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WIND PROFILE MEASUREMENTS AT THE MOD-1 SITE AT BOONE,
NORTH CAROLINA

By
J. Donald Brown

Work Performed Under Contract No. AC06-76RL01830

Research Engineer
Route 2, Box 310
Afton, Virginia

U.S. Department of Energy

Solar Energy

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J. Donald Brown
Research Engineer
Route 2, Box 310
Afton, Virginia 22920

Prepared for
Pacific Northwest Laboratory
Under Agreement B-23100-A-P

Pacific Northwest Laboratory
Richland, Washington 99352

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CAROLINA

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INTRODUCTION

To complete the measurement of wind profiles at Boone, North Carolina, we gathered four types of data at the MOD-1 wind turbine site at Boone, North Carolina during the period 13-21 March 1979. The recorded data included:

- A. Nacelle profiles: Fifty-eight nacelle profiles (0-42 meters) were taken using a line and pulley system attached to the end of the generator nacelle. Six of these profiles were done on the downwind end of the nacelle; 52 at the upwind end.
- B. Turbulence measurements: Twenty-two 20-minute fixed level operations were done to sample turbulence fields (2 sec sample rate). Sixteen of these time periods were sampled on the nacelle line and pulley arrangement at various heights
- C. Vertical velocity component of flow: During the 20-min fixed level operations the vertical wind speed component was also measured and was visually judged to be of significant magnitude.
- D. Temperature profiles: All wind measurements were accompanied by simultaneous temperature measurements.

The results of analysis of each of these sets of observations are presented in three parts. Part I, a report entitled "Wind shear and gustiness at the MOD-1 site, Boone, North Carolina," and Part III, the data list, figures and tables from the analysis, are presented after this introduction. Part II of this analysis was published as the following article:

Garstang, M., J. W. Snow and G. D. Emmitt. 1980. "Measurements of Wind Shear at the MOD-1 Site, Boone, N.C." in A Collection of Technical Papers. Proceedings of the AIAA/SERI Wind Energy Conference, April 9-11, 1980, Boulder, Colorado. Available from American Institute of Astronautics and Aeronautics, New York.

FINAL REPORT BOONE II

Part I

WIND SHEAR AND GUSTINESS AT THE MOD-1 SITE,
BOONE, NORTH CAROLINA

by

Michael Garstang, George D. Emmitt
and
J. William Snow

18 June 1980

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WIND SHEAR GUSTINESS AT THE MOD-1 SITE,
BOONE, NORTH CAROLINA

Michael Garstang, George D. Emmitt and J.W. Snow
Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

EXECUTIVE SUMMARY

Three components of the wind field, temperature and pressure were measured by means of tethered balloon-borne sondes from the surface to 175 m (577 ft) and by means of a nacelle mounted system, from the surface to hub height of 43 m (140 ft). Measurements were taken over a ten day period at the Mod-1 Site in Boone, N.C. Composite wind profiles are presented for different flow and stability regimes. The most extreme shears, on the order of $.3 \text{ s}^{-1}$, were found between 10 m (33 ft) and hub height. Individual profiles of wind and temperature show the effect of nocturnal cooling and accompanying surface stratification on the intensity of the wind shear. Gustiness measured in terms of departures of one and two standard deviations above and below the mean, occurs at all heights across the rotor of the Mod-1 machine. Most frequent gustiness, however, occurs at and below hub height with periods up to 8 secs. Similar fluctuations are observed in the vertical component of the velocity field and in the direction of the horizontal wind.

The depth of the shearing layer is critically related to hub height and rotor radius. The depth of the shearing layer appears to vary most significantly with thermal stratification; strong surface inversions producing shallow intense shearing layers; adiabatic conditions reflecting only topographically induced shear. For a given site and a given generator, hub height should be guided by the depth of the mean shear layer under adiabatic conditions plus the radius of the rotor.

INTRODUCTION

Wind profile measurements were made at the Mod-1 Wind Turbine site on Howard Knob, Boone, N.C. over a 10-day period from 13 March to 22 March 1979.

Measurements were made using a 25 m^3 (900 cu ft) tethered balloon up to altitudes of 170 m (560 ft) and a line and pulley system attached to the downwind end of the generator nacelle at approximately 43 m (140 ft) above the ground. Figure 1 shows the physical layout of the balloon and tower measuring systems. The balloon, when at the maximum altitude of 170 m (560 ft), had a maximum horizontal displacement of 60 m (200 ft). In general the horizontal displacement of the balloon was much less than 30 m (100 ft).

