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Wake Characteristics of the MOD-2 Wind Turbine at Medicine Bow, Wyoming

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ABSTRACT

The present paper summarizes results obtained from profile measurements of the MOD-2 wind turbine wake at Medicine Bow, Wyoming. Vertical profiles of wind speed, potential temperature, and turbulence at 3 and 7 rotor diameters downstream of the turbine, taken under near neutral or slightly stable atmospheric conditions, are presented. Turbulence levels measured in a downstream traverse of the wake from 3 to 10 rotor diameters at hub height are also presented. The reported turbulence levels are in the 1 to 20 Hz band which includes the low frequency structural modes of the MOD-2 rotor. These results indicate that the microscale or small-scale turbulence characteristics of the wake are observable to at least 7 rotor diameters, and possibly beyond 10 rotor diameters, downstream of the turbine. The turbulence imparted to the wake remains at significantly high levels beyond 7 rotor diameters; it may significantly affect the aeroacoustic and aeroelastic responses of a downstream turbine rotor and thus influence minimum wind turbine array spacing requirements.

NOMENCLATURE

$\sqrt{b_1}$	skewness coefficient
b_2	kurtosis coefficient
D	rotor diameters (m)
g	gravitational constant (= 9.81 m/s^2)
h	balloon height relative to MOD-2 tower base height (m)
n	number of data observations
p_2	atmospheric pressure (kPa)
R^2	square of the multiple correlation coefficient
Ri	Richardson number
s	standard deviation
T	air temperature (K)
U	wind speed (m/s)
x_i	data observation
Δh	layer thickness (m)
θ	potential temperature (K)

INTRODUCTION

Most efforts to characterize the wake of a horizontal axis wind turbine have focused on the mean characteristics. In particular, the parameter of greatest interest has been the velocity (energy) deficit in the wake. This velocity deficit which decreases with downstream distance, has been considered the primary determinant of minimum spacing requirements between wind turbines in an array. However, research at the Solar Energy Research Institute (SERI) has indicated that the microscale or detailed characteristics of the wake may be of equal import [1,2,3]. These small scale or turbulent motions may not significantly affect the energy output of a downstream turbine, but the potential aeroelastic and aeroacoustic effects could adversely impact the operation, reliability, lifetime, and cost of that turbine.

In an effort to characterize and understand the wake dynamics of a large horizontal axis wind turbine more fully, tests were conducted on the MOD-2 wind turbine at Medicine Bow, Wyoming, in November 1983. Using an instrumentation package supported by a tethered balloon, vertical profiles of wind speed, potential temperature, and turbulence were measured in the MOD-2 wake. The turbulence content of the wake was obtained by a hot film anemometer with the output filtered to a bandwidth of 1 to 20 Hz. This bandwidth corresponds to turbulence space scales ranging from ~1.5 to 32 blade chords (at the 80% span location) and a turbulence excitation range of ~3.5 to 69 P (1 P = 0.292 Hz = 17.5 rpm). Prior testing of the MOD-2 wind turbine at Goodnoe Hills, Washington [1,2] and wind tunnel testing of symmetric airfoil sections [3] indicated that this range of turbulence excitation, which includes the low frequency structural modes of the MOD-2 wind turbine rotor, is important in determining both the aeroelastic and aeroacoustic responses of the turbine rotor to atmospheric turbulence.

The vertical profiles of wind speed, potential temperature, and turbulence were measured both with and without turbine operation at 3, 5, and 7 rotor diameters downstream of the MOD-2 turbine to isolate the contribution of the wake to ambient atmospheric conditions as a function of downstream distance. In addition, two downstream traverses of the wake from 3 to 10 rotor diameters at approximately hub height were conducted for both above and below rated wind speed conditions. This paper summarizes results obtained during these wake measurements.

EXPERIMENTAL SET-UP AND PROCEDURES

Measurements in the MOD-2 wake at Medicine Bow, Wyoming were accomplished with a tethered balloon system incorporating an Atmospheric Instrumentation Research (AIR) Inc. Model TS-1BR-2 balloon, an AIR Model TS-3A-SP Tethersonde atmospheric sounding probe, and a Thermal Systems Inc. (TSI) Model 1610-EC hot film anemometer. Balloon height was controlled by a winch mounted on the bed of a pickup truck.

The predominent wind direction during November at the Medicine Bow site is 248° true [4]. Accordingly, a test track that extended 976 m (3200 ft) from the MOD-2 was laid out toward 68° (true). Reflective markers were set at 61m (200 ft) intervals along the track with additional markers at 15.2 m (50-ft) increments near the 3D, 5D, 7D, and 10D locations (1 D = 91.5 m = 300 ft). These markers were used to gauge the downstream position of the balloon in the wake. A nearly constant downstream distance was maintained during profiling by movement of the pickup truck.

The AIR Model TS-3A-SP probe provided measurements of atmospheric pressure, wind speed, wind direction, and temperature at an interval of 10 seconds between readings, i.e., a 0.1 Hz sampling frequency. The probe was linked via radio telemetry to an AIR Model TS-2A-GS ground station which in turn was connected to a Hewlett-Packard HP-85A desktop computer. The HP-85A computer permitted real-time calculation of balloon height as derived from the hydrostatic equation, i.e.,

$$h = 14.636\,(T_o + T)\ln(p_o/p), \tag{1}$$

where the subscript o denotes the values obtained at the base height of the tower. The potential temperature at each height, given by

$$\theta = T(100/p)^{0.286} \tag{2}$$

where p is in kPa, was also calculated in real time.

