which two-second free stream data were available, and most of these data were collected

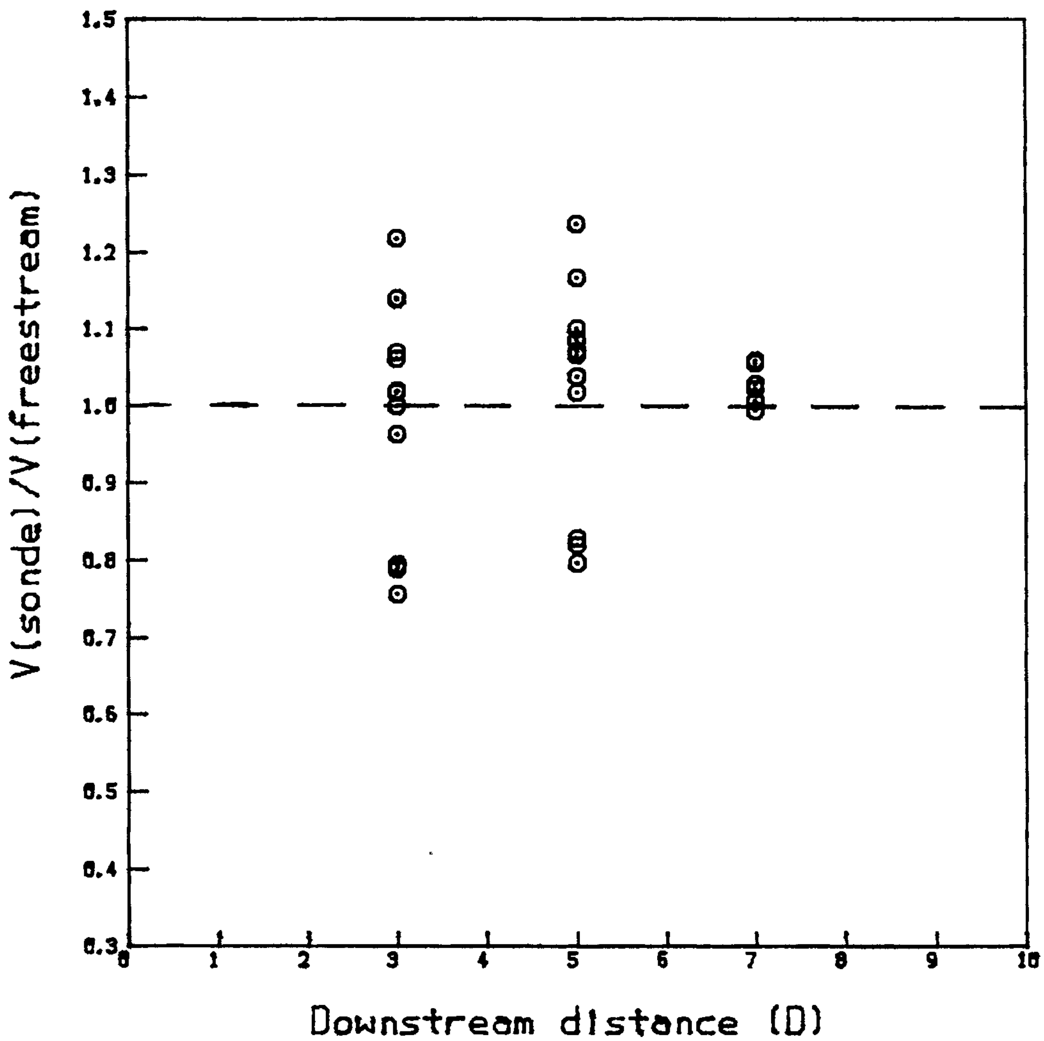

FIGURE 8. Measured Velocity Ratios, Turbine Off

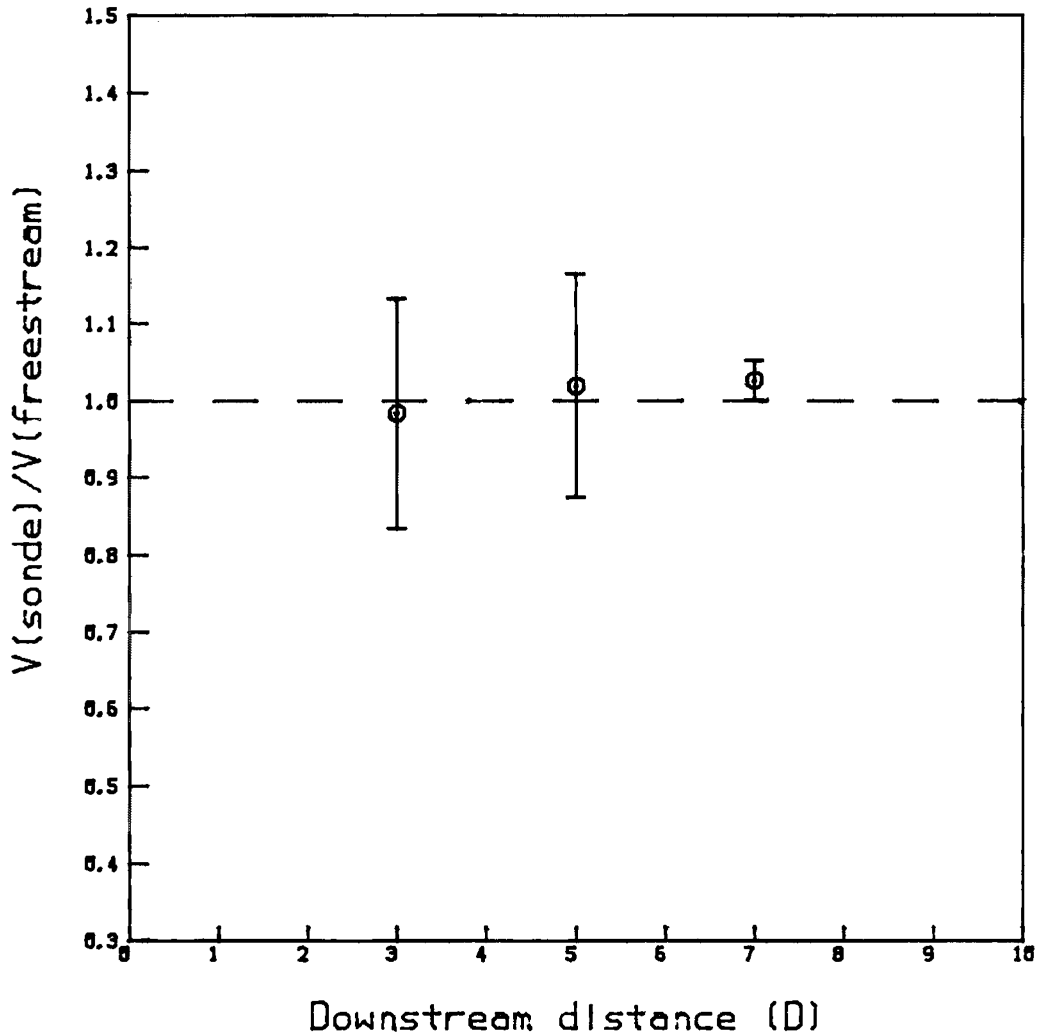

FIGURE 9. Averaged Velocity Ratios, Turbine Off

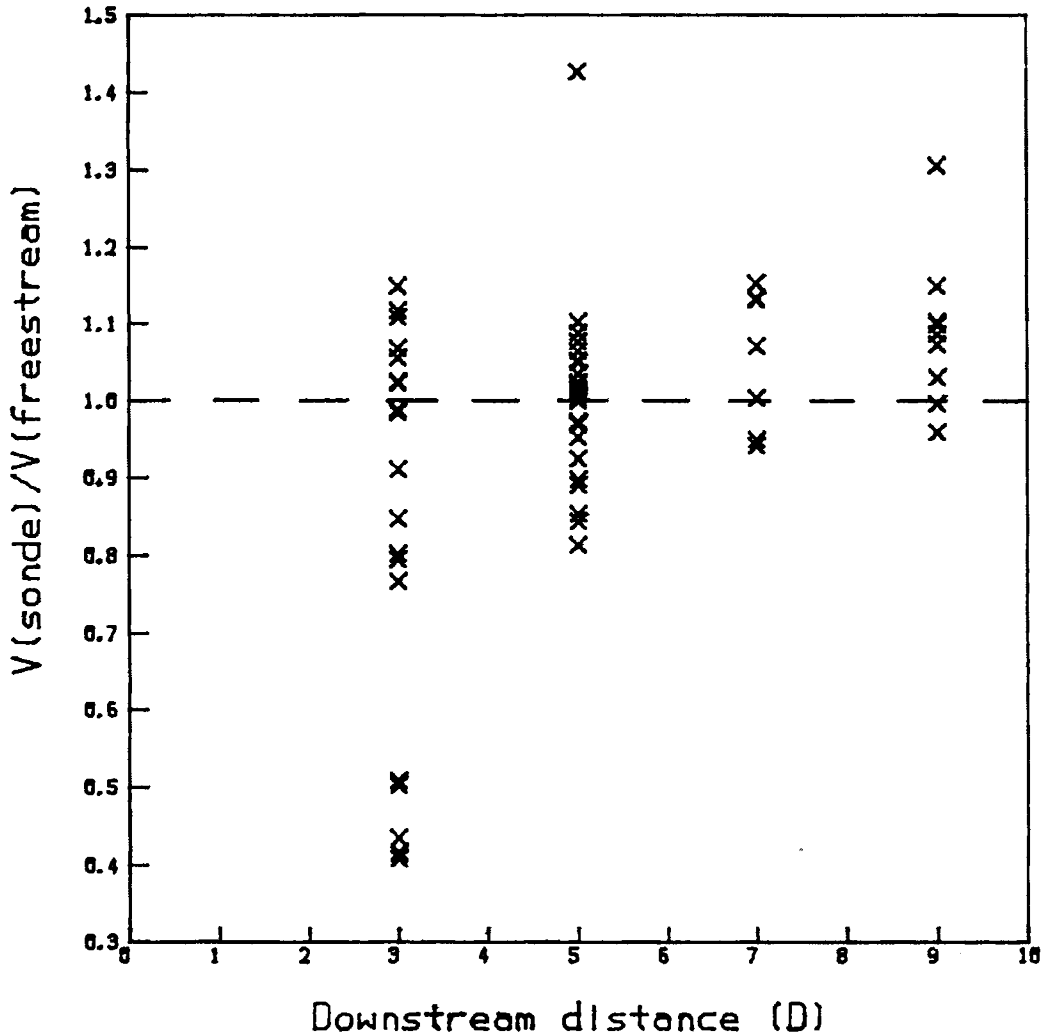

FIGURE 10. Measured Velocity Ratios, Turbine On

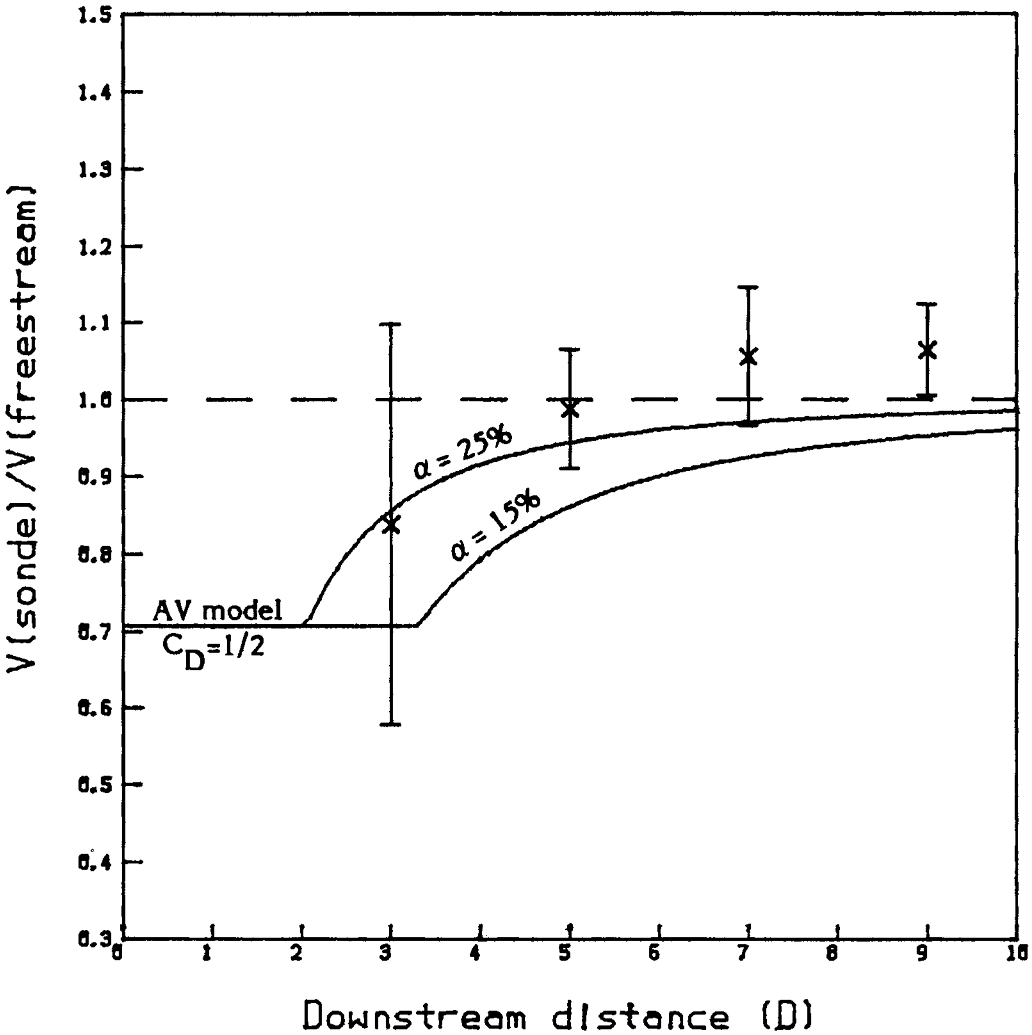

FIGURE 11. Average Velocity Ratios, Turbine On

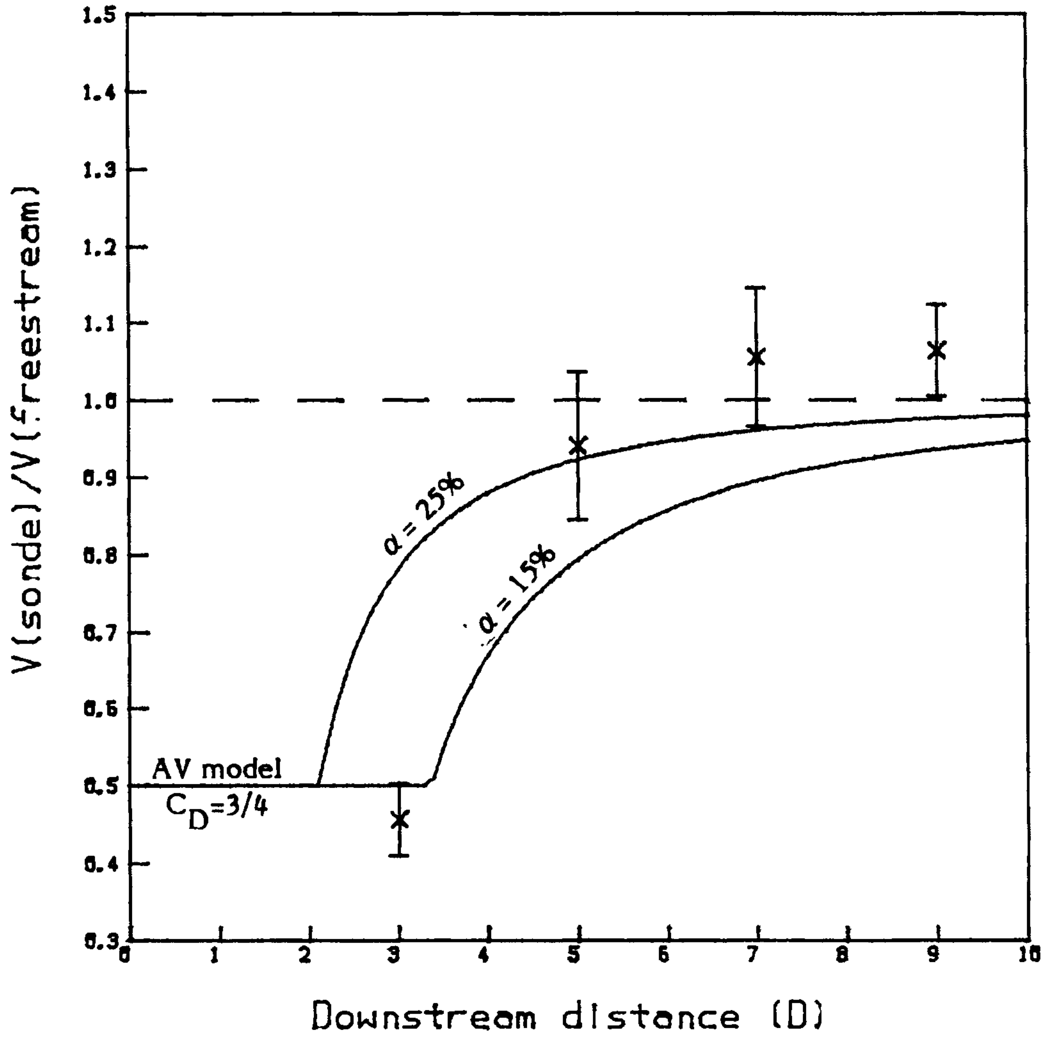

FIGURE 12. Average Velocity Ratios for High Wind Speeds, Turbine On

either with the turbine off or with the sonde positioned next to the BPA tower. The next step was to sort by wind speed. The wake measurements were divided into two categories, for free stream wind speeds above and below 30 mph. It appeared that the greatest wake deficit generally corresponded to high wind speed conditions. The high wind speed data points were therefore averaged and a new graph plotted (Figure 12). A dramatic deficit at 3D and a significant effect at 5D were now visible. The figure again shows typical predictions using the AV wake model for comparison.

