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STATUS OF WAKE AND ARRAY LOSS RESEARCH

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STATUS OF WAKE AND ARRAY LOSS RESEARCH

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ABSTRACT

In recent years, many projects have evaluated wind turbine wake effects and resultant array losses in both Europe and the United States. This paper examines the status of current knowledge about wake effects and array losses and suggests future research.

Single-turbine wake characteristics have been studied extensively and are generally described well by existing theoretical models. Field measurements of wake effects in wind turbine arrays are largely limited to small arrays, with 2 to 4 rows of turbines. Few data have been published on wake effects within large arrays. Measurements of wake deficits downwind of large arrays indicate that deficits are substantially larger and extend farther downwind than expected. Although array design models have been developed, these models have been tested and verified using only limited data from a few rows of wind turbines in complex terrain, whereas some of the largest arrays have more than 40 rows of wind turbines.

Planned cooperative efforts with the wind industry will obtain existing data relevant to analyzing energy deficits within large arrays and identifying data sets for potential use in array model verification efforts. Future research being considered include a cooperative research experiment to obtain more definitive data on wake deficits and turbulence within and downwind of large arrays.

INTRODUCTION

Large wind power generation plants, often called "wind farms," generally consist of many wind turbines installed in arrays (i.e., organized clusters). For a given land area, it is desirable to place the wind turbines as close together as possible to maximize energy production. However, if wind turbines are too closely spaced, wake interference effects could be significant, resulting in a considerable reduction in the efficiency of the array's energy production. Some arrays with tightly spaced turbines have produced substantially less energy than expected based on wind resource assessments. In some densely packed arrays where turbines have failed prematurely, it has been suspected that these failures might be caused by excessive turbulence associated with wake effects.

Knowledge of wind turbine wake effects is crucial for optimizing the spacing and layout of turbines in arrays so that energy capture is maximized but array losses and turbulence-induced mechanical loads stay within acceptable limits. Many research projects have examined individual wind turbine wake effects and array losses that stem from multiple turbine wake effects. The degree of consistency in recent research results has become a major issue. Another important issue is the adequacy of the current knowledge for determining the optimum layout of turbines in arrays. Finally, an issue that has taken on increasing importance in California recently is characterized by the term "wind rights." Developers have claimed that production from their arrays dropped significantly when other developers installed turbine arrays upwind at distances that at the time were considered large enough to prevent resource depletion at the downwind array.

The three primary methods of wake and array loss research have been numerical modeling, wind tunnel simulations, and field measurement. Numerical models now exist that can be used in array design applications in complex terrain areas (Lissaman et al. 1990; Veenhuizen et al. 1989). However, their accuracy and reliability in predicting wake-induced energy deficits and turbulence in large arrays is unknown. The verification of numerical

models with field data has been limited to wake data from single turbines and small arrays (with only 2 to 4 rows of turbines) in complex terrain where ambient flow variability complicates verification efforts. Wind tunnel experiments are demonstrating greater promise as a tool in array design, but verification of wind tunnel measurements is also constrained by the lack of field measurements from large arrays. Full-scale field measurement of wake effects in arrays is expensive and difficult to perform, and that is why field measurements have been limited largely to single turbines and small arrays.

A data base of literature on wind turbine wakes and wake effects has recently been published (Cleijne 1990). Although it lists many publications available on this subject, others, such as some of the studies referenced in this paper, have not been included.

SINGLE TURBINE WAKE EFFECTS

There have been many field measurement studies of single-wind turbine wakes in both the United States and Europe. Field measurements of turbine wakes have mostly been made using meteorological towers or, in some cases, kites. Properties of the wake structure have been examined at downwind distances as close as 0.5 rotor diameters (D) and as far as ~10 D. Wake properties analyzed have included mean wind speed deficits, turbulence, and cross-sectional and vertical profiles. Wake properties have been examined as a function of the ambient wind speed (or turbine thrust coefficient) and turbulence level. In some studies, power deficits have been measured at turbines operating in the wake of an upwind turbine.

Experimental data generally verify theoretical predictions that the wake velocity deficit and downwind decay rate (i.e., change in velocity deficit with respect to downwind distance) are largely determined by two factors: the turbine's thrust coefficient and the ambient turbulence. The initial velocity deficit depends on the amount of momentum extracted from the ambient flow, which is a function of the turbine's thrust coefficient. Turbine thrust coefficients are generally highest at low wind speeds and decrease with increasing wind speed. The published data on wake deficits have often been analyzed as a function of wind speed rather than thrust coefficient. Wake measurement data generally verify that deficits are highest at high thrust coefficients (low wind speeds) and lowest at low thrust coefficients (high wind speeds), as shown in Figure 1 for downwind distances from 1.5 to 8 D (Liu et al. 1988). The wake decay rate is a function of the thrust coefficient (wind speed), as is evident in Figure 1, with largest decay rates at high thrust coefficients (low wind speeds).

