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OPERATIONAL MODEL FOR THE DESIGN OF OPTIMUM WIND FARM ARRAYS

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SUMMARY

For cost-effective wind farm design and operation, a tool is needed to provide a rapid estimate of energy production for a general array in a nonuniform wind field on complex terrain. The report describes Phase I of a project to develop an interactive computer code, which operates on a personal microcomputer for design and modification of wind farms.

The code operates on an Apple Macintosh Plus computer as described. The terrain contours for a specified site are input and displayed on the screen. The user inputs wind rose data defining the wind distribution, magnitude, direction and frequency. The code then calculates and plots isovents on the site map. The user then selects any type of wind turbine generator (WTG) and positions them on to the site map. As each WTG is sited the energy output, array interference and site efficiency is calculated and displayed The WTGs can be relocated, removed, added, or changed by the user with almost instantaneous updates on the effect of the change.

In the technical work a new algorithm for array interference of intermixed types and sites of WTGs in nonuniform flow was developed based on the Lissaman model. After a study of wind flow models, the Jackson and Hunt model was selected for interaction with the Lissaman wake model. There was preliminary development of an algorithm for the effects of turbulence on WTG performance and structures. This provides an indication of damage to WTGs due to extreme turbulence. Software has been developed, coded and operated for a flat terrain case and a typical complex terrain case using operating topographic, meteorological, array interference and WTG performance modules, combined with a temporary read-in wind flow algorithm. The code gives energy production, and the terrain and array effects of each WTG and demonstrates the interactive features.

The conclusion is that the development of a method for wind farm optimization is attainable. The technical algorithms and software can all be developed and incorporated into a versatile, easy to use computer program.

The progress made in Phase I was greater than expected, with all technical methods determined and much of the computer code written. Therefore, it is recommended that a Phase II be initiated to complete the code by developing and installing the wind flow model and finalizing the turbulence/structural algorithm.

Potential application outside the wind energy industry is limited but within the industry the program will benefit wind farm developers, operators, financiers and insurance groups. Industry members have voiced support for the program's application in designing new wind farms, evaluating performance enhancement and retrofit scenarios of existing wind farms, and tracking energy and revenue projections.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

1. INTRODUCTION

1.1 Background

To improve existing wind farms, as well as to design new ones, requires an accurate method of evaluating the wind resource in a particular terrain and choosing the best sites for the WTGs. Bankers and other financial organizations, like wind farm operators and developers, have become sophisticated in their understanding of the wind resource, and demand detailed and rational revenue predictions. Modern wind farms must be optimized for production and revenue and this information must report not only mean or expected values, but also the variations due to various fluctuations and uncertainties as well as some method of assessing the reliability and repeatability of the estimate. Such methods have not been readily available to the wind farm developer. The models that exist have been expensive, difficult to run, and unreliable.

Changes in perception, advances in wind turbine and fluid mechanics theory and in computer technology have now made it possible to take a significant step forward in wind energy. The perceptual changes support the view that optimal wind farms are both necessary and possible. The theoretical developments involve the fact that for the first time it is possible to calculate the performance of a real wind farm in a real wind on real terrain. Finally, the improved software and extended capacity of personal computers with their excellent graphics displays and interactive programming has made it possible to automate and integrate these theoretical performance methods. This now places the most advanced wind-turbine array design process and decision making information at the disposal of any individual, university or energy bureau having access to a personal computer.

The work described here represents the first step in creating a state-of-the-art wind farm computer design program. This interactive program will respond almost instantaneously to user commands and employ the most advanced technological algorithms available. This is the first phase of a project of which the final goal is to make the code available as a commercial product.

1.2 Research Objectives

The objective of this work is to determine the feasibility of constructing a computer model to predict the performance of a wind farm on irregular terrain. This code should be interactive in the sense that the user can change WTG locations graphically and receive a very rapid listing of the energy characteristics of this new array. The object was to develop technical algorithms to serve as components of the complete model and to investigate the software requirements for implementing these algorithms on desktop microcomputers.

All the above research objectives have been met and considerably more progress has been made than anticipated. Not only have software requirements been investigated, but friendly software has actually been written and debugged which is currently running and contains most of the features required.

2. SCHEMATIC DESCRIPTION

A method of designing wind farm arrays using an interactive computer program has been developed by AV. Figure 2-1 shows the general flow process and user interactions of the wind farm design program. The computer program, currently designated AVFARM, operates on an Apple Macintosh Plus computer. Table 2-1 shows the status of development of the program.

