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CALCULATION OF WAKE POWER LOSSES IN A TWO-LEVEL ARRAY: A SIMPLE CASE STUDY

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Richland, Washington 99352

SUMMARY

It is sometimes desirable to increase the power-producing capacity of a wind turbine array. Usually capacity is increased by purchasing additional property and installing more turbines. However, property around an existing array may be unavailable or prohibitively expensive, thereby precluding this option. Another method of adding capacity is to install another array of turbines whose hub height is above the existing array. This method may be an attractive alternative if wake interference is small between the new and existing turbine levels.

This report estimates the wake interference that could be expected in a two-level array. Interference is estimated for a typical situation that may be encountered by a wind farm developer. A modified Lissaman array model is used to make the wake interference calculations.

The model calculations show that the wake interference between the two levels is small--at least for the turbine characteristics and turbine layouts considered in this report. (The windwise spacings are about 5.4 and 10.8D for the lower and upper levels of turbines, respectively.) Power losses are about 5% or less at rated speed. Thus, two-level arrays may be a viable way of increasing the generating capacity of existing wind farms.

CONTENTS

FIGURES

1.0 INTRODUCTION

This report addresses a wake interference problem. It is proposed to increase the power-producing capacity of a wind farm by adding additional turbines to an existing array of identical turbines. The proposed turbines would be placed within the boundaries of the original array and the hub height of these turbines would be greater than that of the existing turbines. This would create a two-level array and wake interference between the new and existing turbines would occur. However, if this interference proved to be small, then an efficient increase in power production could be realized without purchasing additional land. This report is concerned with estimating the wake interference.

The problem of estimating wake interference is attacked through a case study of a particular array. This array is located in relatively flat terrain in the San Gorgonio Pass area of southern California and is composed of commercially available turbines. The array is acted upon by winds that are primarily from the west (270°).

The wake calculations that follow were made using the well-known Lissaman array model (Lissaman 1982). As array power estimates made by this model have never been verified by comparison to actual array power data, it is not yet known how well the model performs. It is important to realize that the results presented in this report are based on an unverified numerical model.

2.0 METHODOLOGY

The first step of this effort was to modify the Lissaman model to handle turbines of different hub heights. This could only be done easily by introducing two assumptions. The first of these is that the wind speed is assumed to be constant with height. This is not a realistic assumption. For the two hub heights considered in this study (60 and 120 ft), the turbines in the upper level would experience a larger wind speed than those in the lower level. The enhanced power output of the upper level, resulting from the increased wind speed, is not considered in this report.

The second assumption is that all turbines in the array are identical (except for their hub heights). This assumption could only be relaxed by making extensive and time-consuming revisions to the Lissaman code.

When the modification of the code was completed, the model was put through a number of quality assurance checks to assure proper functioning. It passed all checks.

Next the physical layout for the wind turbines was digitized. This layout is shown in Figure 1; the 84 existing turbines with a hub height of 60 ft are shown as circles, and the 42 proposed turbines of 120-ft hub height are indicated by a cross. The layout of smaller turbines is exactly as they are now positioned on a wind farm in San Gorgonio Pass in southern California. For the small-hub-height turbines, the east-west spacing is 350 ft and the north-south spacing is 90 ft. The proposed turbines will have an east-west spacing of 700 ft and the same north-south spacing of 90 ft. They will be arranged so that along the first and third north-south columns of existing turbines, one large hub-height turbine will be exactly half-way between two of the existing turbines. (This layout will be modified for additional testing as will be described later.) To distinguish between the turbine layouts, the one shown in Figure 1 is designated layout A.