The wind direction data and their relation to the balloon azimuthal position were next scrutinized. Although no obvious trends could be seen, it was apparent from the large variation in the difference between balloon position and wind direction (up to $\sim 20^{\circ}$) that the objective of measuring on the wake centerline is very difficult to achieve in the existing field conditions. This was at least partly due to the lack of a real-time display of wind direction.

Table 1 gives the sensitivity of the velocity ratio to off-centerline measurements as predicted by the AV wake model. The table shows that corrections for balloon position errors of 5° (or even 10° at small downstream distances) could be significant. However, this is not consistent with test accuracy of the existing data for several reasons. First, the wind direction data from the BPA tower cannot be validated and an offset of a few degrees would significantly change the correction factors. Second (and more important), the complexity of the site topography could cause a flow field such that the wake centerline does not follow a straight path downstream from the turbine in the direction of the free stream direction. While it was possible to position the balloon to within about 1° of the nacelle direction, the wake may have been swept sideways by veering winds which varied slowly over the site. Such an effect would have had the largest consequences for measurements at extreme downstream distances where the velocity deficit is already the smallest. Third, the free stream wind direction was not constant with time, causing wake meander. Thus, even if the balloon were positioned on the mean wake centerline during a measurement period, the observed average wake velocity deficit would be lower than the corresponding instantaneous centerline value due to wake meander. As shown in Figure 2, as far as time average values are concerned, wake meander is equivalent to an increased wake growth rate. This effect, therefore, reduces the observed velocity wake deficit, further complicating far wake measurements.