Figure 1. General layout (not to scale) of measurement systems. Balloon line angles from the vertical at 170 m (560 ft) were never more than 20°C.

The 280 balloon and 58 nacelle soundings were made with a boundary layer sonde which was raised and lowered at about 1 m s^{-1} (3 ft s^{-1}). The sonde transmitted wind speed to a ground receiving station once every two seconds giving a vertical resolution of 2 m (6 ft). Additional information such as temperature, pressure, vertical velocity and wind direction are available every 4 seconds.

The purpose of this paper is to show to what extent, in the presence of the fairly marked topography of the Boone site, the vertical shear of horizontal wind is a function of wind speed, wind direction and the static stability of the atmosphere close to the ground. We further verify that the levels of turbulence are considerably higher in the region of shear than in the more uniform current above the shearing layer.

MEAN PROFILES

At the Boone site the most exposed slopes in the topography are to the SE. To the NW, slopes are severe but their effect on the wind may be moderated by adjacent higher ground in that direction. Figure 2 illustrates a cross section of the topography in the prevailing wind directions which are the NW and SE. We present examples of mean profiles for these two directions.

Figure 2. A vertical 4 mi NW/SE section through the Boone Mod-1 tower site. The horizontal scale is 2 inches to 1 mi with a vertical exaggeration of 1:5.28.

Figures 3a and b show mean profiles for moderate NNW and moderate SSE winds on 19 and 21 March 1979 respectively. Marked low level shear between the surface and 40 m (130 ft) is present for both the NW flow (Fig. 3a) and the SSE flow (Fig. 3b), with relatively uniform flow above 40 m (130 ft). The shear of the mean profile on the early morning of 19th March (Fig. 3a) is more intense than for the afternoon of 21st March (Fig. 3b) despite the fact that the SSE flow encounters a sustained slope. This suggests that thermal stratification exacerbates the shear since it is most intense when the near surface air is cold.

Wind speeds on the 18th March (Fig. 4) are well into the operating range of the Mod-1 generator. This moderate to strong NW flow shows intense mean shear in the mean wind speed close to the ground (0-15 m (0-50 ft)) with weak shear above 15 m (50 ft) but pronounced gustiness throughout the measured profile. Although the shear on this day appears to be concentrated in the lowest 15 m (50 ft) of the mean profile, a study of 38 individual soundings taken over a period of 4 hours with the nacelle profiling system showed that for most of the time strong shear layers existed between 12 and 40 m (40 and 130 ft).

Figure 5 is the average of the 38 nacelle profiles. Figures 6a-d show mean nacelle profiles for five time periods which are combined to make up Fig. 5. The variability of the wind is illustrated by the scatter

Figure 3a. Wind profiles (8) made at the Mod-1 generator site, Boone, N.C. on 19 March 1979, 0820-0900 EST. Winds from NNW through total height of profiles. At each 4 m interval above the surface solid dots indicate individual measured speeds (m s^{-1}), open circle - mean values, horizontal line and end segments - plus or minus one standard deviation.

Figure 3b. Same as Figure 3a except date and time are 21 March 1979, 1640-1710 EST, and winds from the SSE.

Figure 4. Same as Figure 3a except date and time are 18 March 1979, 1020-1145 EST, and wind from NW.

of observations in each of the time periods of Fig. 6. The average speed difference (ΔV) between 40 m (130 ft) and 12 m (40 ft) was 1.79 m s^{-1} . However, the actual shears are better summarized in Fig. 7a and b. Figure 7a is a distribution of the speed difference, ΔV , between hub height (40 m (130 ft)) and the tip of the blade (12 m (40 ft)). For approximately 20% of the time the 28 m (90 ft) layer shear is greater than twice the average.

Figure 7b summarizes the statistics for shear in 5 m (16 ft) or thicker layers between 10 and 40 m (33 and 130 ft). Each of the 38 nacelle profiles was smoothed and then inspected for maximum shear layers. Although the average ΔV shear is equivalent to $.064 \text{ s}^{-1}$, all 38 of the nacelle profiles contained layers with shear greater than that figure. In fact for 26T of the profiles there was a five meter layer above 10 m (33 ft) through which the wind speed increased by more than 2.1 m s^{-1} (5 mph).