Wake velocity deficits are greatest at low ambient turbulence intensities (Elliott and Barnard 1990), as demonstrated in Figure 2. Although data on the effect of turbulence intensity on wake velocity deficit is limited at distances beyond about 8 D, at low-turbulence intensities the wake deficit may be significant at distances out to 12 D or more particularly with high thrust coefficients (low wind speeds).

In the near-wake, which typically extends to 2 to 4 D, the wake structure is quite complex, as shown in Figure 3. The analysis shown in Figure 3 is a two dimensional cross-section of the wake, measured using 7 equally spaced anemometers on a hanging boom that was moved to different downwind positions. The hanging boom experiment was conducted by the Pacific Northwest Laboratory, in cooperation with the Fayette Manufacturing Corporation, to collect detailed data on the near-wake structure. At distances less than ~2 D, the maximum deficit is confined to a narrow band around the centerline minimum. Beyond ~2 D, the centerline minimum dissolves and a central wake core develops, with a maximum at the centerline. Greatest centerline deficits occur between 2 and 3 D. Wake-induced turbulence is greatest around the periphery of the rotor disk and at distances of 3 to 5 D. Data on the near-wake structure is of interest not only to those working on improved wake models but also to wind farm developers, because of the problems possible when a turbine operates in the near-wake of another turbine. Wind turbines spaced closely within a row may operate in the near-wake of another turbine when the wind direction is parallel to the row. (In many California wind farms, lateral spacings in a row are typically 1.5 to 3 D.) Many developers have control strategies to shut down many of the turbines when such parallel wind conditions occur.

The cross-wind profile of the wake typically remains fairly symmetric about the centerline in the far-wake. The average width of the wake is 2.6 to 2.8 D at distances of 8 to 10 D (Elliott and Barnard 1990). The width of the wake core (defined as that part of the wake in which the velocity deficit is at least 50% of the maximum velocity deficit) averages about 1.5 to 1.7 D. These data imply that, for wind turbine spacing in a wind farm (with an 8- to

10-D row separation), array losses would be greater for a 2-D lateral spacing than a 3-D spacing as a result of the incremental effects caused by overlapping wakes. Array losses for a 1.5 D lateral spacing would be substantially greater, because not just the wakes but the wake cores would overlap.

The vertical profile of the velocity deficit in the far-wake is not symmetric (Elliott and Barnard 1990; Taylor 1990), as shown in Figure 4. The wake deficits are greater below the hub height than above it, and deficits at the bottom of the rotor disk are substantially greater than those at the top of the rotor disk. This occurs because the ground restricts vertical wake growth thereby concentrating the momentum deficit in a region above the ground but below hub height.

Limited data available on wake turbulence in the far-wake indicate that the turbulence profile in the cross-wind direction is generally symmetric about the centerline of the wake; however, the double maximum apparent at distances less than 6 D is no longer discernable at distances of 8 D and beyond. At 8 to 10 D, wake turbulence at hub height is around 20 to 40% greater than ambient turbulence (Elliott and Barnard 1990; Taylor 1990; Kline 1989). An empirical characterization of wake turbulence, developed from an analysis of available data, indicates that the added turbulence in the wake is a function of the turbine thrust coefficient, ambient turbulence, downwind distance, and length of the near-wake (Hassan 1989). Good agreement was found between wake turbulence given by this empirical characterization and that predicted by an eddy viscosity wake model.

Data on the vertical profile of wake turbulence indicate that wake turbulence is not symmetric about the hub height, but significantly greater above the hub height than below (Taylor 1990). Wake turbulence levels increase significantly with height across the rotor disk. This is consistent with the greater velocity gradients found at the top of the wake, as shown in Figure 4.

Power or energy deficits experienced by a turbine operating in the wake of an upwind turbine are largely determined by the downwind turbine's power-curve characteristics and the wake velocity deficit over the rotor disk. Figure 5 shows the effect of wind speed and turbulence intensity on the power production of a turbine operating in the wake of another turbine about 7 D upwind (Elliott et al. 1988). (Power deficits may be significantly different for turbines with different power-curve characteristics.) The experimental results of Figure 5 were compared to model predictions derived from the 1982 Lissaman model (Lissaman 1982), and agreement was reasonably good.

WAKE EFFECTS IN SMALL ARRAYS

Published data on wake effects in arrays are rather limited, and the data are largely from small arrays with 2 to 4 rows of wind turbines. Most of the data are from areas of complex terrain where spatial variations in the ambient wind speeds may be substantial, thus complicating the analysis of the wake effects. Three field measurement projects to evaluate array wake effects were conducted under the U.S. Department of Energy's Cooperative Field Test Program (CFTP) with industry (Liu et al. 1988; Simon et al. 1987; Nierenberg 1990). The arrays were located in the complex terrain of Altamont Pass and Tehachapi Pass in California. Turbines were shut down for set periods to measure spatial variability of the ambient wind flow in the arrays.