The TSI Model 1610-EC hot film anemometer provided a measure of the atmospheric turbulence levels encountered during the wake tests. The Model 1610-EC was a custom-built 1.52 (10^{-4}) m (6 mil) quartz-coded hot-film probe. The probe and its associated telemetry system were suspended below the balloon by attachment to the tether line just above the AIR probe. The telemetry system, custom-built by Monitron, Inc., provided a dynamic range (signal-to-noise ratio) of 70 dB and a channel frequency response of 0 to 125 Hz. The output signal from the Monitron receiver was linearized by a TSI Model 1052 Linearizer and passed through a 4-pole Butterworth 1 to 20 Hz bandpass filter before being integrated over a 10 second period by a Guildline Model RMS voltmeter. The RMS turbulence level was then passed to the HP-85A computer, combined with the corresponding AIR probe data frame, and stored on disk for further processing.

Meteorological data were obtained from the site's met tower located approximately 1220 m (4000 ft) WNW of the MOD-2 turbine. The nearly level site topography permitted use of the met tower data without unacceptable losses in accuracy due to distance. The 2-minute average data were recorded on a Campbell Scientific Inc. Model CR-21 data logger and cassette tape recorder. The recorded measurements included wind speeds at 15.2 m (50 ft), hub height (61 m), and 106.7 m (350 ft), the barometric pressure at 15.2 m, and the air temperatures at 15.2 m and 106.7 m. The 15.2 m and 106.7 m heights correspond to the bottom and top heights, respectively, of the MOD-2 rotor. The values were used to calculate the gradient Richardson number across the height of the rotor defined by

$$Ri = \frac{g(\theta_2 - \theta_1)/\Delta h}{\bar{\theta}(U_2 - U_1)^2/\Delta h^2} \tag{3}$$

The subscripts 1 and 2 refer to the values obtained at 15.2 m (50 ft) and 106.7 m (350 ft), respectively; h is the rotor diameter (91.5 m), and $\bar{\theta}$ is the mean potential temperature of the layer encompassing the turbine, here estimated by $\bar{\theta} = (\theta_2 + \theta_1)/2$. θ_2 was calculated using the 15.2 m pressure reading and a constant pressure drop of 1.075 Pa/m.

The general test procedure involved first obtaining a vertical profile and a 5-minute reference run at hub height (61 m) with the turbine in operation. The turbine was then shut down to allow the 5-minute reference run and the vertical profile to be repeated under ambient (wakeless) conditions. Each set of measurements required ~45 minutes to complete. Wake profiles were conducted 3, 5, and 7 rotor diameters (3D, 5D, and 7D) downstream of the turbine. Only an incomplete turbine-off profile was obtained at 5D, however, because of a large increase in the ambient wind speed between the turbine-on and turbine-off profiles. In addition, two downstream traverses of the wake from 3D to 10D at approximately hub height were performed for both low and high wind speed conditions, i.e., less than and greater than the MOD-2 rated wind speed (12.5 m/s), respectively.

TEST CONDITIONS

Each wake profile was conducted within the time period of late afternoon to approximately midnight. This time period had been found to be critical in terms of acoustic output during testing of the MOD-1 wind turbine in Boone, North Carolina [3]. However, for the two wake traverses, changes in atmospheric conditions due to snow cover allowed a shift forward of the time period to midday.

The parameters that determined the test conditions were the hub height wind speed and direction and the gradient Richardson number as measured by the site's met tower. Except for one downstream traverse, all of the tests were performed with hub height wind speeds within the range of 6.7-12.5 m/s (15-28 mph), which corresponds to below-rated-power operation of the MOD-2. The one high wind speed traverse was conducted with hub height wind speeds ranging from ~15.0 m/s (33.5 mph) to 18.0 m/s (40 mph) which is well above the rated wind speed of the MOD-2 [12.5 m/s (28 mph)].

Because of the placement of the test track at 68° (true), a wind direction criterion of 248±15° (true) was established before testing began. Most of the wind directions encountered during the testing were close to 248°, which largely eliminated any difficulties in maintaining the balloon within the wake up to a distance of 10D downstream of the turbine.

All of the mean gradient Richardson numbers measured during the tests ranged from 0 to 0.35. Thus, all of the data was obtained under near neutral to slightly stable atmospheric conditions. This result is characteristic of the Medicine Bow site in November from midday to midnight. [4]. Unstable and highly stable conditions were found only when wind speeds were insufficient for testing.

DATA REDUCTION

The instrumentation supported by the balloon provided balloon height, wind speed and direction, potential temperature, and turbulence at a 0.1 Hz sampling frequency. The initial step in the analysis of this data was a statistical rejection of bad height readings. The data were then sorted by height and the same statistical methods were used to identify and reject outliers in the wind speed, potential temperature, and turbulence data. The remaining data provided both mean and detailed profiles of the wake characteristics.

The general procedure for the least-squares smoothing of the profiles incorporated the following:

(1) A least-squares regression of the dependent variable (e.g., wind speed) versus the appropriate independent variable (e.g., height) was calculated. The order of the regression was increased until R^2, the correlation coefficient squared, remained essentially unchanged.

(2) The standard deviation, the skewness coefficient, and the kurtosis coefficient of the residuals obtained in the regression analysis were calculated. The standard deviation, skewness, and kurtosis [5] are given by:

$$s = \sqrt{\sum_{i=1}^{n} x_i^2/(n-1)}, \tag{4}$$

$$\sqrt{b_1} = \sqrt{n} \sum_{i=1}^{n} x_i^3/(n-1)^{1.5}\, s^3, \tag{5}$$

and $$b_2 = n \sum_{i=1}^{n} x_i^4/(n-1)^2 s^4, \qquad (6)$$

respectively. By definition, the mean of the residuals was zero.

(3) A statistical method was chosen for outlier rejection based on the methods and criteria established in the 1982 ASTM Standard No. E178-80 [5]. In general, the standard deviation was used to reject a single outlier, and the skewness and kurtosis were used to reject multiple outliers from one-tailed and two-tailed distributions, respectively. In each case outlier rejection was based on a significance level of 5%.

(4) Steps 1, 2, and 3 were repeated until the residual standard deviation, skewness, and kurtosis satisfied the ASTM criteria for acceptable values [5]. The final regression analysis was taken as representative of the mean profile of the given variable.