Both the new and proposed machines in the array are assumed to be 180-kW turbines. Specifications for these machines are:

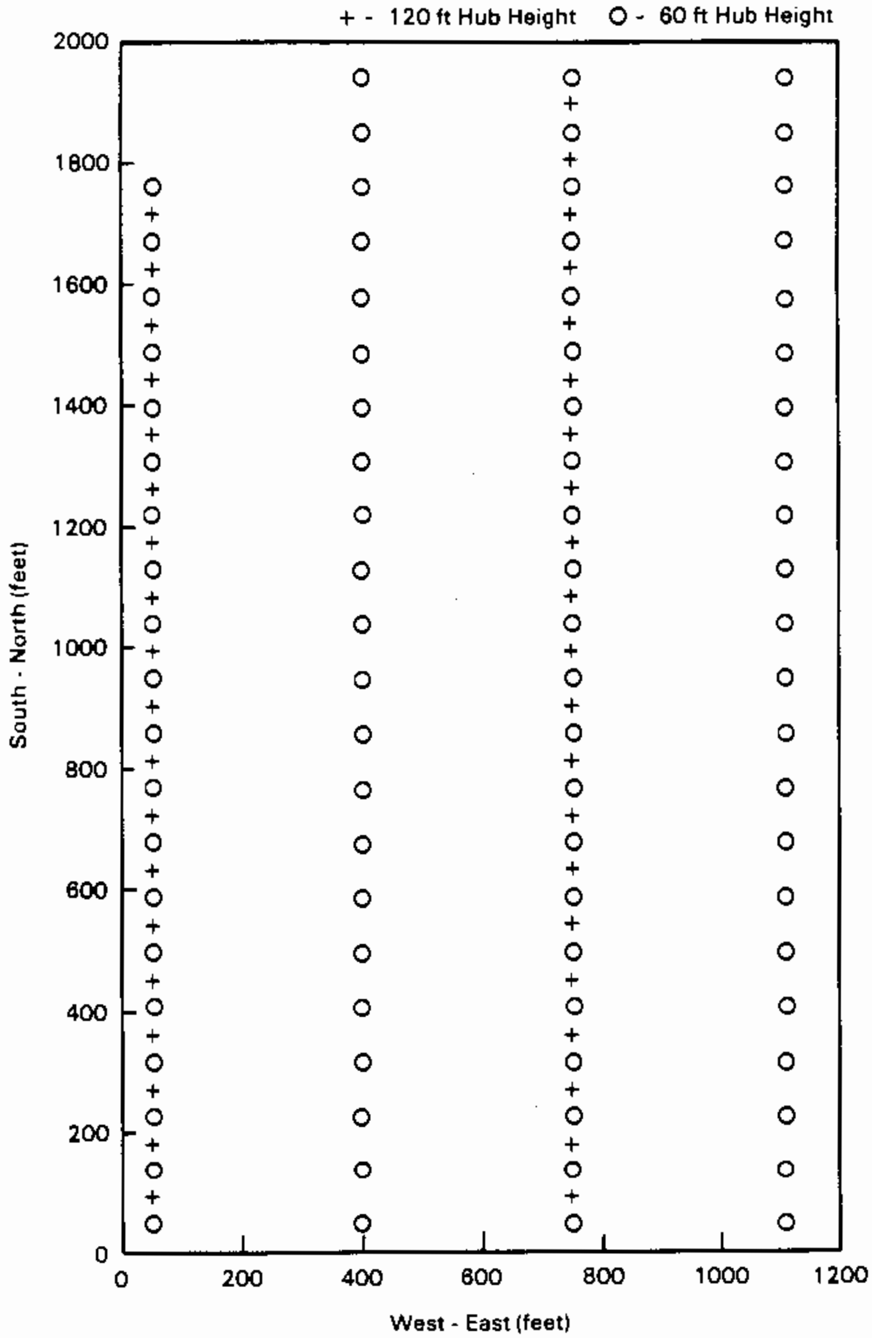

FIGURE 1. Turbine Layout for Wake Interference Test (Layout A)

Rated Power	180 kW
Cut-in Speed	11 mph
Rated Speed	40 mph
Cutout Speed	60 mph
Rotor Diameter	65 ft
Hub Height	60 ft & 120 ft
C_p at Rated Power	0.2
Blade Drag Coefficient (at rated power)	0.14
Rotor Solidity	4.4%
Tip Speed Ratio (at rated power)	3.37

These specifications, typical of commercially available turbines, are used as input into the Lissaman model.