Table 1 presents a comparison of the row average energy deficits, measured in winds of ~10 m/s in these projects. (Deficits were examined for three arrays in the Altamont project and one array each in the Fayette and FloWind projects.) These data indicate that deficits in the third row are about 50% greater than in the second row. Differences in energy deficits may be due to a combination of factors, such as differences in the wind turbine spacing, the turbines' thrust coefficients and power coefficients, the ambient turbulence levels, and terrain effects on the wind flow.

In all three projects, the energy deficits were found to decrease with increasing wind speed. Figure 6 shows, for the Altamont project, the average energy deficits versus wind speed for the second row at 8-9 D downwind. The energy deficits are generally highest (15-16%) at low wind speeds (7-9 m/s) and decrease to about 2-4% in 15-m/s winds. In the third row, the inverse relationship between energy deficits and wind speeds is even more pronounced, as deficits decreased from ~25% in 8-m/s winds to ~5% in 14-m/s winds.

Individual turbine deficits often varied considerably within a row. Terrain both enhanced and diminished ambient wind speeds. Turbines at sites with lower wind resource had higher wake deficits, and their energy production was lowered further. Thus, because of the inverse relationship between wind speed and wake deficits. terrain effects can significantly increase wake deficits.

Two tests were conducted in the Altamont project to examine row energy deficits at 16 D downwind. Surprisingly, the deficits were almost the same as those measured at 8-9 D (i.e., 10-13% in 10-m/s winds). The persistence of the wake was attributed to the climatology of Altamont Pass, where a shallow stable layer often exists with light winds above the layer. Therefore, replenishment of momentum from above the wake is limited, and the wake persists to much greater distances than would be expected in other locations where the wake dissipates more rapidly by vertical mixing of higher winds from above.

The influence of ambient turbulence levels on wake deficits was analyzed in the Fayette project, but no evidence was found to support the inverse relationship between turbulence levels and wake effects. However, another study (Kline 1989) conducted in an 11-D (downwind spacing) by 2-D (lateral spacing) array of Howden 330-kW turbines in Altamont Pass found that wake deficits were substantially greater under low-turbulence levels (stable conditions) than under high-turbulence levels (unstable conditions). In stable conditions, second-row energy deficits were 13% in winds of about 10 m/s and negligible in winds above 14 m/s. In unstable conditions, wake deficits were negligible at all wind speeds.

WAKE EFFECTS WITHIN AND DOWNWIND OF LARGE ARRAYS

Limited data on row-by-row energy deficits have been published for a 7-row array with a 9-D row separation and 2-D lateral spacing (Lynette 1986). The array is located on flat terrain in San Gorgonio Pass in California. Energy production was tabulated for a 6-month period and included a wide variety of wind speeds. The results, shown in Figure 7, indicate a 20% energy loss between the first and seventh rows. The incremental energy loss between any 2 rows decreases the further the rows are from the turbines farthest upwind. Stratification of the energy deficits versus wind speed or ambient turbulence was not performed. Other sites may have significantly different wake deficits, because of the effects of site-dependent characteristics (such as wind speeds, turbulence levels, and terrain effects) on the wake deficits.

Although no other data on array wake losses in large arrays have been published, a few measurement studies have investigated wake deficits downwind of large arrays. In one area of Altamont Pass, wind data were collected at the site before and after a 50-MW array was installed upwind of the site in the prevailing wind direction. Lateral spacing in the 50-MW array was about 1.3 D, which is unusually tight. Potential energy deficits in a hypothetical array immediately downwind of the existing 50-MW array were estimated to be about 20%, as shown in Figure 8 (Nierenberg and Kline 1989). Potential deficits of about 15% were estimated for a large area, extending 5 km downwind of the 50-MW array. In other studies, even larger deficits (20 to 40%) immediately downwind of large arrays have been projected.

Analysis of data collected both upwind and downwind of another large array on flat terrain in San Gorgonio Pass demonstrated the importance of assessing the effects of ambient flow variations in large arrays as a result of terrain influences outside the array (Kelley 1989). The array consists of 41 rows of turbines with a 7-D row separation and 2-D lateral spacing. Meteorological towers were installed immediately upwind and downwind of the wind farm to collect data for analyzing array effects on the ambient inflow. Canyon drainage winds prevalent during the late evening to early morning caused very turbulent winds at the upwind tower but not at the downwind tower. To estimate array wake effects, it was necessary to use daytime periods only, so canyon drainage flows did not occur. Figure 9 shows the wake velocity deficits and turbulence modifications in row 41. Velocity deficits approach 30% in 8-m/s winds and 22% in 22-m/s winds. Turbulence levels in row 41 are actually lower than ambient turbulence in winds below 10 m/s but they are over 40% higher in winds above 20 m/s.