After the least-squares data reduction method was completed, the smoothed data were used to generate detailed wake profiles. To obtain the detailed profiles, the wind speed, potential temperature, and turbulence data were first linearly interpolated to provide a 1.0 Hz sampling rate and then lowpass-filtered. Linear interpolation was necessary because unacceptable instabilities were found in all of the higher order interpolators tested. These instabilities were caused by locally high wind shears occasionally found between successive data points in combination with height gaps in the data.

The interpolated data were lowpass-filtered with a nonrecursive, finite impulse response (FIR) digital filter with 81 weights. The equivalent 8-pole lowpass filter had a passband corner frequency of 0.03 Hz, a stopband corner frequency of 0.06 Hz, and a number of desirable features including insignificant passband ripple and a linear phase characteristic. A frequency response plot of the digital filter is shown in Figure 1. A recursive, infinite impulse response (IIR), 8-pole Butterworth-type digital filter with a flat passband frequency response and a 48 dB/octave rolloff was tried but rejected because of its inherent nonlinear phase shift characteristic.

RESULTS

Because of space limitations, only the results obtained from wake profiles taken at 3 and 7 rotor diameters downstream of the turbine and the high wind speed wake traverse are presented. These profiles and the traverse are representative of the MOD-2 wake characteristics found at the Medicine Bow site. The test conditions for the two profiles and the traverse are given in Tables 1 and 2. Table 1 presents met tower data for the mean hub height wind speeds and directions and the gradient Richardson number as defined by Eq. (3). Table 2 gives the times and corresponding met tower wind speed data for each profile.

The wind speed deficits found at hub height are shown in Table 3 as a function of downstream distance from the rotor. These results are based on comparisons of the mean hub height wind speeds obtained from the 5-minute turbine-on reference runs and the corresponding met tower data for all of the wake measurements performed on the Medicine Bow MOD-2. Considering differences in test conditions (including terrain effects), the results presented in Table 3 appear to be in good agreement with earlier wake measurements conducted on the MOD-2 wind turbines in Goodnoe Hills, Washington [6].

Profile/ Traverse	Mean Wind Speed (m/s)	Richardson Number	Mean True Wind Direction
3D turbine on	11.9	0.14	240.0°
3D turbine off	9.0	0.21	238.0°
7D turbine on	12.2	0.10	255.0°
7D turbine off	11.1	0.35	259.7°
Traverse	15.6	0.29	240.5°

Table 1. Test Conditions for the Wake Profiles at 3 and 7 Rotor Diameters and the High Wind Speed Wake Traverse (Wind Speeds and Directions are Hub Height Values from Met Tower Data)

Profile	Balloon Height (m)	Time (MST)	U_{Tower} (m/s)
	10.1	0:66	7.5
3D turbine-on	61.0	0:62	12.6
	106.7	0:55	13.8
	10.1	0:32	3.7
3D turbine-off	61.0	0:36	8.4
	106.7	0:42	10.7
	10.1	16:24	8.3
7D turbine-on	61.0	16:28	12.1
	106.7	16:34	13.4
	10.1	17:24	6.0
7D turbine-off	61.0	17:20	11.1
	106.7	17:14	12.1

Table 2. Test Conditions for the Wake Profiles at 3 and 7 Rotor Diameters Based on Met Tower Data

Downstream Distance	U_{Tower} (m/s)	$U_{Balloon}$ (m/s)	Wind Speed Deficit
3D (274.4 m)	14.0	9.7	31%
3D (274.4 m)	11.8	7.9	33%
5D (457.3 m)	11.8	8.0	32%
7D (640.2 m)	12.4	11.1.	10%
10D (914.6 m)	16.3	16.3	0%
10D (914.6 m)	8.8	8.9	0%

Table 3. Percentage Wind Speed Deficits at Hub Height in the MOD-2 Wake Based on Met Tower Data and 5 Minute Reference Run Balloon Data

Figures 2 and 3 show the balloon height versus time plots for the 3D and 7D profiles, respectively. In each figure, the (a) plot is the turbine-on (wake) data and the (b) plot is the turbine-off (wakeless) data. These plots shows the behavior of the balloon and the time of day for each profile. The fitted curves are based on the regression analyses and original data points are denoted by • .

Figures 4, 5, 6, and 7 show mean and detailed profiles of wind speed, potential temperature, and mean square turbulence (m^2/s^2) as a function of height. In each plot, the axes have been transposed with height being on the ordinate. Figures 4 and 5 give the turbine-on and turbine-off profiles obtained at 3D while Figures 6 and 7 show the turbine-on and turbine-off profiles taken at 7D, respectively. The corresponding original data points are denoted by an x with removed outliers being circled. In each figure, plots (a), (c), and (e) show the mean profiles based on the regression analyses and plots (b), (d), and (f) show the detailed profiles with outlier points removed from the plots. The corresponding values of R^2, the correlation coefficient squared, are shown in each mean profile plot.

In comparing the turbine-off and turbine-on profiles in Figures 4, 5, 6, and 7, a note of caution is necessary. The period of day during which these profiles were obtained is characterized by relatively rapid changes in atmospheric conditions. Hence, an uncritical comparison of the turbine-on and turbine-off results can be misleading due to the time lapses between measurement of the profiles during a test run. These time lapses result in significant changes in test conditions, as shown in Tables 1 and 2. The changes in wind speed and hydrodynamic stability (Richardson number) explain in part the differences between the turbine-on and turbine-off turbulence readings. However, an examination of all of the Medicine Bow MOD-2 wake data indicates that the primary source of these differences is the turbulence imparted to the wake by the MOD-2 rotor.

Comparisons of the detailed turbine-on and turbine-off profiles of wind speed and the 1 to 20 Hz band mean square turbulence levels at 7D are shown in Figures 8 and 9. The turbulence comparison in Figure 9 indicates that the turbulence in the MOD-2 wake at 7 rotor diameters is significantly above ambient levels. Except for a small layer at approximately 20 m, the difference in the turbulence levels between the turbine-on and turbine-off profiles exceeds one order of magnitude throughout the rotor layer. Also note the stronger wind-shear layers evident in the turbine-on profile at 7D shown in Figure 8. A strong shear layer can be a hydrodynamic source of turbulence, thus indicating that turbulence production may exist in the MOD-2 wake up to, and possibly beyond, 7 rotor diameters.