To gauge the effect of adding an upper level of turbines, the average power output per turbine of the new array is compared to the average power output of this array if no wake interaction between levels were allowed. This comparison shows the number of kilowatts that are lost (per turbine) as a result of adding an upper level of turbines. The loss is a function of wind speed, wind direction, and transverse turbulence intensity.

Calculation of this power loss is simple. For a given set of the abovementioned meteorological variables, the Lissaman model is exercised for only the lower level of turbines, and the calculated power output is called P_ℓ. For this calculation the upper level of turbines is assumed to be turned off. Then the lower level is turned off, and the power output, called P_u, is calculated for the upper level. Finally, both levels are assumed to be operating and the model calculates P_b, the power output of the entire array.

The value P_b includes both the power losses caused by wakes generated in each level acting upon turbines in the same level, and losses caused by wake interference between levels. The values P_ℓ and P_u only include wake losses in the lower and upper levels, respectively. The value P_b is then less than the sum of P_ℓ and P_u, and this difference, $P_\ell + P_u - P_b$, is an estimate of the power loss due to wake interference between levels. This is what the wind farm developer loses by adding an additional level of turbines. For the results that follow, the power loss (or power output) has been normalized by the total number of turbines in the array, which is 126. The result is the power loss (or power output) per turbine.

3.0 RESULTS

The power loss has been calculated for a matrix of meteorological conditions that are thought to well represent those found at a wind farm in San Gorgonio Pass. The strong winds at this site are from the west, and the model was run for wind directions from 250° to 290° in increments of 5°.

For each wind direction, a transverse turbulence intensity must be specified. (The transverse intensity is that component of the turbulence intensity perpendicular to the wind velocity). Measurements of this parameter close to the site in question are not known to exist, and a range of transverse turbulence intensities was assumed that represents low, medium, and high values of this parameter for flat terrain. These values are 3%, 8%, and 12%, respectively.

Finally, for each wind direction and turbulence intensity the model calculates the power output of the array for wind speeds of 0 to 60 mph.

Figure 2 shows the power loss per turbine as a function of wind speed for three different transverse turbulence intensities. In this figure the wind direction is assumed to be 270°. (The calculations are quite insensitive to wind direction in the range 250° to 290° and results for other wind directions will not be shown.) Figure 2 shows the maximum power loss per turbine to be about 10 kW at about 40 mph. (The power gain around 50 mph for the 3% turbulence cannot be real. In the Lissaman model, the array efficiency is calculated assuming that all the machines are operating at the rated power coefficient. The resulting efficiency is then extrapolated to predict the performance of the array at other wind speeds. This technique causes some error in array power calculations near the cut-in and rated speeds. For the 3% turbulence level, this error manifests itself by the anomalous power gain and the small spike near the cut-in speed.)

The power loss increases with transverse turbulence intensity. The reason for this is that the power loss due to wake interaction between levels is caused by the vertical growth of wakes from one level into the other level. The growth rate of the wake radius (as a function of downstream distance from