FUTURE RESEARCH NEEDS

Although array design models have been developed in both the United States and Europe, their reliability and accuracy in predicting wake effects in large arrays are unknown. The major limitation to making the field measurements in large arrays for use in model verification has been their great cost and complexity. However, even in the absence of such measurements, it should be possible to obtain data on energy production for turbines (or at least turbine rows) in some large arrays. Any information on specific characteristics of particular turbines (such as variations in blade setting angles, soiling of blades, etc.) that could affect turbine energy production would be desirable. Data on wind conditions are needed as well; fortunately, these data should already be available for some arrays. Cooperative pooling of these data is needed to develop a broader data base for analyzing and better understanding wake deficits within large arrays. Data are needed for different geographical areas and different meteorological conditions to better evaluate how these factors influence wake effects. These data may help us in answering some very basic questions: Do wake deficits reach an equilibrium value in large arrays, and what factors does the equilibrium value depend on?

Cooperative efforts must be initiated to obtain field measurements necessary for analyzing wake effects within and downwind of large arrays. Data are needed not only on wake deficits but also on wake turbulence and on variations of these quantities with ambient wind speed, turbulence, stability, height, and turbine spacing. Spatial variability in the ambient wind flow should be well documented, and data on the depth and behavior of the energy-bearing layer would be useful, particularly in analyzing wake persistence and resource depletion. Some developers have installed many anemometers throughout their site areas to assess the wind resource variability and eliminate undesirable locations. Some of these wind farms might be excellent candidates for wake measurement studies, since knowledge of wind flow over the site is essential for accurately estimating and modeling wake effects. As previously noted, wind flow may vary considerably even in flat areas if they located in the vicinity of complex terrain.

The employment of wind turbulence characterization systems (TCS), such as those recently designed by Pacific Northwest Laboratory (Wendell et al. 1991), could provide data necessary to more accurately characterize the wake structure and turbulence conditions in arrays. The TCS data can be analyzed to estimate spatial coherence and time/length scales within wind turbine wakes and arrays. The data can also be analyzed to estimate wake-induced blade loads and rotor fatigue. Some of these systems are currently installed at sites with complex terrain to learn more about the turbulent characteristics of the winds there.

Advanced wind turbine blades are now available that improve aerodynamic performance and energy production over conventional blades (Tangler et al. 1991). Moreover, lower array losses and reduced wake turbulence in arrays are expected with these advanced blades, which operate at a more favorable blade-pitch angle, resulting in turn in a greater rotor power-to-thrust ratio. These blades will replace conventional blades on many existing turbines, and new turbines will use these advanced blades. Wake and array loss data are needed for this new generation of wind turbine blades to estimate the degree of reduction of array loss and to assess implications for array spacing guidelines. Consideration should be given to conducting a field measurement project that compares wake effects for conventional versus advanced blades and examines wake effects in an array where the advanced blades are being used. These tests would be useful in verifying model predictions of wake effects for the advanced blades.

ACKNOWLEDGMENTS

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TABLE 1. COMPARISON OF ENERGY DEFICITS MEASURED IN THREE PROJECTS

Project/ Location	Turbine Type	Turbine Spacing		Energy Deficits in 10-m/s Winds	
		Downwind	Crosswind	Row 2	Row 3
Fayette/ Altamont Pass	Fayette 95-kW (Horizontal Axis)	10-11 D	3 D	8%	12%
Altamont/ Altamont Pass	Nordtank 65-kW (Horizontal Axis)	8-9 D	2 D	13%	19%
FloWind/ Tehachapi Pass	FloWind 160-kW (Vertical Axis)	8 D	3 D	20%	-