THERMAL STRATIFICATION AND WIND SHEAR

Figures 8a, b and c and Figures 9a and b show individual profiles of wind speed and temperature for NNW and SSE flow respectively on 19 and 21 March. Low level inversions in temperature present in the early morning of each day are eliminated by daytime heating. In each case, the more uniform flow is present down to the top of the inversion. The depth of the shearing layer grows and the magnitude of the shear decreases as the inversion is eroded.

Figure 5. Average of 38 nacelle profiles on 18 March 1979 from 1231-1516 EST.

Figure 6. Nacelle profiles for four time periods on 18 March 1979.

- a) 1231-1308 EST
- b) 1314-1344 EST
- c) 1516-1549 EST
- d) 1551-1615 EST

9 Nacelle Profiles 18 March 1979
1231-1308 EST

Figure 6. a) 1231-1308 EST.

10 Nacelle Profiles 18 March 1979
1314-1344 EST

Figure 6. b) 1314-1344 EST.

II Nacelle Profiles 18 March 1979
1516-1549 EST

Figure 6. c) 1516-1549 EST.

8 Nacelle Profiles 18 March 1979
1551-1615 EST

Figure 6. d) 1551-1615 EST.

Figure 7. Distribution of shear (a) for the layer between 12 and 40 m. The average difference $(V_{40m} - V_{12m}) = \Delta V$ is 1.79 m s^{-1} . (b) Where the maximum difference in speed is obtained in any 5 m or thicker layer between 10 and 40 m for each of the 38 nacelle profiles. Average maximum shear is 0.35 m s^{-1} .

Figure 8a. Individual profiles of temperature (open circles) and wind speed (solid dots) at 0820 EST, 19 March 1979, winds from the NNW. Dashed line is standard lapse rate, -0.65°C per 100 m. Solid lines show a fit by eye to the shearing layer and to the more uniform flow above the shearing layer.

Figure 8b. Same as Figure 8a except time is 0844 EST.

Figure 8c. Same as Figure 8a except time is 1618 EST.

Figure 9a. Individual profiles of temperature (open circles) and wind speed (solid dots) at 0904 EST, 21 March 1979, winds from the SSE. Dashed line is standard lapse rate -0.65°C per 100 m. Solid lines show a fit by eye to the shearing layer and to the more uniform flow above the shearing layer.

Figure 9b. Same as Figure 9a except time is 1639 EST.

The similarities in behavior of the flow regimes from opposite directions over markedly different terrain are pronounced. This might suggest, in common with the behavior of the mean profiles, that thermal stratification plays an important role in determining both the depth and intensity of the low level shearing region. However, detailed examination

of individual profiles suggest that there is more severe shear including possible flow separation for SE winds.

The shearing layer present without thermal stratification (Figs. 8c and 9b) can be ascribed to the effect of the topography of the site. Topographically induced shear under NNW flow (Fig. 8c) is not quite as intense as under SSE flow (Fig. 9b) where individual profiles suggest boundary layer separation.

Variations in the depth of the shearing layer as a function of topography and thermal stratification illustrate that the choice of the hub height of the generator is an important consideration in wind generator installation.

The depth of the shearing layer is critically related to the hub height and blade radius. For the Boone site, under the limited conditions studied, a hub height of $r + 150$ ft, where r is the radius of the blades, would keep the rotor in the more uniform flow and above the shearing layer. Figure 10 superimposes the Mod-1 generator upon the mean SSE flow of Fig. 3b illustrating that hub height at 40 m (140 ft) is near the top of the shearing layer with the lower blade embedded in the region of maximum shear and the upper blade in the region of uniform flow.

Figure 10. The U.S. Mod-1 Wind Turbine Generator superimposed upon the Howard Knob wind profile, late afternoon 21 March 1979. Winds from the SSE.

GUSTINESS

Table 1 shows the mean wind speed, standard deviation and gustiness ($\sigma_u/\bar{u}$) at levels within and above the shearing layer. The highest gustiness is, in general, observed below 40 m (140 ft) level, with maximum values occurring at the lowest level shown (12 m (40 ft)).