A test version of the program is operational on the Macintosh testing the user interactive features and processing speed. A description of the program's operation is given in this section, the figures used in this description were taken directly from the display of the test program as it appears on the Macintosh computer.

Once the program is loaded into the computer, a blank screen with a special series of pull-down menus appears. From the blank screen (Figure 2-2) the menu FARM is selected. The screen then shows a contour (topographic) map of the site (Figure 2-3) plotted from data fed into the program. Figure 2-3 shows this for a bench-type hill with peaks at the north and south ends.

When the TURBINE menu is selected, a list of candidate WTGs is scrolled and any number of similar or different turbines are selected, causing the screen to display a scale diagram of the turbine with its power-versus-speed characteristics, as shown in Figure 2-4. The program assigns an identification symbol to each turbine selected. The turbines are placed by using the mouse to drag their symbol from the store location in the upper left area to the site on the right of the screen. As each turbine is dragged and placed on the site, the count of turbine numbers is appropriately adjusted. Figure 2-5 shows two different types of turbines on their actual locations on the sites.

Now the menu WIND is selected and the average speed and frequency (in percent time) are input for the control station on the site. The program then displays a wind rose (Figure 2-6) showing the wind speed, direction and frequency graphically. The wind rose in the figure shows frequency as the included angle of

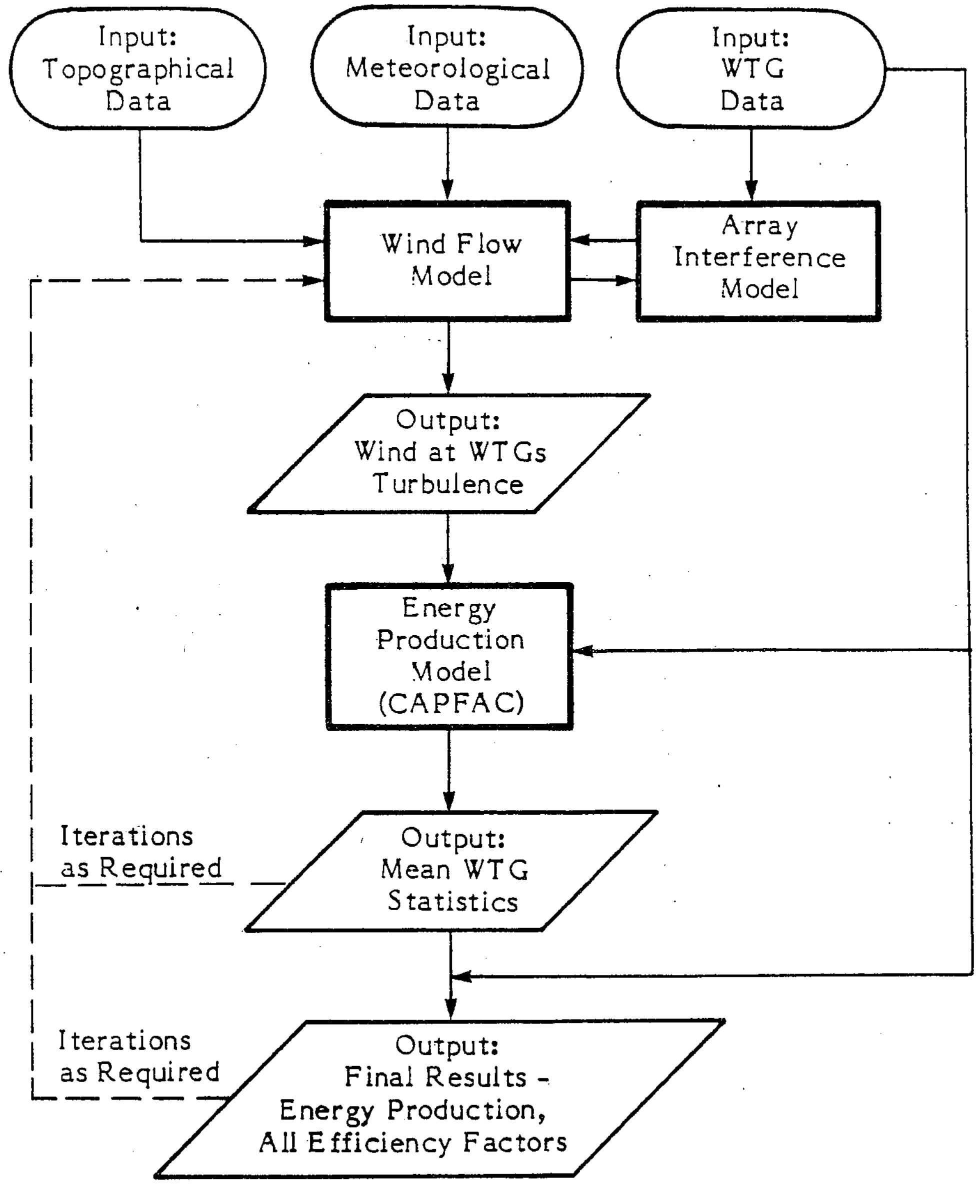
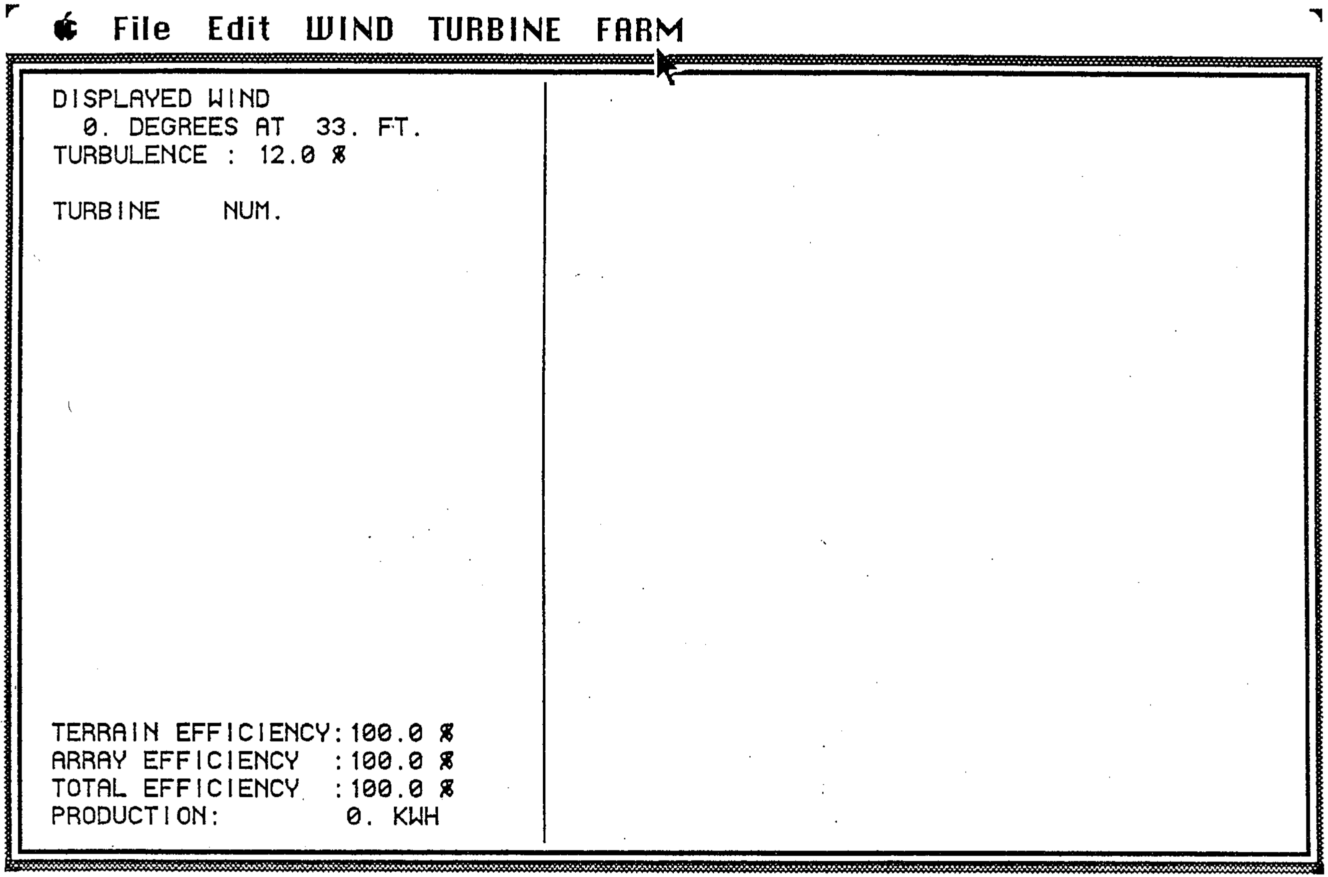


FIGURE 2-1. General process of the wind farm design program.