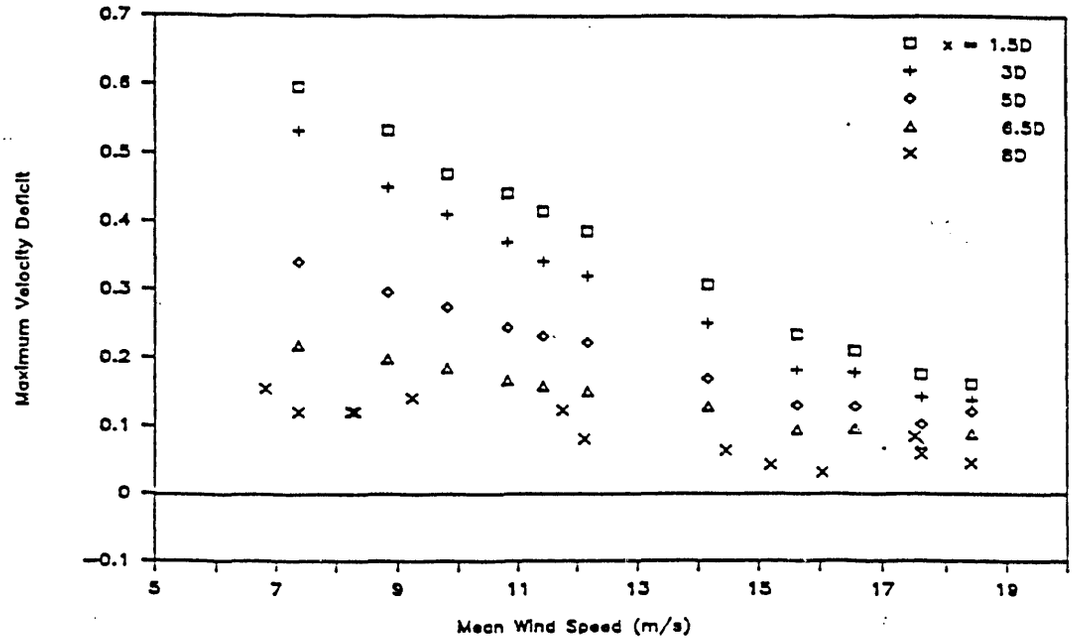

FIG. 1. WAKE VELOCITY DEFICIT VERSUS WIND SPEED AT THE INDICATED DOWNWIND DISTANCES

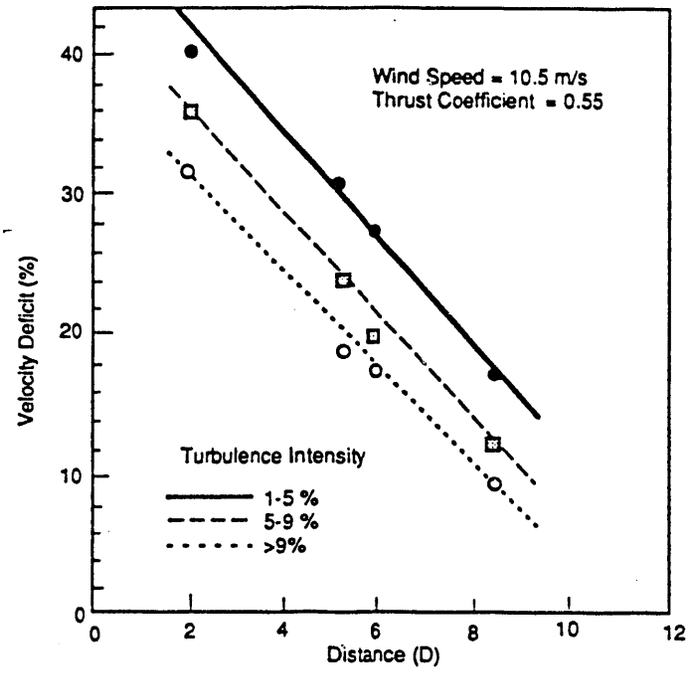

FIG. 2. EFFECTS OF AMBIENT TURBULENCE INTENSITY ON WAKE VELOCITY DEFICITS

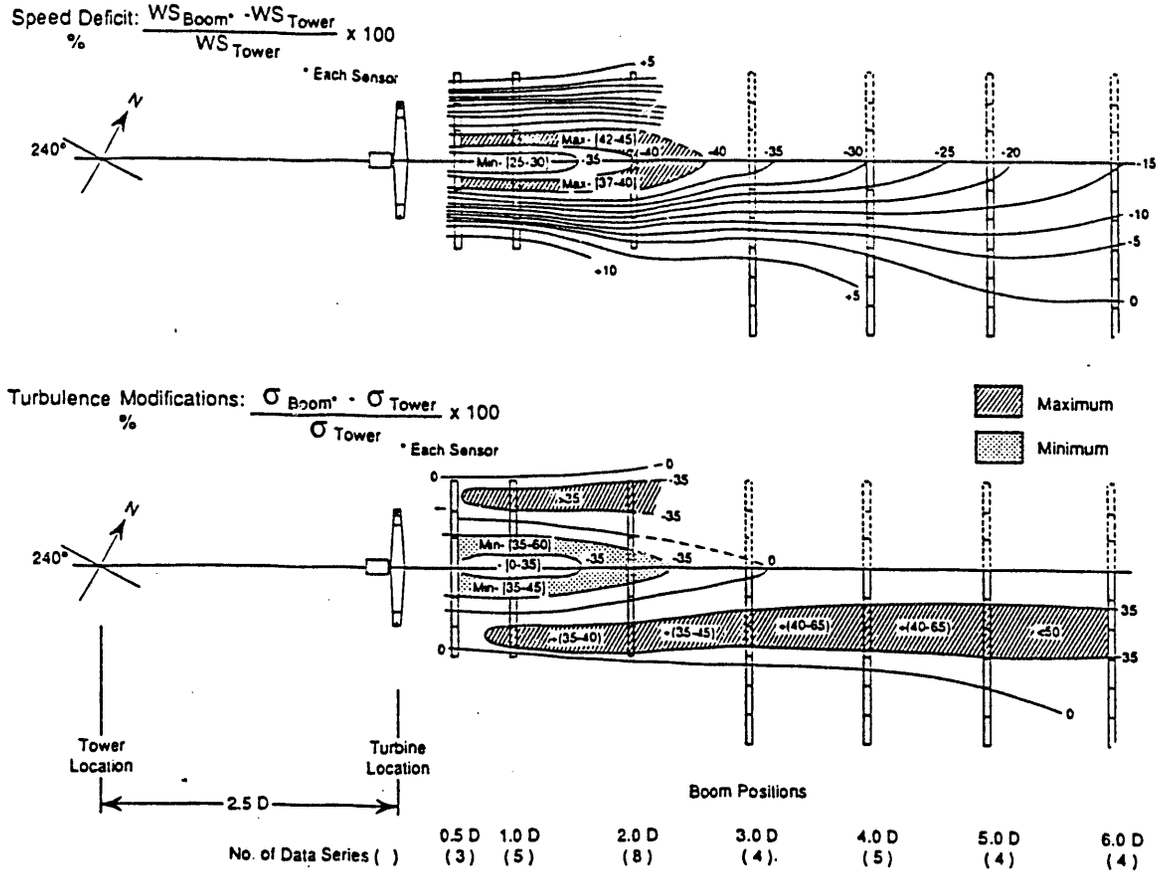