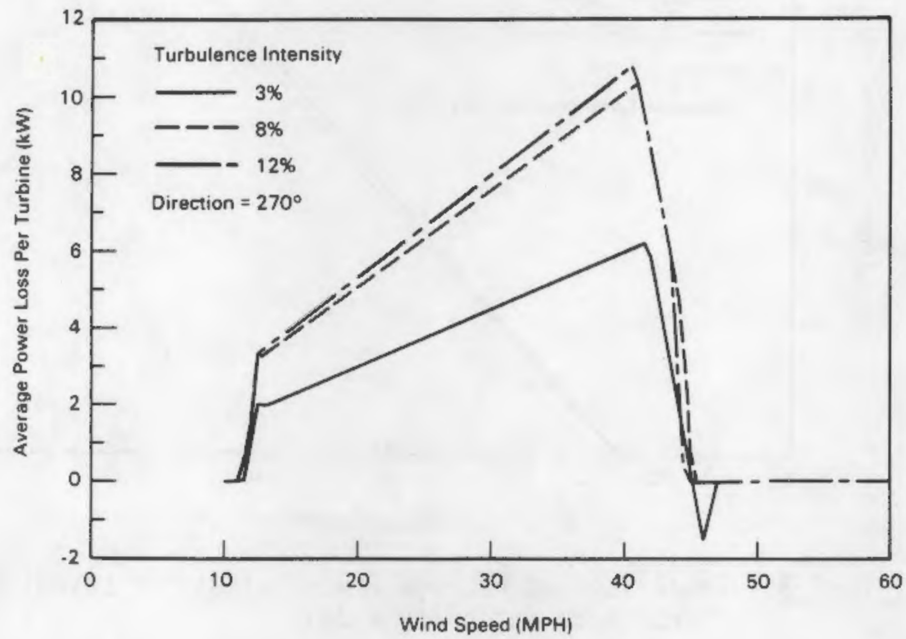

FIGURE 2. Power Loss (per turbine) as a Function of Wind Speed (Layout A)

the turbine) is governed by the transverse turbulence intensity--the greater the turbulence, the larger the growth rate. Higher turbulence levels, therefore, lead to larger wake radii, which in turn cause more wake interference between the vertical levels. This can be termed a "wake edge" effect.

It is useful to compare the power output of the lower and upper arrays ($P_\ell + P_u$) to the output of combined array, P_b. Figures 3, 4, and 5 show the power output plotted against wind speed at three different levels of the transverse turbulence intensity. When viewed in this manner, the power loss (which is the vertical distance between the solid and dotted lines) is rather small.

It is interesting to note that the power outputs of the lower and upper arrays ($P_\ell + P_u$) and the combined array (P_b) increase with transverse turbulence intensity at any given wind speed below about 50 mph. This effect is

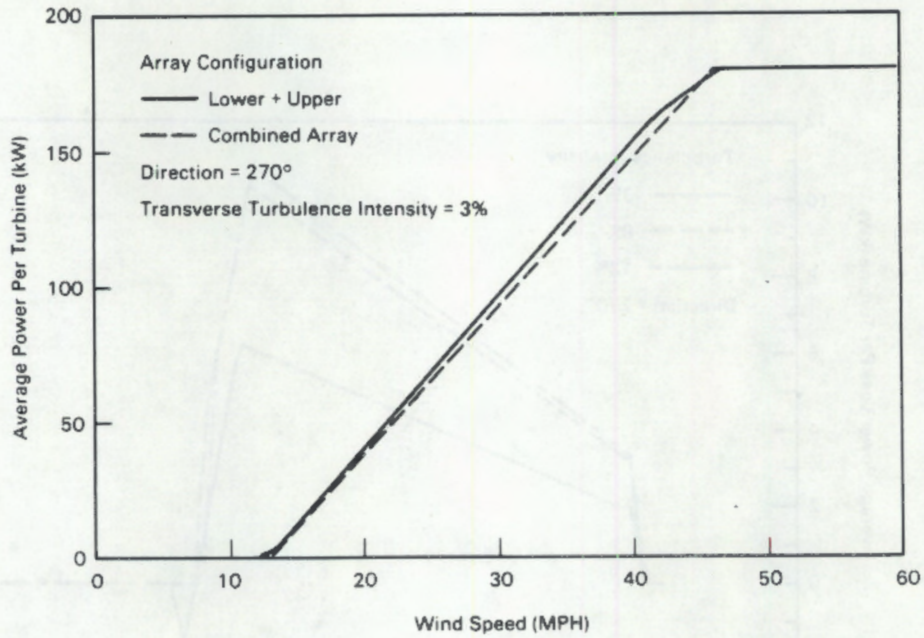

FIGURE 3. Comparison of Average Power Output for Layout A (turbulence intensity = 3%)