TABLE 1. Predicted Wake Velocity Ratio as a Function of Balloon Position Error

Downstream Distance	Azimuthal Error in Balloon Position 0^{o}	5^{o}	10^{o}	15^{o}	20^{o}
3D	0.74	0.80	0.88	0.96	1.00
5D	0.90	0.92	0.96	0.99	1.00
7D	0.94	0.96	0.98	1.00	1.00
9D	0.96	0.97	0.99	1.00	1.00

$\alpha = 10\%$

$C_D = 0.56$

In view of these reasons, it was not considered that there were sufficient data for meaningful direction corrections to be made to the observed wake velocity ratios.

It is possible that the reason for observing the largest velocity deficits at high wind speeds was related to the above considerations. For example, at high wind speeds, the flow field at the site may have been more uniform than at low wind speeds, resulting in a smaller error of the balloon position from the true wake centerline. The relative effects of wake meander may also have been of a lower level so that the actual measured wake velocity deficits were larger.

CONCLUSIONS AND RECOMMENDATIONS

The following summarizes the conclusions drawn from this project:

- o The tethered sonde method of measuring wind speed is convenient and accurate. The sonde can be positioned to within about 30 ft of a desired location. The system was stable in turbulence and high wind.

- o Data from both the BPA tower and the sonde, when operated near the tower supported PNL's findings that there are significant terrain-induced effects on the flow at the tower site.

- o There was considerable scatter between successive 10-minute average velocity ratios with a standard deviation on the order of 15%. This was greater than anticipated but not unusual, given the terrain variability.

- o A distinct wake with a velocity deficit of 50% was measured at 900 ft (3D) downwind of the wind turbine disk; however, at greater distances -- 1500 ft (5D) and 2100 ft (7D) -- the measured deficit is on the order of 5% and sometimes negative (a speed-up), indicating that to the order of experimental accuracy the deficit cannot be defined.

- o Terrain-induced nonuniformities in the wind field probably accounted for some of the scatter observed, even though terrain-induced effects on the background flow field were shown to be small over a long period.

- o An anomalous behavior of the wake at lower speeds (less than 35 mph) was observed in which the measured velocity deficits were much smaller than theory would predict. This may have been due to extensive flow meander at low wind speeds.

- o Considerable effort was made to quantify experimental accuracy and error. At present, there is no defined optimum averaging period and sampling rate. A high frequency of sampling is necessary in order to sense the small-scale turbulence (eddies of scale smaller than the wake) that diffuses the wake. The spatial correlation between the tower and sonde over a short period of time was poor; as longer time periods were used, this correlation improved. However, wake meander probably accounted for the difficulty in resolving an already weak wake from the background flow field. The method used for this experiment showed an acceptable trade-off between quality of data and complexity of instrumentation.

- Exercising the AV analytical wake model gave results consistent with experimental measurements but there was insufficient structure in the experimental data to validate the model.

On the basis of these conclusions, the following recommendations are made:

- Further wake measurement programs are required to obtain a larger data base for wake analysis. These should be conducted with the goal of determining the energy capture at downwind positions rather than detailed wake properties.

- Analysis of the data obtained in this experiment indicated that a more detailed measurement scheme is not appropriate now, and that future emphasis should be devoted to experimental accuracy, and to proper methods of statistically processing data. It may prove advantageous to take data for long periods at fixed downwind positions regardless of changes in wind direction rather than trying to chase the wake centerline. For example, after taking, say, three hours of data at 7D along the prevailing wind direction radial, the sonde would be moved first to one side by 3D for three hours and then to the other for a futher three hours.

- At least two tethered sonde systems should be used in a future program, one directly upstream of the turbine and one or more downstream. This will ensure that the free stream reference anemometer gives a true picture of the winds seen by the rotor. In addition, this method will avoid differences in up- and downstream measurement systems in terms of response, sampling rate, etc. Multiple downstream sondes would give a more reliable indication of wake velocity recovery and/or velocity profile by providing simultaneous data from various positions in the wake.

- If a future program were to be performed at Goodnoe Hills, further examination of the background (turbine-off) flow fields at the site is recommended. The topography of the site is sufficiently complex that wake effects could be masked (or exaggerated) by terrain-induced nonuniformities in the wind field. Alternatively, a measurement program should be considered at a site with flatter terrain and a uniform background wind field, such as Medicine Bow, Wyoming or San Gorgonio Pass, California.

REFERENCES

Lissaman, P.B.S., and E.R. Bate, Jr. 1977. Energy Effectiveness of Arrays of Wind Energy Conversion Systems. Final Report AV-FR-7058 prepared by AeroVironment Inc. for National Swedish Board for Energy Source Development, Stockholm, Sweden.

Lissaman, P.B.S, G.W. Gyatt, and A.D. Zalay. 1982. Numeric Modeling Sensitivity Analysis of the Performance of Wind Turbine Arrays. Final Report PNL-4183 prepared by AeroVironment Inc. for Battelle Pacific Northwest Laboratory, Richland, Washington.

Zambrano, T.G., and G.W. Gyatt. 1982. Quality Assurance Plan for Wake Structure Measurements at the MOD-2 Cluster Test Facility at Goodnoe Hills - Task B -- Quantitative Wake Measurements. AV-QS-A-82/608 prepared by AeroVironment Inc. for Battelle Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A

RESULTS FROM UVW AND PROPELLER ANEMOMETER SYSTEMS

Figures A-1 and A-2 show 10-minute average measurements of wind speed recorded when the balloon was flown next to the reference meteorological tower. The differences between the readings are probably due to calibration errors. Each graph also shows the "least squares fit" straight line used to correct the data from the tower; the sonde calibration was assumed to be correct on the basis of SWA documentation.

The tables which follow Figures A-1 and A-2 summarize the data collected.