Plots of the wind speeds and mean square turbulence levels found at hub height during the high wind speed traverse from 3D to 10D are shown in Figures 10 and 11, respectively. The curves in Figures 10 and 11 are based on regression analyses of both data sets. Statistical analyses of the balloon height readings and the regression residuals were employed to identify outliers in the data. When a bad height, wind speed, or turbulence data point was identified, the entire data frame was removed from the analyses. An examination of the data points in Figures 10 and 11 indicates a number of discontinuities in both data sets. However, a comparison shows a good correlation between the discontinuities evident in each figure. Thus these discontinuities appear to be caused by ambient wind speed fluctuations rather than by physical phenomena inherent to the wake.

The primary factor influencing the increase in wind speed with downstream distance in Figure 10 is wake recovery. However, the fitted curve cannot be used for wake deficit calculations because of ambient wind speed changes during the traverse. The corresponding 2-minute met tower readings varied between 15.0 m/s and 16.4 m/s, thus preventing accurate estimation of the wind speed deficits in the wake.

A comparison of Figure 11 with 10 indicates that the fluctuations in turbulence level may be partially caused by ambient wind speed changes. However, this plot of turbulence levels measured during the high wind speed traverse does provide qualitative, as well as some quantitative, insights into the turbulence characteristics of the MOD-2 wind turbine wake at Medicine Bow. In particular, as the turbulence cascades through the 1 to 20 Hz band (increases in frequency with time), the broad peak in turbulence level at 7D would be expected to occur. The plot in Figure 11 also indicates that the high wake turbulence levels shown in the profiles at 3D and 7D continue to exist beyond 7D and may exceed 10D. Note that the traverse turbulence readings were significantly higher than those found at hub height in the profiles. However, this discrepancy is attributable to the higher ambient wind speeds encountered during the traverse.

CONCLUSIONS

The results presented here support two major conclusions:

(1) The microscale wake characteristics (turbulence and strong wind-shear layers with space scales less than 1 rotor diameter) are observable to at least 7 diameters, and possibly beyond 10 diameters, downstream of the MOD-2 wind turbine at Medicine Bow, Wyoming.

(2) The turbulence imparted to the wake remains at significantly high levels in the 1 to 20 Hz band beyond 7 rotor diameters and may have a significant effect on the aeroacoustic and aeroelastic responses of a downstream MOD-2 wind turbine, thereby affecting minimum turbine array spacing requirements. Spectral analysis of this wake turbulence will be necessary to quantify potential impacts on the downstream turbine as a function of separation distance. Work is presently underway to complete spectral analyses of the turbulence measurements and the vertical wake structure.

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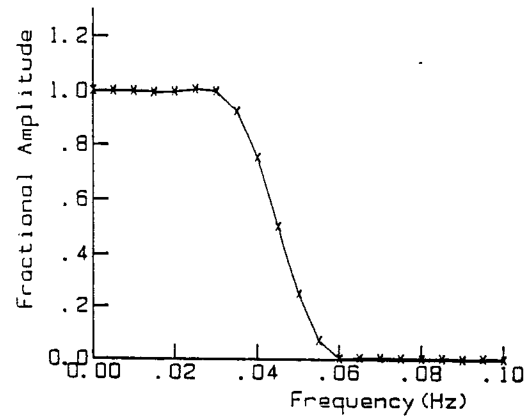

Figure 1. Frequency Response Plot for 81-Weight Digital Lowpass Filter.

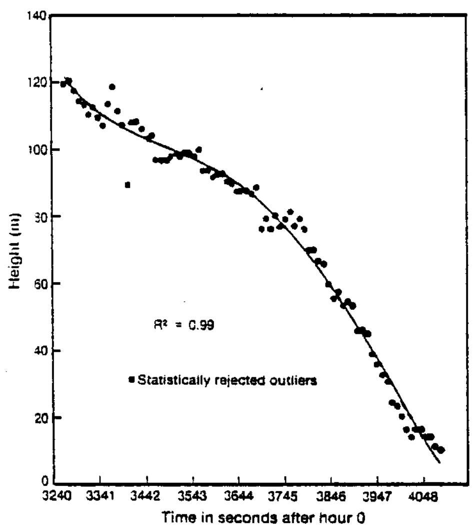

Figure 2(a). Balloon Height vs. Time for Turbine-On Profile at 3D.

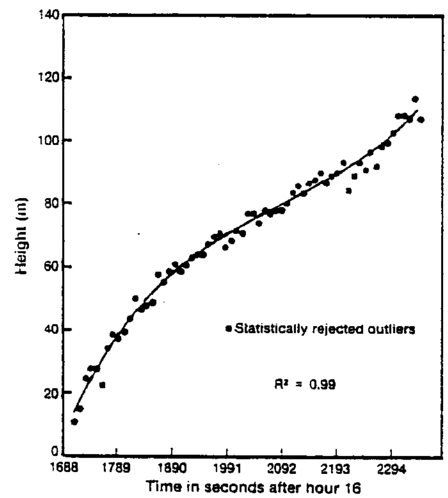

Figure 3(a). Balloon Height vs. Time for Turbine-On Profile at 7D.

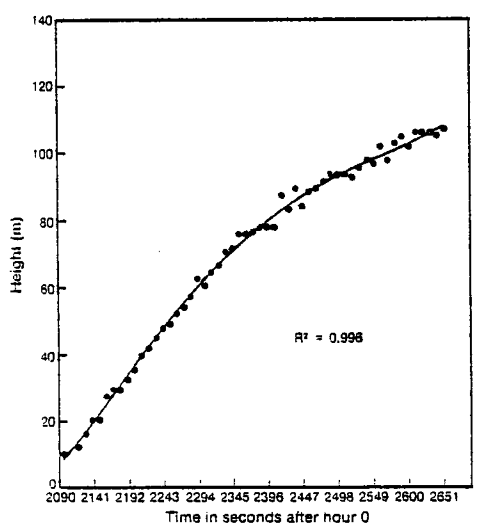

Figure 2(b). Balloon Height vs. Time for Turbine-Off Profile at 3D.