FIG. 3. CROSS SECTION OF THE WAKE SHOWING THE DETAILED STRUCTURE OF THE VELOCITY DEFICIT AND TURBULENCE MODIFICATION

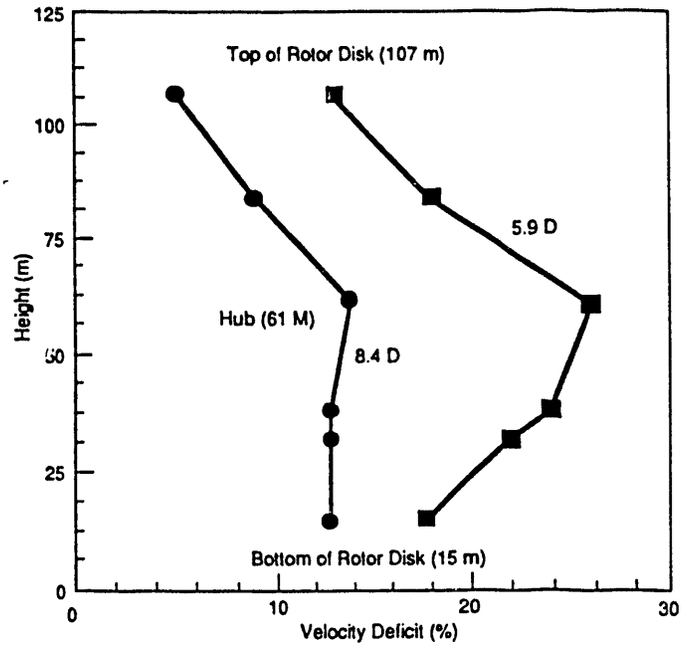

FIG. 4. VERTICAL PROFILE OF THE WAKE VELOCITY DEFICITS AT DISTANCES OF 5.9 AND 8.4 D

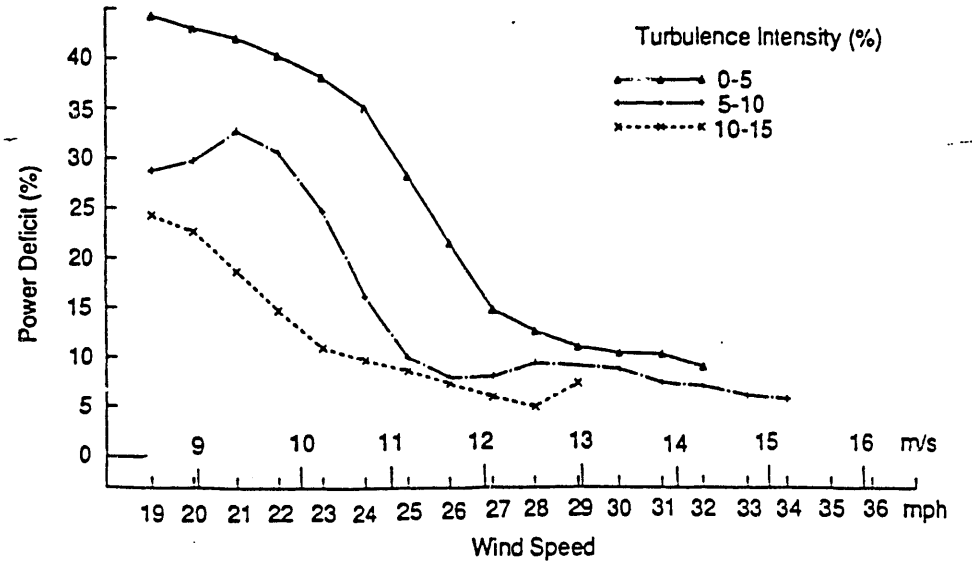