Table 1

Balloon Data					Nacelle Data				
	Day	$\bar{u}$	σ_u	$\sigma_u/\bar{u}$	Day	$\bar{u}$	σ_u	$\sigma_u/\bar{u}$	
NNW	240'	19	7.36	1.55	.21				
	140'				18	7.26	1.57	.22	
	90'				18	6.6	1.3	.20	
	40'				18	4.2	1.2	.29	
SSW	240'	17	3.64	.82	.22				
	140'	17	3.78	.79	.21	17	2.57	.96	.37
	90'				17	3.10	.89	.29	
	40'	17	2.81	.88	.31	17	1.19	.69	.57

The statistics in Table 1 provide information regarding turbulence at different heights in the air stream. The numbers in Table 1 do not, however, provide information on the duration, intensity and frequency of occurrence of wind speed changes from some nominal value such as the mean wind speed. Time series of wind speed and direction such as those shown in Figure 11 suggest that for evaluating the usefulness of the wind for the generation of electrical power, a "gust event" analysis is more appropriate. The results of such an analysis are shown for four cases in Table 2. For example, during a 20 minute period at hub height (43 m), the wind speed fell below 4 m s^{-1} (or 15% of the mean wind power) once for 8 secs, once for 4 secs and 9 times for 2 secs. Over a twenty minute period on 19 March, the winds at 75 m fell below the Mod-1 cut-in speed (3.5 m s^{-1}) twice for periods of 4 and 6 secs.

Fluctuations in the wind over periods of seconds could result in major oscillations in power generation. For example, the power density based on the mean wind at hub height (43 m) for the period 1352-1412 EST on 18 March is 151 W m^{-2} ; the maximum power if all gusts could be utilized is 174 W m^{-2} . No allowance, however, has been made for changes in direction or significant (2σ) decreases in wind which last long enough to take the machine off-line.

Figure 11. Time series of wind speed measurements at 130 ft from 1316 to 1410 EST, 18 March 1979, winds from the NW. Time interval between data points is 40 sec.

[illegible]

Figures 12a, b and c show a 5 minute time series of vertical velocity, horizontal wind speed and wind direction at 27 m, 75 m and 125 m on 18, 17 and 19 March respectively. For the SSW winds which encounter the steep slope illustrated in Figure 2, major vertical velocity excursions are observed. Upward motion approaching 2 m s^{-1} can persist for more than 1 min. Many fluctuations (up and down) of smaller magnitude and duration are observed for both S to SW winds and for the NNW winds. Similar variability is observed in the wind direction which can fluctuate through 120 degrees in about 20 seconds (Figure 12c, 4 min 10 sec to 4 min 30 sec). The fluctuations exhibited in Figure 12 suggest that the severity of macroscale turbulence which is present in rough terrain is on a space and time scale which is likely to influence the performance of wind turbines of the size of the Mod-1 generator.

CONCLUDING REMARKS

At the Boone Mod-1 site maximum shear occurs in the region from hub height 40 m (140 ft) to the surface. This is also likely to be the region of maximum gustiness or turbulent scale fluctuations.

Thermal stratification caused by nocturnal cooling at the surface creating a low level temperature inversion appears to intensify and lower the height of the surface shearing layer.

Although there appears to be fairly pronounced changes in the topography encountered by winds from the SSE versus winds from NNW the character of the shear from each of these directions is similar. Both wind directions respond in a similar way to nighttime cooling and daytime heating. In the absence of thermal stratification the shear that exists for the two directions described is undoubtedly due to the topography of the site. Mean wind shear, however, is the result of spectrum of shearing conditions which fluctuate in intensity over short periods of time (minutes). Design considering only mean shear might, therefore, be conceptually incomplete.

Macroscale turbulent fluctuations with periods of numbers of seconds occur at all heights of the rotor. Based on short (20 min) time series, departures of one standard deviation from the mean with periods up to 8 seconds or approximately 5 revolutions of the Mod-1 blade, are relatively common. Similar fluctuations are observed in the vertical component of the velocity field and in the direction of the horizontal wind, suggesting that three-dimensional eddies are shedding off the face of the knob.

The depth of the shearing layer is critically related to hub height and rotor radius. The depth of the shearing layer appears to vary most significantly with thermal stratification; strong surface inversions producing shallow intense shearing layers; adiabatic conditions reflecting only topographically induced shear. For a given site and a given generator, hub height should be guided by the depth of the mean shear layer under adiabatic conditions plus the radius of the rotor.

Figure 12. Time series of vertical velocity, horizontal wind speed and direction at

- a) 27 m on 18 March 1979, 1416-1421 EST - winds NNW
- b) 75 m on 17 March 1979, 1527-1532 EST - winds from S to SW
- c) 125 m on 19 March 1979, 1309-1314 EST - winds NNW.