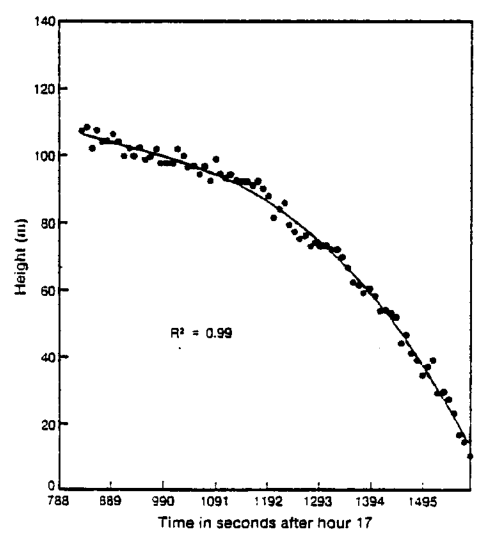

Figure 3(b). Balloon Height vs. Time for Turbine-Off Profile at 7D.

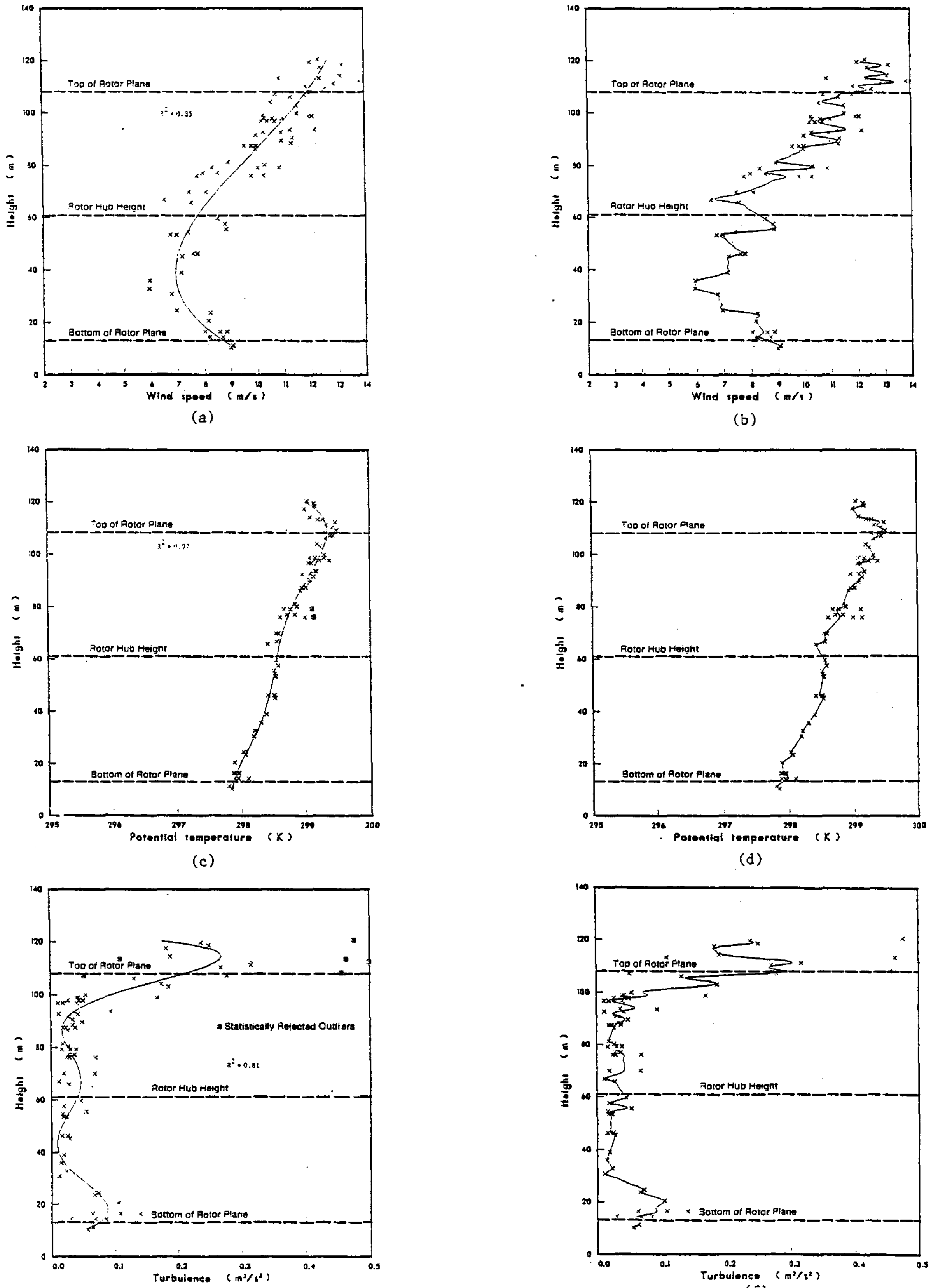

Figure 4. Mean and Detailed Wake Profiles of Wind Speed, Potential Temperature, and Turbulence at Three Rotor Diameters (3D) (Turbine Operating).