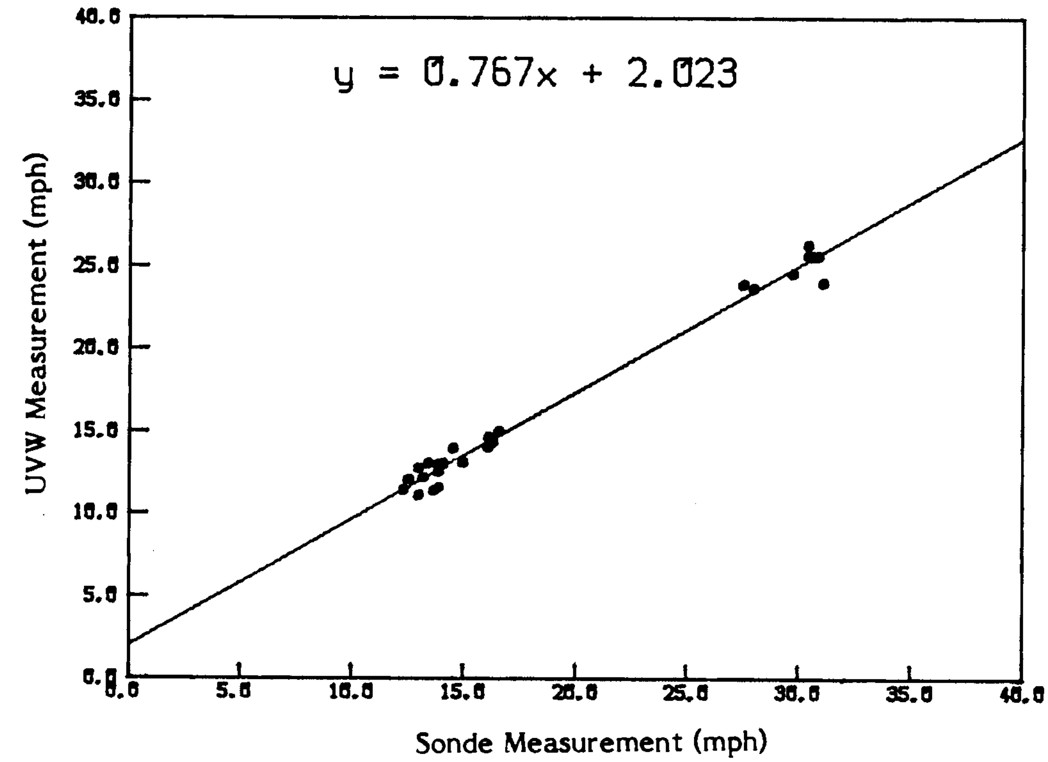

FIGURE A-1. 10-Minute Average Measurements from UVW and Sonde Anemometers

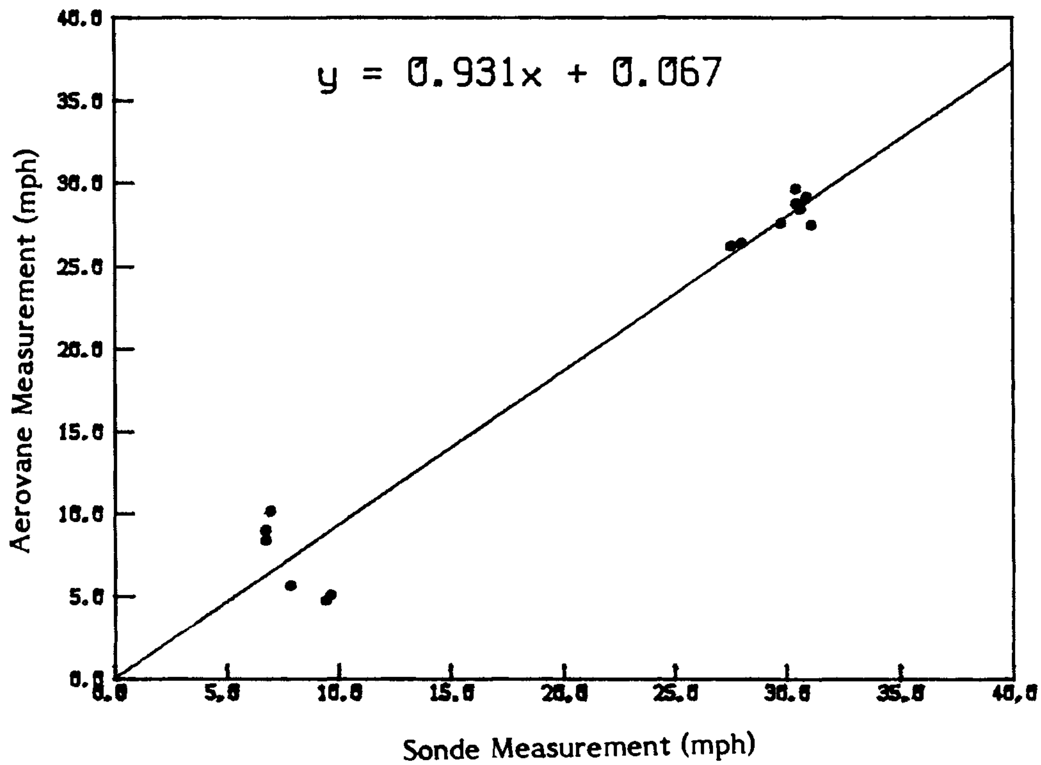

FIGURE A-2. 10-Minute Average Measurements from Aerovane and Sonde Anemometers

DEFINITIONS OF COLUMN HEADINGS

Start time:	The date (month/day) & time (hrs:mins:secs) at the start of the 10 minute recording period.
Stop time:	The date (month/day) & time (hrs:mins:secs) at the end of the 10 minute recording period.
Vbal:	The average horizontal wind speed recorded by the sonde over the 10 minute recording period.
Tbal:	The horizontal turbulence (standard deviation of horizontal wind speed/mean horizontal wind speed) recorded by the sonde over the 10 minute recording period.
Stk:	The azimuthal position of the sonde measured from the grid of stakes downstream of the turbine.
Vuvw:	The average horizontal wind speed recorded by the uvw anemometer system at the 195ft level of the BPA tower over the 10 minute recording period.
Vvan:	The average horizontal wind speed recorded by the single propellor anemometer at the 195ft level of the BPA tower over the 10 minute recording period.
Vcal:	The corrected average horizontal wind speed recorded at the 195 ft level of the BPA tower over the 10 minute recording period.
Dir:	The mean wind direction recorded at the 195ft level of the BPA tower over the 10 minute recording period.
Tl:	The horizontal longitudinal (windwise) turbulence (standard deviation of horizontal longitudinal (windwise) wind speed/mean horizontal wind speed) recorded at the 195ft level of the BPA tower over the 10 minute recording period.
Th:	The horizontal crosswind turbulence (standard deviation of horizontal crosswind wind speed/mean horizontal wind speed) recorded at the 195ft level of the BPA tower over the 10 minute recording period.
Tv:	The vertical turbulence (standard deviation of vertical wind speed/mean horizontal wind speed) recorded at the 195ft level of the BPA tower over the 10 minute recording period.