27 Meters on 18 March 1979 1416-1421 EST Winds NNW

75 Meters on 17 March 1979 1527-1532 EST Winds S-SW

125 Meters on 19 March 1979 1309-1314 EST Winds NNW

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FINAL REPORT BOONE II

Part III

BOONE MOD-1 SITE, N.C.: DATA LIST,
FIGURES AND TABLES

by

George D. Emmitt, Michael Garstang
and
J.W. Snow

26 June 1980

LISTING OF DATA

The following tables list the observations taken with the tethered balloon and nacelle system. The observations listed represent the complete usable data set and include those observations which form the basis for analyses contained in Part I and Part II of this report.

Table I contains the list of tethered balloon soundings where both the up and down profiles have been listed together with surface observations of wind, temperature and pressure taken intermittently during balloon profile and fixed level operations.

Table II lists all of the usable fixed level periods.

Table III contains the up-down pairs of profiles (therefore total number of profiles is double the number listed) taken with the nacelle system.

All of the data listed in Tables I, II and III are on magnetic tape. Wind measurements are recorded at 2 sec intervals; temperature and pressure is recorded every 4 sec.

FIGURES

Thirty-eight nacelle profiles are summarized in Figure 1. Figures 2-5 show 4 nacelle profiles over shorter intervals of time together with the wind speed at 5 m intervals.

Figures 6-33 display individual nacelle profiles.

Figures 34-38 show the vertical velocity, horizontal velocity and horizontal wind direction at the bottom of blade (Figure 34), at the center of the bottom blade (Figure 35), at the top of the blade (Figures 36-37) and above the rotor (Figure 38).

TABLES

Tables IV-XIII provide gust statistics at 12, 27, 43, 75 and 125 m. Also listed in these tables is the mean, standard deviation, mean power density calculated from the mean wind and the maximum power density calculated from the 2 sec wind values.

Table I. Tethered balloon soundings from the surface to a maximum altitude of 170 m above the surface. Rate of ascent/descent of the balloon is 1 m s^{-1} , however, total elapsed time of ascent, time at altitude and descent is listed. Time at altitude was usually 30 sec.

Profile Number	Date	Start Time (EST)	Stop Time (EST)	Up/Down	Winds $\text{m s}^{-1}/\text{degrees}$	Surface Temperature $^{\circ}\text{C}$	Pressure (mb)
008	16 March 1979	15:33:00	15:40:00	Up/down			
009	"	15:45:00	15:51:45	Up/down			
010	"	15:57:00	16:03:40	Up/down		7.3	876.4
011	"	16:08:00	16:15:00	Up/down	02/95	7.5	876.4
012	"	16:21:00	16:28:30	Up/down	.1/100	7.6	876.4
013	"	16:30:00	16:37:45	Up/down	1/120	7.8	876.5
018	17 March 1979	14:19:00	14:26:00	Up/down			
022	"	14:51:00	14:58:00	Up/down			
026	"	16:52:00	16:59:30	Up/down		4.5	876.9
030	"	17:24:00	17:36:00	Up/down	1.0/222	3.3	876.8
031	18 March 1979	10:18:00	10:25:15	Up/down			
032	"	10:32:00	10:36:10	Up	4.5/241		874.1
033	"	10:40:00	11:07:27	Down			
034	"	11:16:00	11:22:50	Down/up	3.3/343	8.3	873.8
035	"	11:28:00	11:36:00	Down/up	4.5/307		873.8
036	"	11:39:00	11:44:00	Down/up	3.6/313	8.5	873.6
037	"	17:02:00	17:07:25	Up			
039	"	17:20:00	17:26:40	Down/up			
041	"	17:43:00	17:55:40	Down/up			871.5
043	19 March 1979	08:19:00	08:22:50	Up		9.4	871.7
045	"	08:40:30	08:47:25	Down/up		10.5	
046	"	08:49:30	08:55:55	Down/up	1.0/310		
047	"	08:58:30	09:04:40	Down/up		10.5	871.9
048	"	09:07:30	09:13:50	Down/up	1.0/300		
050	"	09:28:30	09:34:40	Down/up	2.0/300		
052	"	09:46:30	09:52:35	Down/up	1.2/270	11.7	871.8
056	"	11:08:30	11:12:00	Up	1.8/310	13.2	871.0
058	"	11:40:30	11:46:15	Down/up	3.2/290	14.5	870.6
062	"	12:14:30	12:20:00	Down/up			
065	"	12:50:30	12:55:55	Down/up	1.5/310		870.4
066	"	14:44:30	14:49:45	Down/up		17.5	869.4
071	"	15:39:30	15:44:30	Down/up		17.5	869.1
074	"	16:17:30	16:22:15	Down/up			

Table I (cont.)