FIG. 5. EFFECTS OF WIND SPEED AND TURBULENCE INTENSITY ON WAKE POWER DEFICITS

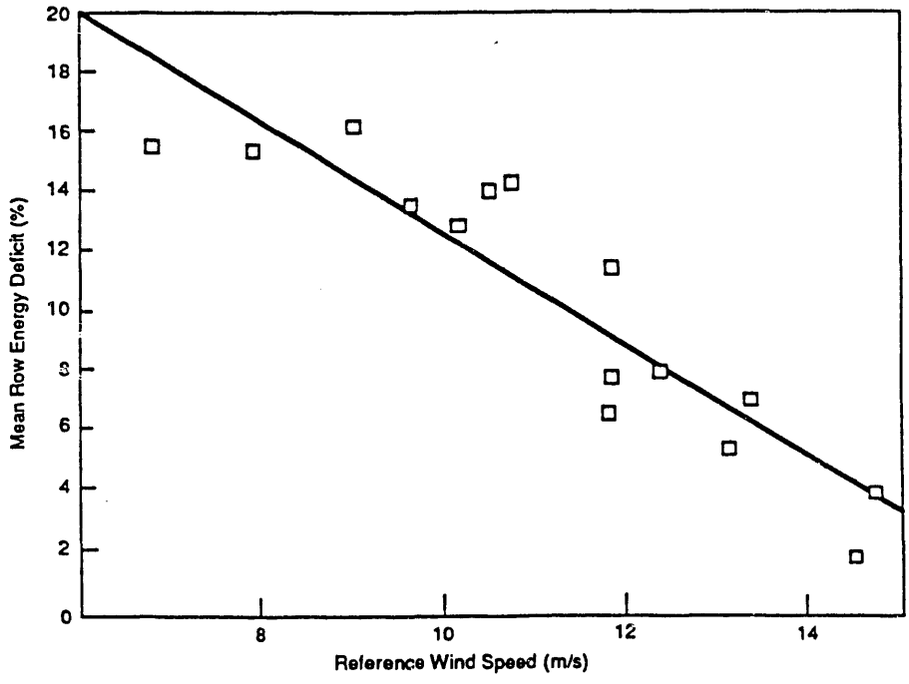

FIG. 6. ROW AVERAGE ENERGY DEFICITS VERSUS WIND SPEED

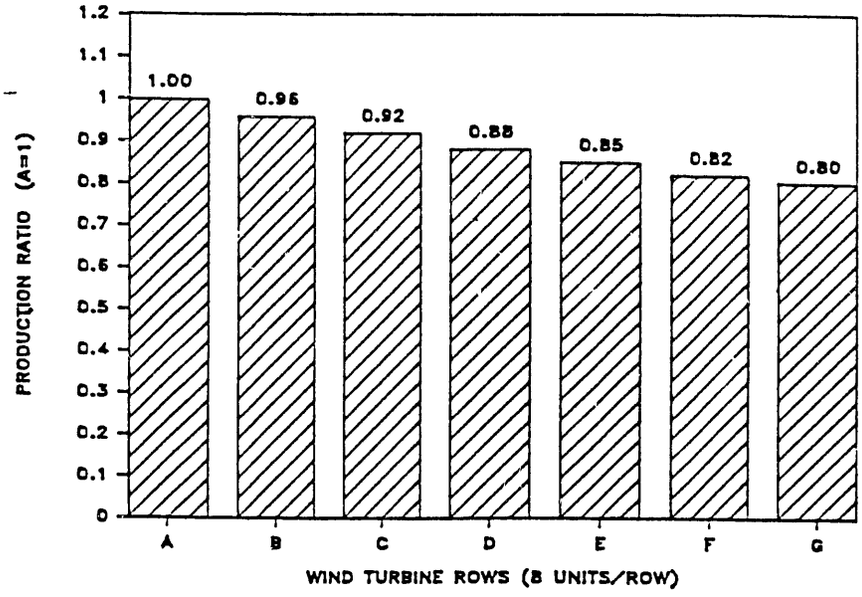

FIG. 7. ENERGY PRODUCTION RATIOS (INDICATED ROW/ROW A) IN A 7-ROW ARRAY

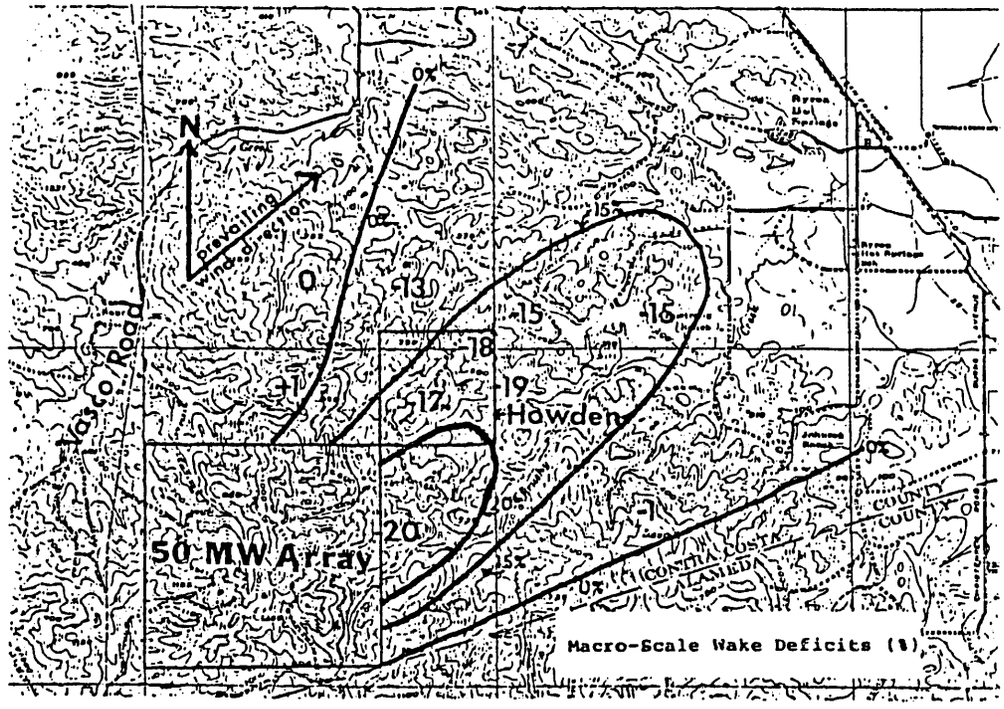