CALIBRATION DATA

Start time	Stop time	Vbal	Tbal	Vuvw	Vvan	Dir	Tl	Th	Tv
7/16 15:50:10	7/16 16: 0: 8	13.0	0.21	11.1	----	146	-----	-----	-----
7/16 16: 0: 9	7/16 16:10: 8	13.9	0.24	13.0	----	147	-----	-----	-----
7/16 16:10: 9	7/16 16:20: 8	13.9	0.63	11.6	----	152	-----	-----	-----
7/16 16:20: 9	7/16 16:30: 8	13.6	0.16	11.4	----	144	-----	-----	-----
7/16 16:30: 9	7/16 16:40: 8	12.3	0.22	11.5	----	135	-----	-----	-----
7/16 16:40: 9	7/16 16:50: 8	13.2	0.36	12.2	----	146	-----	-----	-----
7/16 16:50: 9	7/16 17: 0: 8	14.1	0.21	13.1	----	146	-----	-----	-----
7/16 17:11: 0	7/16 17:20:58	16.1	0.24	14.0	----	142	-----	-----	-----
7/16 17:20:59	7/16 17:30:58	15.0	0.25	13.1	----	141	-----	-----	-----
7/16 17:30:59	7/16 17:40:58	16.1	0.19	14.1	----	148	-----	-----	-----
7/16 17:40:59	7/16 17:50:58	16.6	0.09	15.0	----	140	-----	-----	-----
7/16 17:50:59	7/16 18: 0:58	14.5	0.15	14.0	----	142	-----	-----	-----
7/16 18: 0:59	7/16 18:10:58	16.3	0.19	14.4	----	143	-----	-----	-----
7/16 18:10:59	7/16 18:20:58	16.1	0.15	14.6	----	138	-----	-----	-----
7/16 18:20:59	7/16 18:30:58	14.1	0.10	13.0	----	142	-----	-----	-----
7/16 18:30:59	7/16 18:40:58	13.9	0.15	12.6	----	138	-----	-----	-----
7/16 18:56: 0	7/16 19: 5:58	13.4	0.10	13.1	----	137	-----	-----	-----
7/16 19: 5:59	7/16 19:15:58	12.5	0.14	12.1	----	144	-----	-----	-----
7/16 19:15:59	7/16 19:25:58	13.0	0.07	12.8	----	146	-----	-----	-----
7/28 22: 5: 8	7/28 22:15: 8	9.4	0.38	5.0	4.8	337	0.155	0.259	0.056
7/28 22:15: 8	7/28 22:25: 8	9.6	0.33	5.7	5.1	323	0.095	0.091	0.037
7/28 22:36: 0	7/28 22:45:58	7.8	0.14	6.9	5.7	315	0.087	0.072	0.032
7/28 22:55:59	7/28 23: 5:58	6.7	0.13	----	8.4	284	-----	-----	-----
7/28 23: 5:59	7/29 23:15:58	6.7	0.07	----	9.1	281	-----	-----	-----
7/28 23:15:59	7/28 23:25:58	6.9	0.06	----	10.2	279	-----	-----	-----
7/30 17:27: 7	7/30 17:37: 5	27.5	0.18	23.9	26.3	260	0.139	0.087	0.077
7/30 17:43: 0	7/30 17:52:58	28.0	0.22	23.7	26.4	261	0.180	0.112	0.071
7/30 17:52:59	7/30 18: 2:58	29.8	0.23	24.6	27.6	261	0.114	0.105	0.060
7/30 18: 2:59	7/30 18:12:58	30.6	0.18	25.6	28.5	263	0.114	0.112	0.060
7/30 18:12:59	7/30 18:22:58	30.4	0.17	25.7	28.8	263	0.124	0.102	0.061
7/30 19:22: 0	7/30 19:31:58	30.4	0.21	26.3	29.7	265	0.077	0.089	0.047
7/30 19:50:10	7/30 20: 0: 8	30.9	0.12	25.6	29.2	268	0.049	0.097	0.041
7/30 20: 0: 9	7/30 20:10: 8	31.1	0.16	24.1	27.5	267	0.060	0.104	0.044

3-D WAKE MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/14 21:25:30	7/14 21:35:28	18.1	1.23	265	18.3	259	-----	-----	-----
7/14 21:35:29	7/14 21:45:28	15.7	1.44	265	14.7	249	-----	-----	-----
7/15 19:28:10	7/15 19:38: 8	15.0	0.72	265	17.7	263	-----	-----	-----
7/15 19:38: 9	7/15 19:48: 8	8.5	6.53	265	20.8	259	-----	-----	-----
7/15 21: 6:10	7/15 21:16: 8	20.1	0.24	255	17.5	271	-----	-----	-----
7/15 21:16: 9	7/15 21:26: 8	22.4	0.99	255	20.2	275	-----	-----	-----
7/15 21:26: 9	7/15 21:36: 8	23.7	0.24	255	21.2	274	-----	-----	-----
7/15 21:36: 9	7/15 21:46: 8	26.6	0.81	255	25.2	275	-----	-----	-----
7/15 21:46: 9	7/15 21:56: 8	26.6	0.29	255	26.0	272	-----	-----	-----
7/31 17:15: 0	7/31 17:24:58	18.3	0.30	257	23.0	250	-----	-----	-----
7/31 17:24:59	7/31 17:34:58	18.1	0.26	257	23.6	255	-----	-----	-----
7/31 17:34:59	7/31 17:44:58	20.1	0.51	257	19.6	246	-----	-----	-----
7/31 17:44:59	7/31 17:54:58	20.1	0.32	257	20.4	258	-----	-----	-----
7/31 17:54:59	7/31 18: 4:58	21.7	0.20	257	23.8	263	-----	-----	-----
7/31 18: 4:59	7/31 18:14:58	19.5	0.39	257	24.3	276	-----	-----	-----
7/31 19:31: 0	7/31 19:40:58	19.0	0.33	272	37.3	261	-----	-----	-----
7/31 19:40:59	7/31 19:50:58	17.4	0.32	272	42.0	268	-----	-----	-----
7/31 19:50:59	7/31 20: 0:58	18.1	0.33	272	43.4	268	-----	-----	-----
7/31 20: 0:59	7/31 20:10:58	19.0	0.18	272	43.7	268	-----	-----	-----
7/31 20:10:59	7/31 20:20:58	22.4	0.28	272	44.6	218	-----	-----	-----

3-D BACKGROUND MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/14 21:45:29	7/14 21:55:28	16.3	0.49	265	14.3	243	-----	-----	-----
7/14 21:55:29	7/14 22: 5:28	12.3	0.62	265	10.1	225	-----	-----	-----
7/31 2: 0: 0	7/31 2: 9:58	32.2	0.11	260	30.1	261	0.056	0.057	0.037
7/31 2: 9:59	7/31 2:19:58	31.1	0.18	260	29.3	262	0.065	0.076	0.039
7/31 2:19:59	7/31 2:29:58	28.9	0.12	260	30.0	260	0.069	0.081	0.047
7/31 2:29:59	7/31 2:39:58	29.5	0.10	260	29.5	261	0.072	0.079	0.046
7/31 2:39:59	7/31 2:49:58	30.9	0.12	260	30.3	260	0.064	0.076	0.037
7/31 3: 0: 0	7/31 3: 9:58	30.0	0.08	260	29.5	260	0.059	0.056	0.031
7/31 18:20: 0	7/31 18:29:58	22.4	0.20	257	28.2	266	-----	-----	-----
7/31 18:29:59	7/31 18:39:58	22.1	0.14	257	28.0	264	-----	-----	-----
7/31 19: 0: 0	7/31 19: 9:58	23.0	0.17	250	30.4	260	-----	-----	-----