Profile Number	Date	Start Time (EST)	Stop Time (EST)	Up/Down	Winds m s^{-1} /degrees	Surface Temperature °C	Pressure (mb)
075	19 March 1979	16:24:30	16:27:10	Down		14.5	869.0
076	20 March 1979	09:02:30	09:07:55	Down/up	.2/310	10.1	869.1
080	"	09:48:30	09:53:40	Down/up	calm	11.8	869.0
085	"	10:26:30	10:31:25	Down/up	.5/310		868.6
086	"	14:04:30	14:09:20	Down/up	3.0/290	17.7	866.9
089	"	14:29:30	14:34:45	Down/up	2.0/300		
092	"	14:55:30	15:00:35	Down/up		16.6	866.5
094	"	15:15:30	15:20:25	Down/up			
098	"	16:22:30	16:27:40	Down/up			
102	"	16:56:30	17:01:30	Down/up		15.8	866.3
105	"	17:31:30	17:34:30	Down			
106	21 March 1979	09:04:30	09:10:15	Down/up		11.1	868.4
107	"	09:13:30	09:18:25	Down/up			
108	"	09:27:30	09:33:15	Down/up	.5/075		
112	"	10:08:30	10:13:15	Down/up	1.0/120	15.5	868.6
115	"	10:37:35	10:42:20	Down/up		15.8	
116	"	12:39:30	12:44:58	Down/up			
120	"	13:19:30	13:25:15	Down/up	.2/80	16.8	868.3
124	"	14:01:40	14:06:50	Down/up		15.2	867.6
126	"	15:44:30	15:49:57	Down/up	.2/60	16.9	867.6
131	"	16:30:30	16:35:57	Down/up	.2/100		
132	"	16:49:40	16:44:54	Down/up			
133	"	16:48:30	16:53:55	Down/up			
134	"	16:57:30	17:02:50	Down/up	calm	15.2	867.8
135	"	17:06:30	17:11:55	Down/up			
136	22 March 1979	08:26:30	08:35:59	Down/up			
138	"	08:50:30	08:55:55	Down/up	.2/140	7.5	870.4
140	"	09:08:30	09:13:56	Down/up	.2/115		
141	"	09:19:30	09:24:45	Down/up			
142	"	09:29:30	09:34:45	Down/up			
143	"	09:38:37	09:44:10	Down/up	.2/120		
144	"	09:47:30	09:52:50	Down/up			
145	"	09:56:30	09:59:25	Down	.1/070	6.9	870.5

Table II. Tethered balloon measurements at fixed altitudes above the ground corresponding to bottom of the blade (~ 12 m), center of bottom blade (~ 27 m), hub height (~ 43 m), top of blade (~ 75 m) and above the rotor (125 m).

Profile Number	Date	Start Time (EST)	Stop Time (EST)	Winds $\text{m s}^{-1}/\text{degrees}$	Surface Temperature $^{\circ}\text{C}$	Pressure (mb)
903	17 March 1979	09:36:10	10:16:10			
904	"	10:37:00	10:57:00			
905	"	12:00:00	12:17:00			
906	"	15:27:00	16:32:00	calm	13.8	877.2
907	18 March 1979	13:52:00	14:12:00			
908	"	14:16:00	14:36:00			
909	19 March 1979	13:09:00	13:15:00			870.4
910	"	14:09:00	14:40:00	3.0/310	18.3	869.6
912	21 March 1979	11:03:00	12:07:00		15.8	868.7
913	"	14:25:00	15:39:00		16.5	867.5
914	"	17:18:00	17:26:02	calm	15.4	867.8

Table III. Nacelle profiles made from the surface to hub height (~ 43 m).
Ascent/descent rate and procedure as Table I.

Profile Number	Date	Start Time (EST)	Stop Time (EST)
07	17 March 1979	08:37:00	08:41:00
08	"	09:08:00	09:11:45
10	18 March 1979	12:30:00	12:34:15
11	"	12:40:00	12:44:20
12	"	12:48:03	12:52:20
13	"	12:55:00	13:00:55
14	"	13:05:00	13:09:20
15	"	13:13:00	13:17:30
16	"	13:20:00	13:24:35
17	"	13:27:00	13:31:20
18	"	13:34:00	13:38:20
19	"	13:41:00	13:45:20
20	"	15:15:00	15:19:30
21	"	15:22:00	15:26:20
22	"	15:28:00	15:32:15
23	"	15:36:00	15:39:13
24	"	15:42:00	15:45:09
25	"	15:49:00	15:52:08
26	"	15:55:00	15:58:11
27	"	16:01:00	16:04:04
28	"	16:08:00	16:10:55
29	"	16:15:00	16:17:42

Figure 1. Average of 38 nacelle profiles on 18 March 1979.