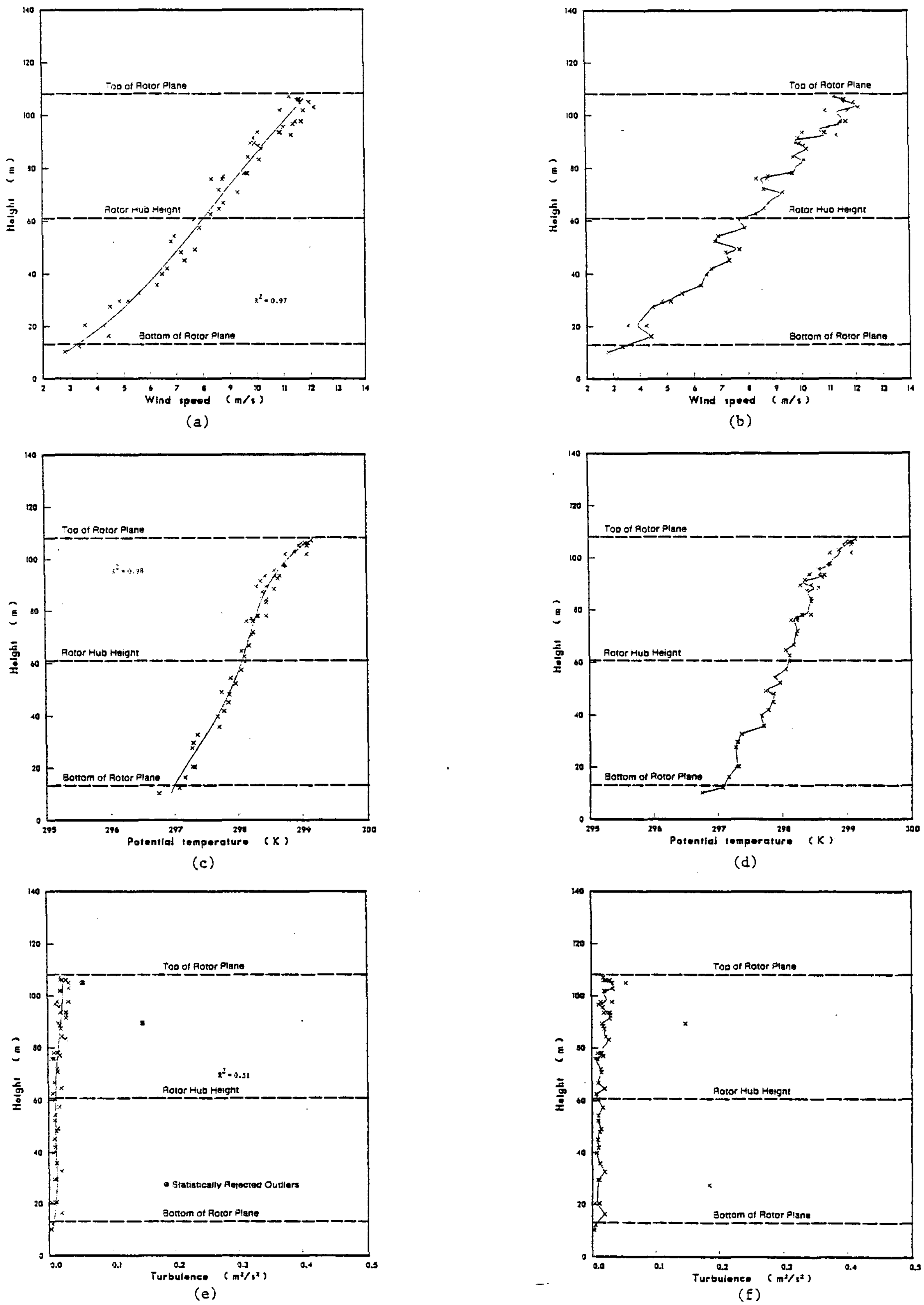

Figure 5. Mean and Detailed Profiles of Wind Speed, Potential Temperature, and Turbulence Measured at Three Diameters (3D) After Turbine Shut Down (Turbine Off).