FIG. 8. ESTIMATED MACROSCALE WAKE ENERGY DEFICITS (%) IN THE ALTAMONT PASS

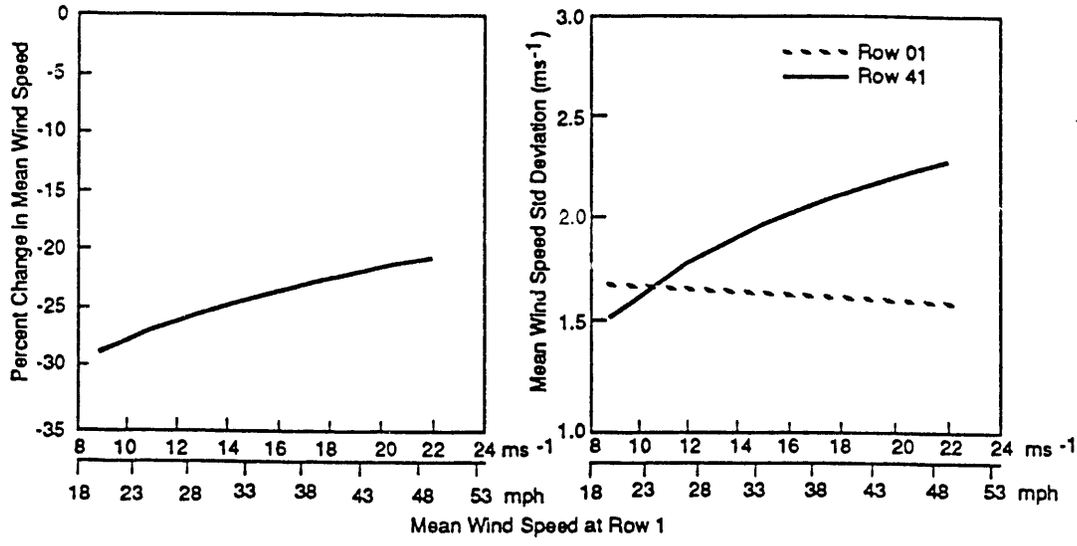

FIG. 9. VELOCITY DEFICIT AT ROW 41 (LEFT) AND COMPARISON OF WIND SPEED STANDARD DEVIATION AT ROW 1 AND ROW 41 (RIGHT)

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