Figures 2-5. Nacelle profiles for four time periods on 18 March 1979.

9 Nacelle Profiles 18 March 1979
1231-1308 EST

Figure 2.

10 Nacelle Profiles 18 March 1979
1314 - 1344 EST

Figure 3.

II Nacelle Profiles 18 March 1979
1516-1549 EST

Figure 4.

8 Nacelle Profiles 18 March 1979
1551-1615 EST

Figure 5.

Figures 6-33. Nacelle profiles for 18 March 1979. All profiles are EST.

18 March 1979 12:31

Figure 6.

18 March 1979 12:32.5

Figure 7.

18 March 1979 1241

Figure 8.

18 March 1979 12:49

Figure 9.

18 March 1979 12:51

Figure 10.

18 March 1979 12:57

Figure 11.

18 March 1979 12:59

Figure 12.

18 March 1979 13:06

Figure 13.

18 March 1979 13:08

Figure 14.

18 March 1979 13:14

Figure 15.

18 March 1979 13:16

Figure 16.

18 March 1979 13:23

Figure 18.

18 March 1979 13:21

Figure 17.

18 March 1979 13:28

Figure 19.

18 March 1979 13:30

Figure 20.

18 March 1979 13:35

Figure 21.

18 March 1979 13:37

Figure 22.

18 March 1979 13:42

Figure 23.

18 March 1979 13:44

Figure 24.

18 March 1979 15:16

Figure 25.

18 March 1979 15:18

Figure 26.

18 March 1979 15:23

Figure 27.

18 March 1979 15:25

Figure 28.

18 March 1979 15:29

Figure 29.

18 March 1979 15:31

Figure 30.

18 March 1979 15:36

Figure 31.

18 March 1979 15:38

Figure 32.

18 March 1979 15:42

Figure 33.

Figure 34. Vertical velocity, horizontal velocity and horizontal wind direction at the bottom of the blade.

12 Meters on 17 March 1979 0934-0939 EST Winds N

Figure 35. Vertical velocity, horizontal velocity and horizontal wind direction at the center of the bottom blade.

75 Meters on 17 March 1979 1527-1532 EST Winds S-SW

Figure 36. Vertical velocity, horizontal velocity and horizontal wind direction at the top of the blade.

75 Meters on 21 March 1979 1718-1723 EST Winds NE

Figure 37. Vertical velocity, horizontal velocity and horizontal wind direction at the top of the blade.

Figure 38. Vertical velocity, horizontal velocity and horizontal wind direction above the rotor.

Table IV: Gust statistics at 12 m on 17 March 1979, 0934-0954 EST.

Mean (m s^{-1}): 0.94

Standard Deviation (m s^{-1}): 0.94

Mean (watts m^{-2}): 0.31

Power Maximum (watts m^{-2}): 3.06

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	0	6	4	1
4	0	0	0	3
6	0	0	2	0
8	0	0	1	0
10	0	2	0	0
12	0	2	0	0
14	0	0	0	0
16	0	2	1	0
18	0	0	0	0
20	0	0	0	0
22	0	0	0	0
24	0	0	0	0
26	0	0	0	0
28	0	0	0	0
30	0	1	0	0

Table V. Gust statistics at 27 m on 17 March 1979, 1200-1220 EST.

Mean (m s^{-1}): 2.97

Standard Deviation (m s^{-1}): 1.17

Mean (watts m^{-2}): 9.92

Power Maximum (watts m^{-2}): 14.98

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	0	5	13	3
4	1	5	5	1
6	1	4	1	0
8	0	1	3	0
10	0	0	0	0
12	0	1	2	0
14	1	1	1	0
16	1	0	0	0
18	0	0	1	0
20	0	0	1	0

Table VI. Gust statistics at 43 m on 17 March 1979, 1037-1057 EST.