5-D WAKE MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/15 22:10:10	7/15 22:20: 8	23.9	1.96	265	22.2	262	-----	-----	-----
7/15 22:20: 9	7/15 22:30: 8	24.6	0.36	265	24.5	272	-----	-----	-----
7/15 22:30: 9	7/15 22:40: 8	27.1	0.03	265	24.9	276	-----	-----	-----
7/15 22:40: 9	7/15 22:50: 8	26.2	0.03	265	25.9	276	-----	-----	-----
7/15 22:50: 9	7/15 23: 0: 8	25.3	0.09	265	25.3	278	-----	-----	-----
7/15 23: 0: 9	7/15 23:10: 8	23.9	0.07	265	23.4	274	-----	-----	-----
7/15 23:10: 9	7/15 23:20: 8	23.0	0.17	265	21.6	270	-----	-----	-----
7/15 23:24:10	7/15 23:34: 8	20.8	1.35	265	19.8	264	-----	-----	-----
7/15 23:54:10	7/16 0: 4: 8	23.7	0.12	260	22.9	271	-----	-----	-----
7/16 0: 4: 9	7/16 0:14: 8	23.3	0.10	260	22.5	276	-----	-----	-----
7/16 0:14: 9	7/16 0:24: 8	22.1	0.10	260	21.0	273	-----	-----	-----
7/16 0:43:10	7/16 0:53: 8	19.0	0.13	265	18.8	270	-----	-----	-----
7/16 0:53: 9	7/16 1: 3: 8	16.8	0.35	265	18.7	266	-----	-----	-----
7/16 1: 3: 9	7/16 1:13: 8	16.8	0.24	265	16.4	267	-----	-----	-----
7/16 1:13: 9	7/16 1:23: 8	14.1	0.22	265	14.5	265	-----	-----	-----
7/16 1:23: 9	7/16 1:33: 8	14.1	0.11	265	14.8	267	-----	-----	-----
7/16 1:43: 0	7/16 1:52:58	14.8	0.15	265	16.0	273	-----	-----	-----
7/30 20:50: 0	7/30 20:59:58	32.4	0.14	257	22.7	273	0.147	0.124	0.091
7/31 20:40: 0	7/31 20:49:58	37.1	0.11	265	38.3	248	-----	-----	-----
7/31 20:49:59	7/31 20:59:58	38.5	0.03	265	39.6	251	-----	-----	-----
7/31 20:59:59	7/31 21: 9:58	38.5	0.06	265	37.9	244	-----	-----	-----
7/31 21:18: 0	7/31 21:27:58	38.7	0.08	265	35.1	236	-----	-----	-----
7/31 22:24:59	7/31 22:34:58	34.0	0.15	270	41.8	252	-----	-----	-----
7/31 22:34:59	7/31 22:44:58	36.0	0.22	270	40.4	252	-----	-----	-----
7/31 23:12: 0	7/31 23:21:58	36.7	0.21	255	43.5	258	-----	-----	-----
7/31 23:21:59	7/31 23:31:58	35.1	0.10	255	41.1	255	-----	-----	-----
7/31 23:31:59	7/31 23:41:58	35.1	0.11	255	34.8	249	-----	-----	-----

5-D BACKGROUND MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/30 22:30: 0	7/30 22:39:58	32.7	0.03	257	31.5	262	0.101	0.096	0.066
7/30 22:39:59	7/30 22:49:58	32.4	0.05	257	30.4	261	0.116	0.082	0.064
7/30 22:49:59	7/30 22:59:58	30.2	0.06	257	28.2	264	0.121	0.105	0.065
7/30 22:59:59	7/30 23: 9:58	30.6	0.11	257	28.2	266	0.105	0.096	0.060
7/30 23: 9:59	7/30 23:19:58	33.6	0.11	257	28.8	267	0.110	0.085	0.051
7/30 23:19:59	7/30 23:29:58	32.0	0.10	257	25.9	268	0.145	0.119	0.082
7/31 1:12: 0	7/31 1:21:58	30.6	0.13	260	27.8	269	0.096	0.085	0.050
7/31 21:30: 0	7/31 21:39:58	36.5	0.15	265	35.9	252	0.122	0.089	0.055
7/31 21:39:58	7/31 21:49:58	32.0	0.15	265	40.2	251	0.070	0.051	0.039
7/31 21:55: 0	7/31 22: 4:58	33.3	0.11	270	40.2	254	0.065	0.047	0.039
7/31 22: 4:59	7/31 22:14:58	31.8	0.17	270	38.8	257	0.051	0.064	0.032

7-D WAKE MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/14 15:56:30	7/14 16: 6:28	25.1	0.26	255	25.0	248	-----	-----	-----
7/14 16: 6:29	7/14 16:16:28	26.6	0.26	255	28.0	251	-----	-----	-----
7/14 16:16:29	7/14 16:26:28	24.2	0.25	255	22.6	255	-----	-----	-----
7/14 16:26:29	7/14 16:36:28	23.3	0.19	255	20.2	265	-----	-----	-----
7/14 16:36:29	7/14 16:46:28	25.9	0.30	255	22.9	273	-----	-----	-----
7/14 16:46:29	7/14 16:56:28	28.0	0.25	255	24.7	262	-----	-----	-----
8/ 1 0: 0: 0	8/ 1 0: 9:58	34.4	0.15	255	36.5	251	-----	-----	-----

7-D BACKGROUND MEASUREMENTS

Start time		Stop time		Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/31	3:45: 0	7/31	3:54:58	31.5	0.11	263	31.7	258	0.044	0.061	0.022
7/31	3:54:59	7/31	4: 4:58	32.2	0.08	263	31.5	251	-----	-----	-----
7/31	4: 4:59	7/31	4:14:58	32.4	0.03	263	30.6	250	-----	-----	-----
7/31	4:14:59	7/31	4:24:58	31.5	0.12	263	31.3	253	-----	-----	-----
7/31	4:24:59	7/31	4:34:58	32.4	0.10	263	30.7	257	-----	-----	-----
7/31	4:34:59	7/31	4:44:58	32.7	0.05	263	31.8	256	-----	-----	-----