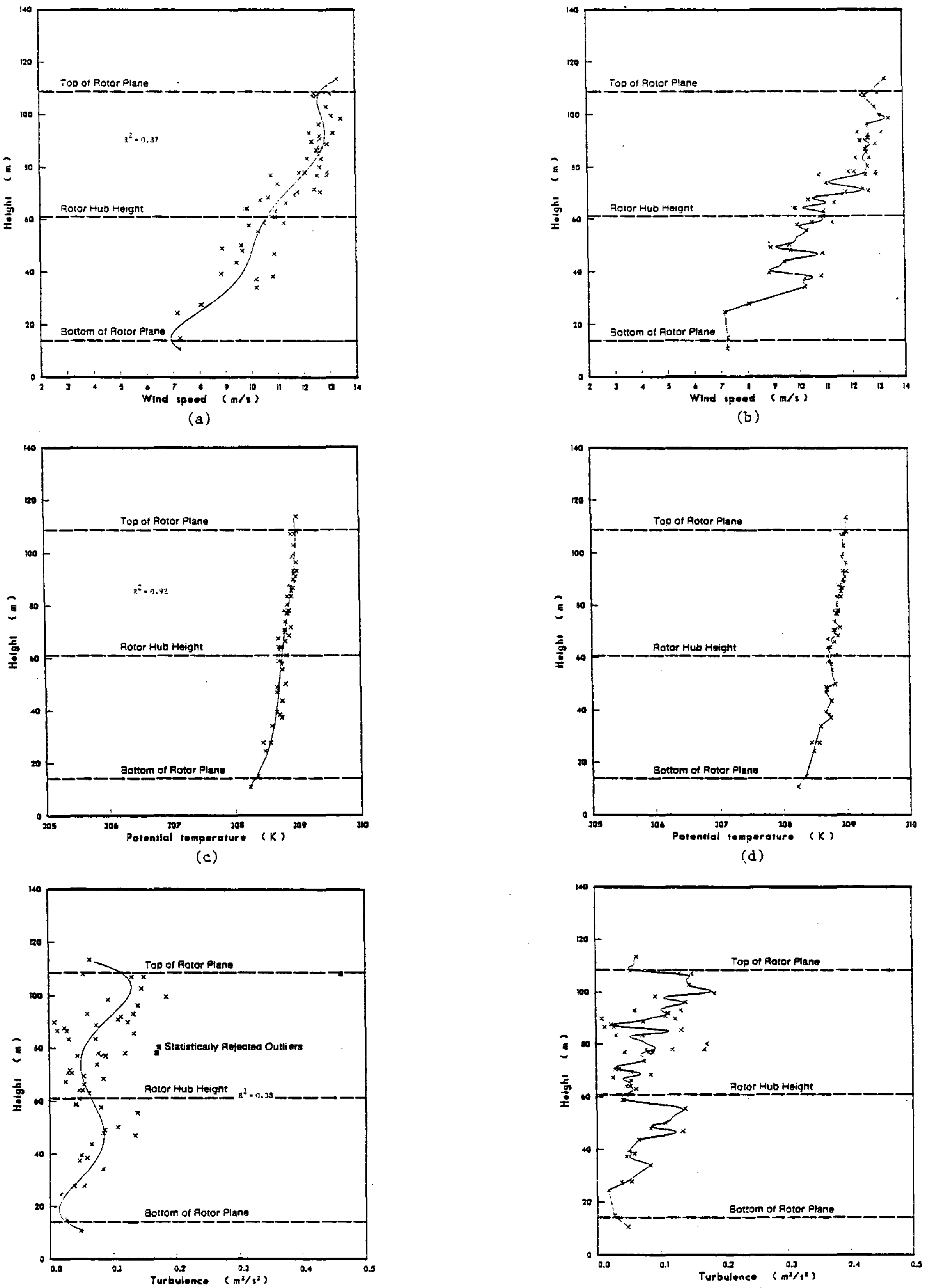

Figure 6. Mean and Detailed Wake Profiles of Wind Speed, Potential Temperature, and Turbulence at Seven Rotor Diameters (7D) (Turbine Operating).

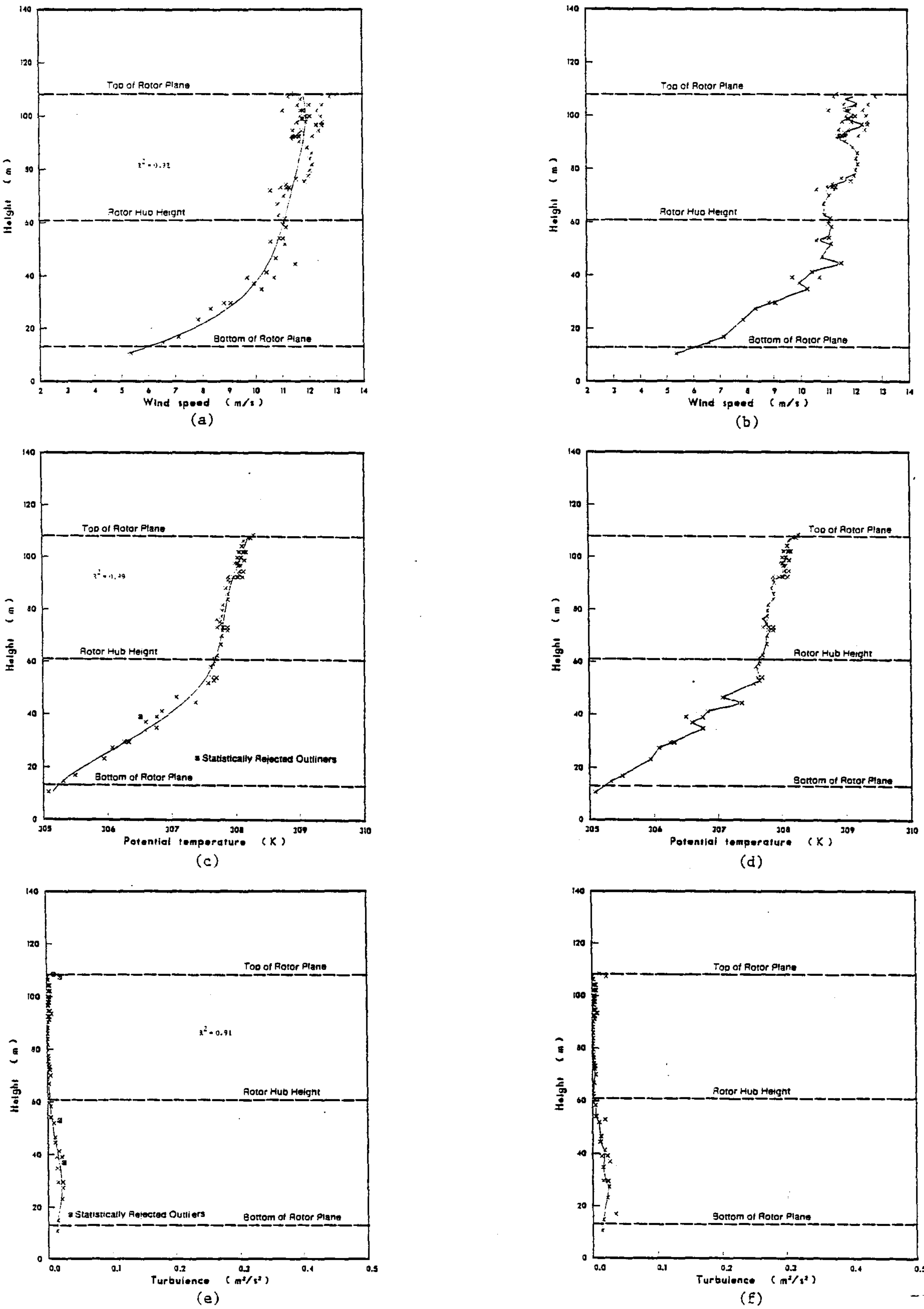

Figure 7. Mean and Detailed Profiles of Wind Speed, Potential Temperature, and Turbulence Measured at Seven Diameters (7D) After Turbine Shut Down (Turbine Off).