Mean (m s^{-1}): 2.79
 Standard Deviation (m s^{-1}): 1.39
 Mean (watts m^{-2}): 8.21
 Power Maximum (watts m^{-2}): 17.92

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	2	9	7	2
4	1	4	4	1
6	0	2	2	0
8	0	3	1	0
10	0	2	0	0
12	0	1	0	0
14	0	1	0	0
16	0	1	1	0
18	0	1	0	0
20	0	1	0	0
22	0	0	1	0
24	0	0	0	0
26	0	0	0	0
28	0	0	0	0
30	0	0	0	0
32	0	0	1	0

Table VII. Gust statistics at 75 m on 17 March 1979, 1527-1545 EST.

Mean (m s^{-1}): 4.03
 Standard Deviation (m s^{-1}): 0.98
 Mean (watts m^{-2}): 24.82
 Power Maximum (watts m^{-2}): 29.42

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	4	14	13	6
4	3	7	2	1
6	0	1	4	0
8	0	2	2	1
10	0	2	0	0
12	0	1	1	0
14	0	0	1	0
16	0	0	0	0
18	0	0	1	1
20	0	0	0	0
22	0	2	0	0
24	0	0	1	0
26	0	0	0	0
28	0	0	0	0
30	0	1	1	0

Table VIII. Gust statistics at 27 m on 18 March 1979, 1416-1436 EST.

Mean (m s^{-1}): 6.74
 Standard Deviation (m s^{-1}): 1.23
 Mean (watts m^{-2}): 115.79
 Power Maximum (watts m^{-2}): 127.36

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	2	6	11	3
4	2	0	4	1
6	0	3	2	0
8	0	3	0	0
10	0	0	0	0
12	0	0	0	0
14	0	0	1	0
16	0	1	0	0
18	0	0	0	0
20	0	1	0	0

Table IX. Gust statistics at 43 m on 18 March 1979, 1352-1412 EST.

Mean (m s^{-1}): 7.36
 Standard Deviation (m s^{-1}): 1.66
 Mean (watts m^{-2}): 150.67
 Power Maximum (watts m^{-2}): 173.88

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	9	16	16	6
4	1	10	4	3
6	0	3	3	2
8	1	1	0	0
10	0	1	1	0
12	0	3	0	1
14	0	0	1	0
16	0	0	0	0
18	0	0	0	0
20	0	0	0	0
22	0	1	0	0
24	0	0	0	0
26	0	1	0	0

Table X. Gust statistics at 75 m on 19 March 1979, 1409-1429 EST.

Mean (m s^{-1}): 6.68
 Standard Deviation (m s^{-1}): 1.61
 Mean (watts m^{-2}): 112.55
 Power Maximum (watts m^{-2}): 132.15

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	2	13	16	4
4	1	10	7	1
6	1	2	2	0
8	0	1	2	0
10	0	1	2	0
12	0	1	0	0
14	0	1	2	0
16	0	0	1	0
18	0	0	0	0
20	0	0	0	0
22	0	0	0	0
24	0	0	1	0
26	0	0	0	0
28	0	0	0	0
30	0	0	0	0
32	0	0	0	0
34	0	1	0	0
36	0	0	1	0

Table XI. Gust statistics at 125 m on 19 March 1979, 1309-1315 EST.

Mean (m s^{-1}): 5.65
 Standard Deviation (m s^{-1}): 0.88
 Mean (watts m^{-2}): 68.23
 Power Maximum (watts m^{-2}): 73.18

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	1	8	4	1
4	0	4	3	1
6	0	2	2	0
8	0	0	1	0
10	0	1	1	0
12	0	0	1	0

Table XII. Gust statistics at 75 m on 21 March 1979, 1718-1726 EST.

Mean (m s^{-1}): 5.06
 Standard Deviation (m s^{-1}): 0.55
 Mean (watts m^{-2}): 48.89
 Power Maximum (watts m^{-2}): 50.61

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	3	5	13	0
4	2	2	1	0
6	1	1	1	1
8	0	1	0	1
10	0	0	0	0
12	0	0	1	0
14	0	1	1	0
16	0	0	0	0
18	0	1	0	0

Table XIII. Gust statistics at 125 m on 21 March 1979, 1425-1433 EST.

Mean (m s^{-1}): 4.08
 Standard Deviation (m s^{-1}): 1.06
 Mean (watts m^{-2}): 25.70
 Power Maximum (watts m^{-2}): 31.20

Duration	-2σ	-1σ	$+1\sigma$	$+2\sigma$
2	1	9	3	1
4	0	3	2	1
5	0	2	0	0
8	0	0	1	0
10	0	0	0	1
12	0	0	2	0
14	0	1	0	0
16	0	0	1	0