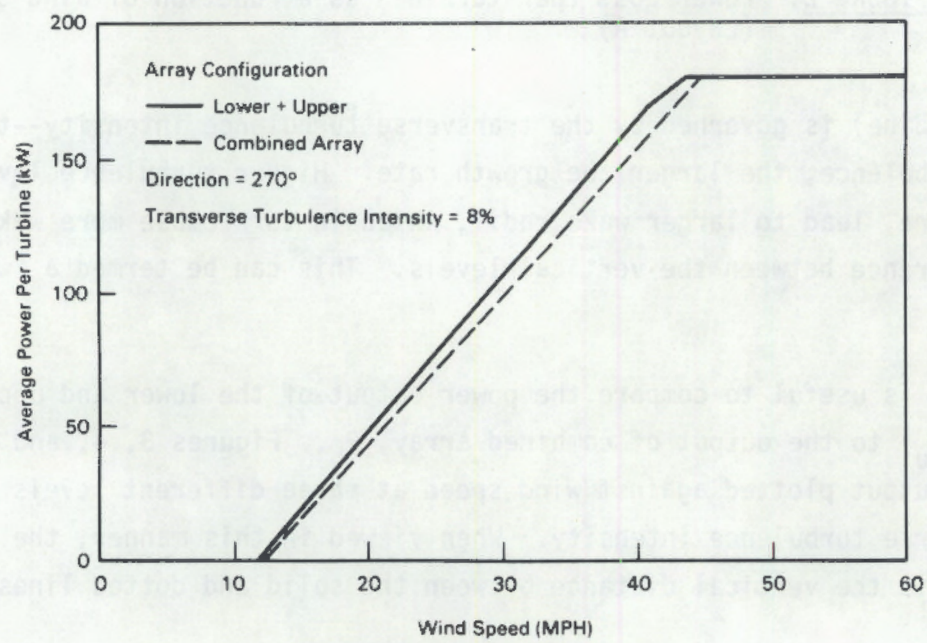

FIGURE 4. Comparison of Average Power Output for Layout A (turbulence intensity = 8%)

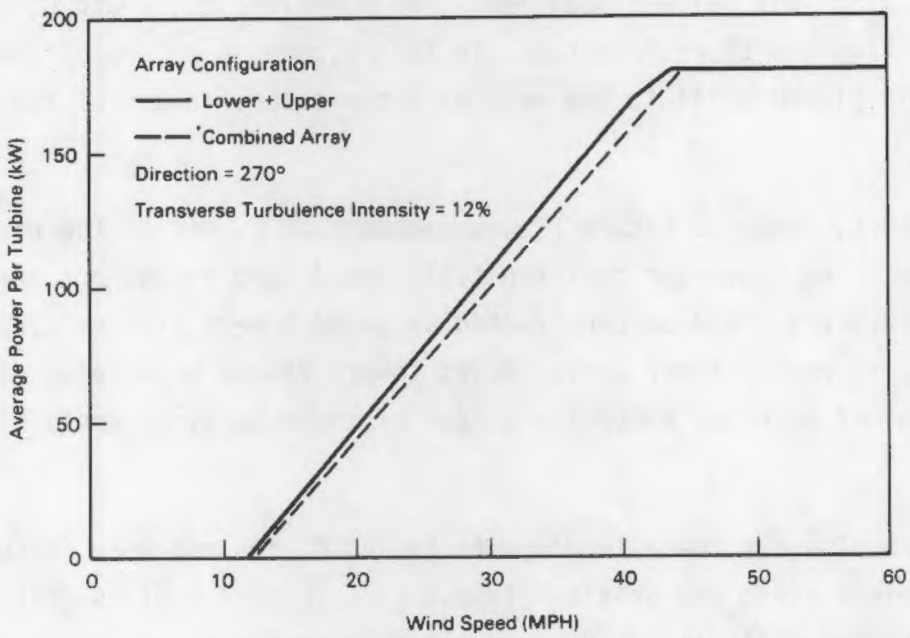

FIGURE 5. Comparison of Average Power Output for Layout A (turbulence intensity = 12%)

usually observed in single-level array calculations. It results from the decrease of the momentum deficit close to the wake centerline as the transverse turbulence intensity increases. In a single-level array, when the turbines are aligned so that one is directly downwind of another (or nearly so), the downwind turbines are affected most strongly by the deficit near the centerline. (The deficit near the wake edge does not impinge upon the downwind rotor.) As the "near centerline" deficit decreases with greater turbulence, the power output of the array becomes larger. This can be called a "wake centerline" effect.