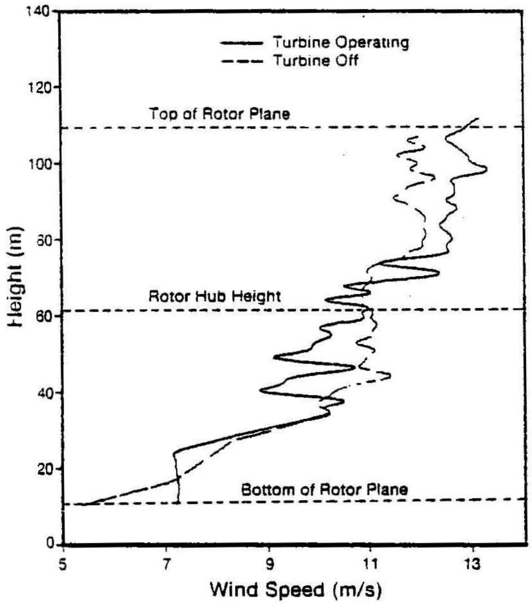

Figure 8. Comparison of Detailed Turbine-On and Turbine-Off Wind Speed Profiles at Seven Rotor Diameters (7D).

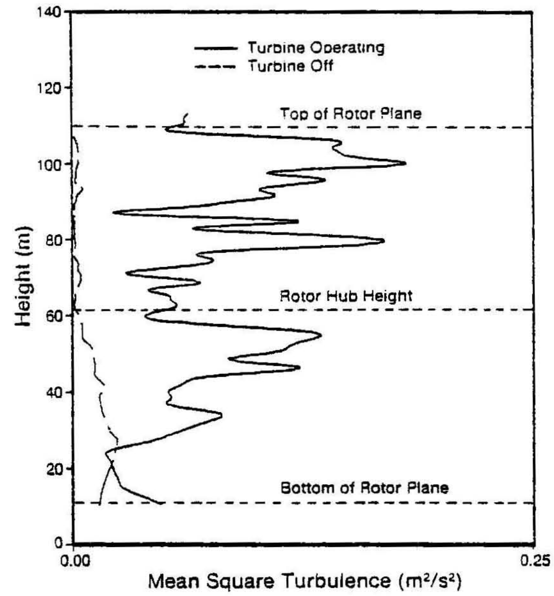

Figure 9. Comparison of Detailed Turbine-On and Turbine-Off Turbulence Profiles at Seven Rotor Diameters (7D).

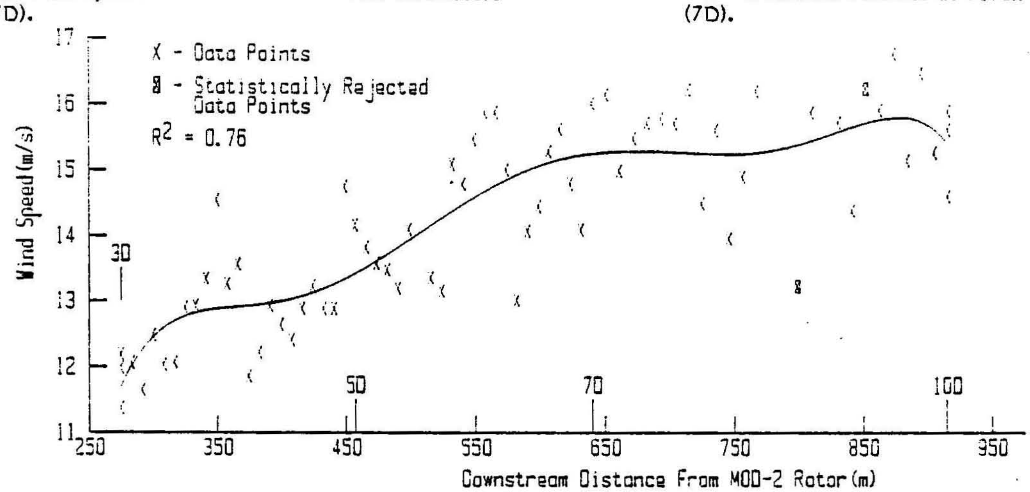

Figure 10. Wind Speed vs. Downstream Distance in the Wake-High Wind Speed Traverse at Hub Height.

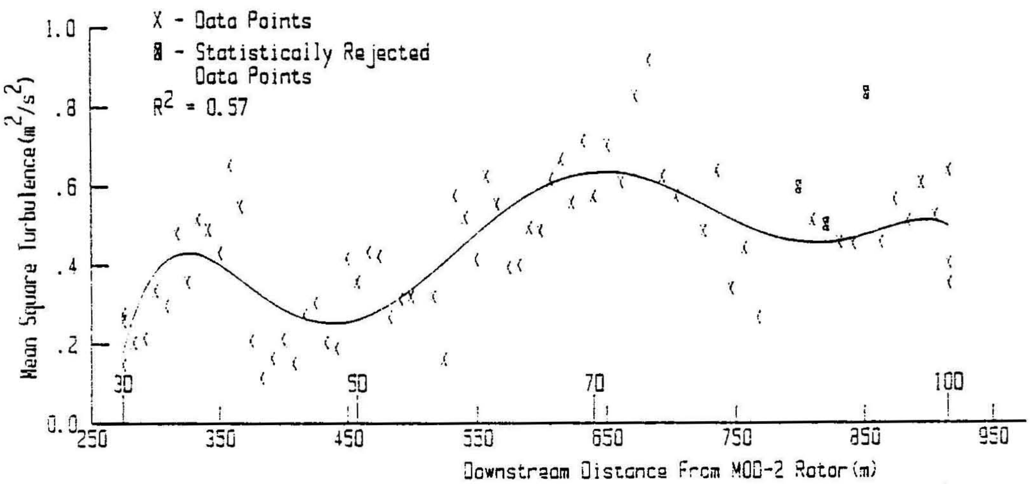

Figure 11. Turbulence Levels vs. Downstream Distance in the Wake-High Wind Speed Traverse at Hub Height.