9-D WAKE MEASUREMENTS

Start time	Stop time	Vbal	Tbal	Stk	Vcal	Dir	Tl	Th	Tv
7/14 17:35:30	7/14 17:45:28	25.5	0.37	260	25.6	274	-----	-----	-----
7/14 17:57: 0	7/14 18: 6:58	24.8	0.34	260	22.5	272	-----	-----	-----
7/14 18: 6:59	7/14 18:16:58	23.9	0.23	260	22.0	270	-----	-----	-----
7/14 18:16:59	7/14 18:26:58	25.5	0.18	260	22.2	271	-----	-----	-----
7/14 18:26:59	7/14 18:36:58	26.2	0.25	260	27.3	276	-----	-----	-----
7/14 19:30:30	7/14 19:40:28	23.7	0.35	270	23.0	266	-----	-----	-----
7/14 19:40:29	7/14 19:50:28	24.4	0.18	270	22.2	268	-----	-----	-----
7/14 19:50:29	7/14 20: 0:28	26.4	0.22	270	24.6	278	-----	-----	-----
7/14 20: 0:29	7/14 20:10:28	22.6	0.22	270	17.3	270	-----	-----	-----

DISTRIBUTION

No. of Copies	
OFFSITE	
	D. Ancona Department of Energy Wind Energy Technology Division 1000 Independence Avenue Forrestal Building, Room 5F059 Washington, DC 20585
	C. I. Aspliden Battelle Memorial Institute Washington Operations Office 2030 M Street N.W. Washington, DC 20036
	L. V. Divone Department of Energy Wind Energy Technology Division 1000 Independence Avenue Forrestal Building, Room 5F059 Washington, DC 20585
	G. P. Tennyson Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87110
27	DOE Technical Information Center
10	P.B.S. Lissaman Aerovironment, Inc. 145 Vista Avenue Pasadena, CA 91107
	K. C. Spengler American Meteorological Society 45 Beacon Street Boston, MA 02108
	T. Gray American Wind Energy Association 2010 Massachusetts Avenue N.W. Washington, DC 20036

No. of Copies	
5	M. Bovarnick Wind Turbine Group Boeing Engineering & Construction P.O. Box 3707 Seattle, WA 98124
	N. Butler Bonneville Power Administration P.O. Box 3621 Portland, OR 97208
2	E. J. Warchol/R. H. Holeman Bonneville Power Administration P.O. Box 3621 Portland, OR 97208
	S. J. Hightower Bureau of Reclamation Denver Federal Center Building 67, Code 254 Denver, CO 80225
	R. N. Clark Department of Agriculture S.W. Great Plains Research Center Bushland, TX 79012
2	E. DeMeo/F. R. Goodman Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94303
	S. R. Andersen ERT, Inc. P.O. Box 2105 Fort Collins, CO 80522
	H.-T. Liu Flow Wind, Corporation 21414-68th Avenue, South Kent, WA 98031

No. of
Copies

J. D. West
HQ MAC/DEEE
Scott AFB, IL 62225

G. G. Worley, Maj. USAF
HQ AF-ESC/RDVA
Tyndall AFB, FL 32403

V. F. Garrett
Montana Energy and MHD Research and Development Institute, Inc.
P.O. Box 3809
Butte, MT 59701

J. Konigsberg
Montana Energy Office
Capital Station
Helena, MT 59601

5 L. Gordon
NASA/Lewis Research Center
Mail-Stop 500-202
21000 Brookpark Road
Cleveland, OH 44135

M. J. Changery
National Oceanic and Atmospheric Administration
National Climatic Center
Federal Building
Asheville, NC 28801

2 R. W. Baker
Atmospheric Sciences Department
Oregon State University
Corvallis, OR 97331

T. J. Healy/C. Hansen
Rockwell International
Rocky Flats Plant
P.O. Box 464
Golden, CO 80401

E. Kadlec
Sandia Laboratories
Division 5443
P.O. Box 5800
Albuquerque, NM 87115

No. of
Copies

R. E. Akins
Sandia Laboratories
Division 5443
P.O. Box 5800
Albuquerque, NM 87115

R. M. Traci
Science Applications, Inc.
P.O. Box 2351
La Jolla, CA 92038

R. Noun
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

2 C. M. Bhumralkar/W. Johnson
Stanford Research Institute, International
333 Ravenswood Avenue
Menlo Park, CA 94025

R. M. Endlich/J. D. Lee
Stanford Research Institute, International
333 Ravenswood Avenue
Menlo Park, CA 94025

B. Bailey
Atmospheric Sciences Research Center
State University of New York at Albany
Albany, NY 12222

N. E. Suhs
Tennessee Valley Authority
1360 Commerce Union Bank Building
Chattanooga, TN 37401

W. R. Thorn, Manager
TERA Corporation
Wind Systems Engineering
2150 Shattuck Avenue
Berkeley, CA 94704

No. of Copies

J.-T. Lin, President
United Industries, Corporation
12835 Bell-Red Road
Bellevue, WA 98005

A. Daniels
University of Hawaii at Manoa
Department of Meteorology
2525 Correa Road
Honolulu, HI 96822

M. Garstang
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22903

S. Hosch
Washington State Energy Office
400 E. Union Avenue, 1st Floor
Olympia, WA 98504

F. S. Seiler
Wind Energy Report
Box 14 - 104 S. Village Avenue
Rockville Centre, NY 11571

E. L. Davis
U.S. Windpower, Inc.
6421 B. South Front Road
Livermore, CA 94550

R. L. Berry
Atmospheric Environment
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
CANADA

R. J. Templin
National Research Council of Canada
National Aeronautical Establishment
M-2 Montreal Road
Ottawa, Ontario K1A OR6
CANADA

No. of Copies

D. Lindley
Taylor Woodrow Construction, Limited
Taywood House
345 Ruislip Road
Southhall, Middlesex UBI 2QX
ENGLAND

D. T. Swift-Hook
Head of Applied Physics Branch
Central Electricity Research Laboratories
Kelvin Avenue
Leatherhead
Surrey, KT 22
UNITED KINGDOM

P. W. Blakely
New Zealand Electricity
Rutherford House
Lambton Quay
Wellington
NEW ZEALAND

N. Cherry
Lincoln College
Canterbury
NEW ZEALAND

O. Ljungstrom
FFA, The Aeronautical Research Institute
Forskningsstationen i Stockholm
Drottning Kristinas Vag 47
S-114 29 Stockholm
SWEDEN

ONSITE

DOE Richland Operations Office

H. E. Ransom/D. R. Segna

No. of Copies		No. of Copies	
43	Pacific Northwest Laboratory		E. L. Owczarski
			D. C. Powell
	W. R. Barchet		J. J. Praino
	J. W. Buck		D. S. Renne
	J. R. Connell		W. F. Sandusky
	C. E. Elderkin		H. L. Wegley
	D. L. Elliott		L. L. Wendell
	R. L. George		R. K. Woodruff
	D. L. Hadley (5)		Technical Information - Library (5)
	S. K. Heflick		Publishing Coordination (2)
	A. H. Miller		WCPE Project Office (15)