In the two-level array, a greater turbulence increases the wake interference between levels as a result of the wake edge effects. However, this is more than compensated for by the decrease in wake interference within each level of the array that results from the wake centerline effect. Therefore, in this study the power output of the array increases with increasing turbulence intensity. (Other two-level arrays could perhaps be designed so the power output decreases with turbulence intensity.)

To investigate the sensitivity of these results to the turbine layout, the original layout (A) was modified. Two more layouts, B and C, are considered. Figure 6 shows layout B. In this figure, a column of the taller turbines is placed 40 ft to the west of every second column of the shorter turbines.

Layout C, shown in Figure 7, was recommended by one of the reviewers of this report. He suggested that the tall towers used to support the upper level of turbines could be constructed as guyed towers (towers supported by guy wires) to reduce their cost. Guyed towers cannot be located close to the lower level of turbines since the blades of these turbines would hit the guy wires.

The results for these two layouts (B and C) are not very different than those obtained using the original layout (A). Layout B gives slightly worse results than A, while layout C gives slightly better results.

Only the power loss (per turbine) for layout C will be shown. Figure 8 shows this loss for a wind direction of 270°. The power loss is slightly less than the loss for layout A for any given level of turbulence. For example, at a windspeed of about 38 mph, there is only a difference of about 2 kW for a transverse turbulence intensity of 12%.

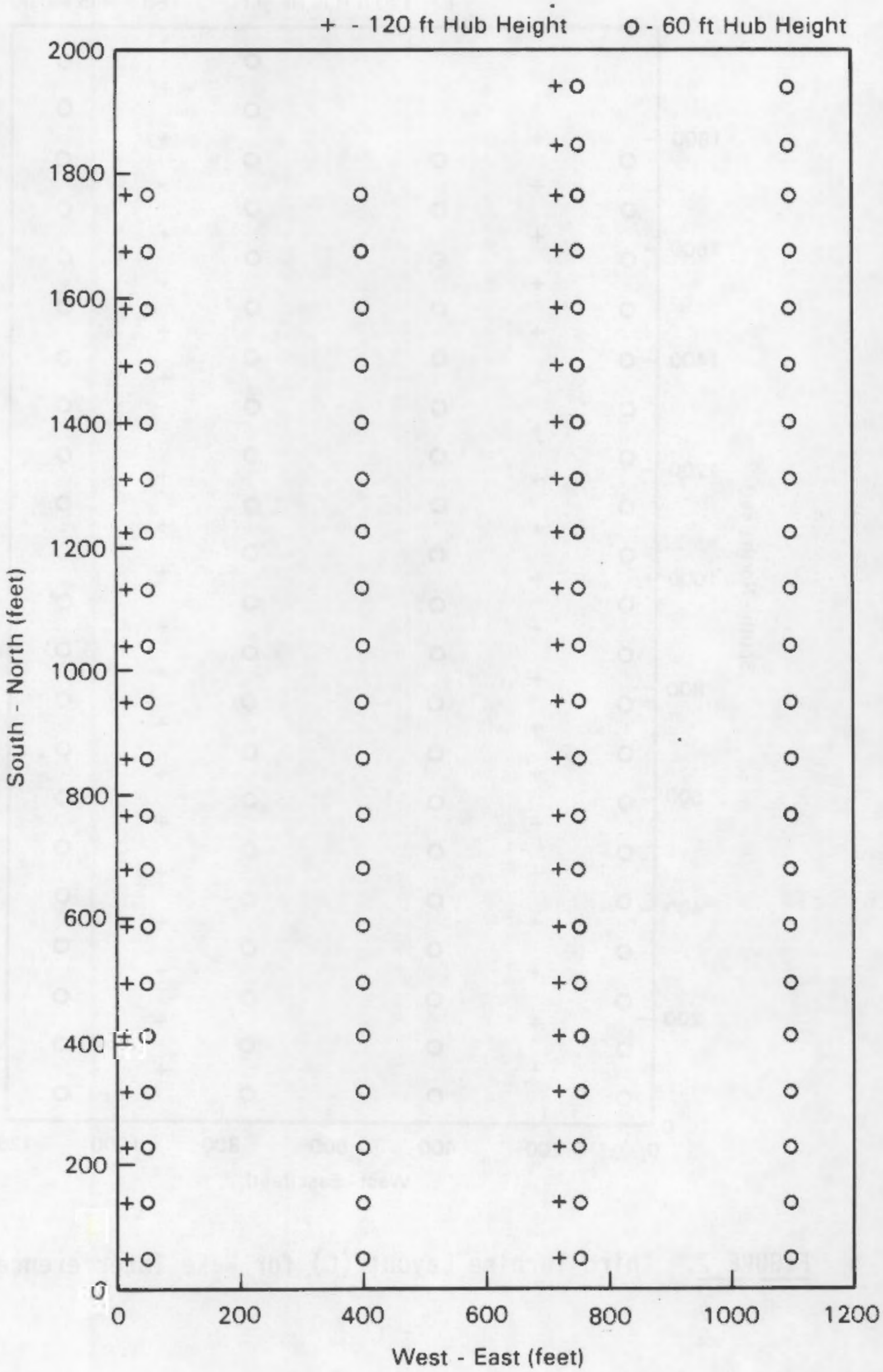

FIGURE 6. Second Turbine Layout (B) for Wake Interference Test

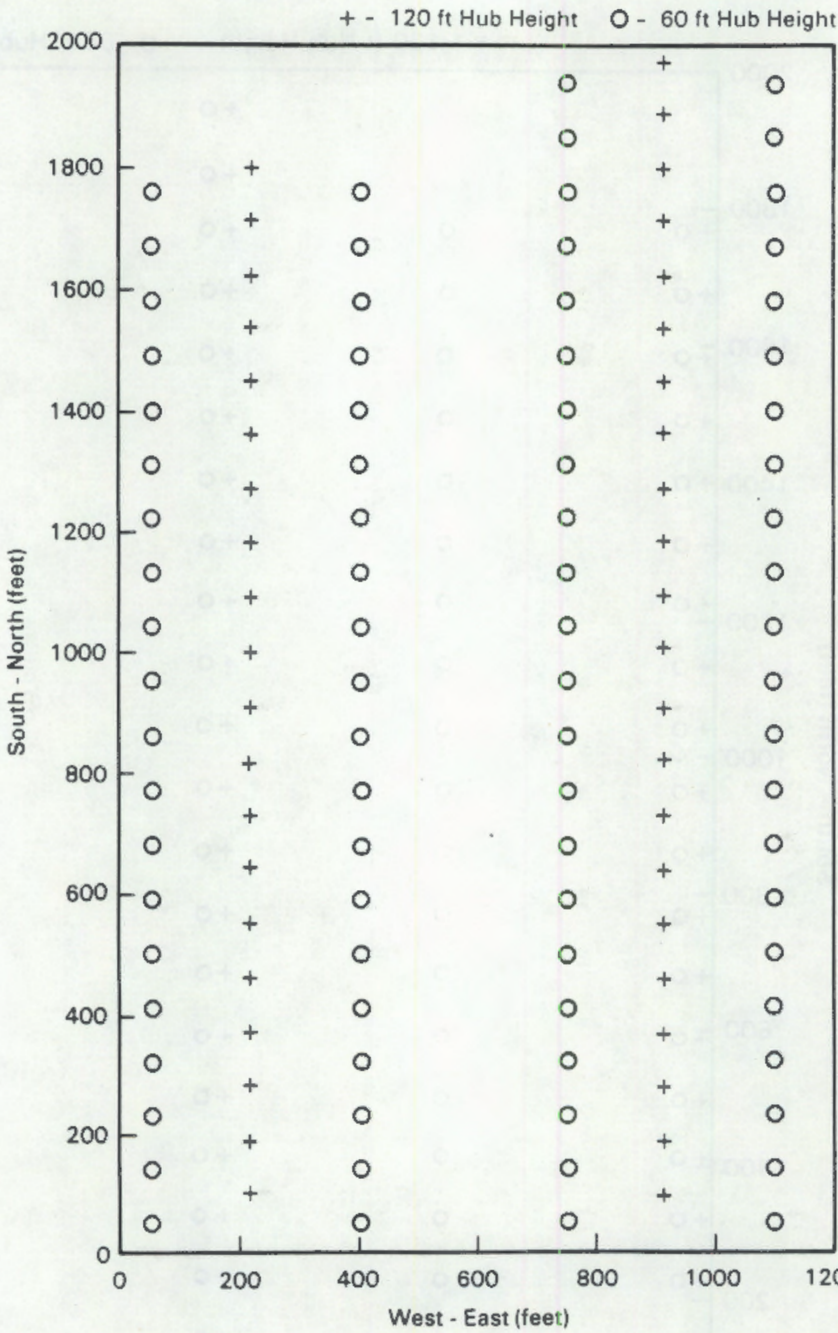

FIGURE 7. Third Turbine Layout (C) for Wake Interference Test

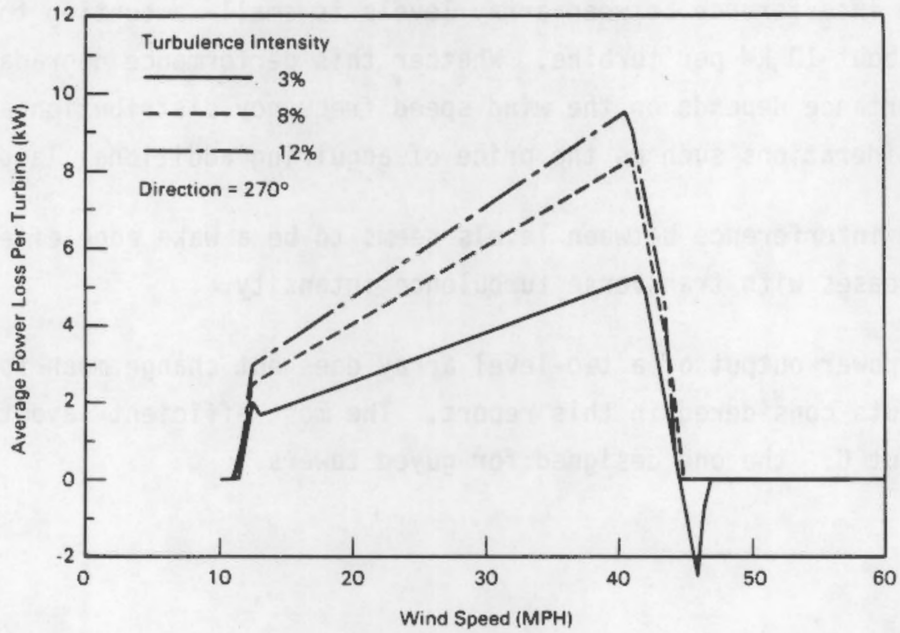

FIGURE 8. Power Loss (per turbine) as a Function of Wind Speed (Layout C)

4.0 CONCLUSIONS

The conclusions drawn from this study are:

1. If the Lissaman array model can be believed, these results show that wake interference between array levels is small--amounting to a maximum of about 10 kW per turbine. Whether this performance degradation is of importance depends on the wind speed frequency distribution and economic considerations such as the price of acquiring additional land.

2. Wake interference between levels seems to be a wake edge effect and increases with transverse turbulence intensity.

3. The power output of a two-level array does not change much for the three layouts considered in this report. The most efficient layout is layout C: the one designed for guyed towers.

5.0 REFERENCE

Lissaman, P.B.S., G. W. Gyatt, and A. D. Zalay. 1982. Numerical Modeling Sensitivity Analysis of the Performance of Wind Turbine Arrays, PNL-4183, Pacific Northwest Laboratory, Richland, Washington.

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