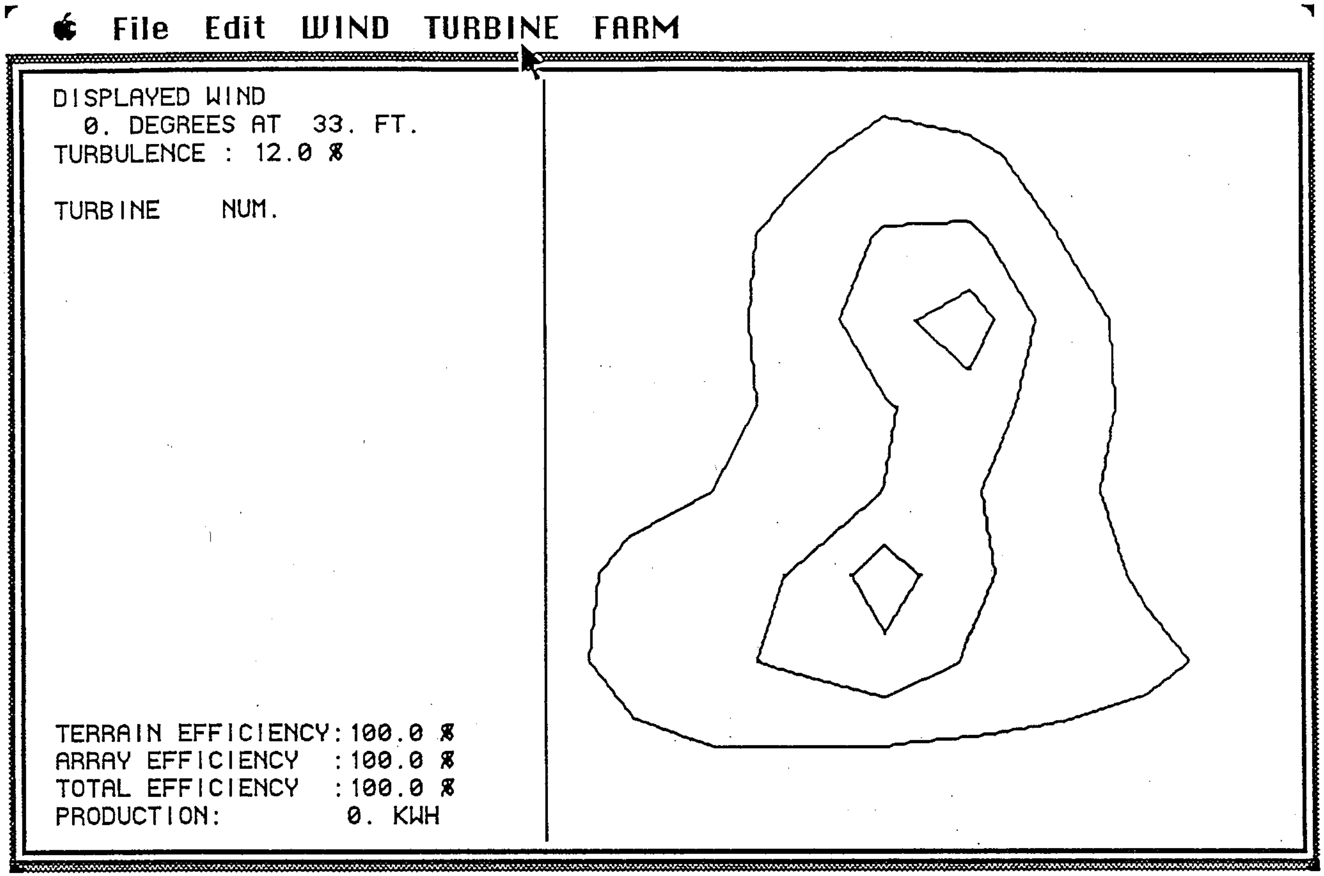
TABLE 2-1 Status of development of AVFARM.

Element	Status
Read in terrain, turbine characteristics, wind data	Complete
Determine wind flow (speed-up factors) for terrain	Still to be done. Analytical method selected.
Locate turbines and design procedure to move around on site	Complete
Show isovents (speed-up factors)	Complete
Show individual turbine production in array on site	Requires only software development.
Calculate production for single turbine or group by season, month, time of purchase, etc. and display spread sheets	Requires only software development.
Conduct statistical analysis to determine expected productions and and variances	Statistical procedure selected. Requires only software development.



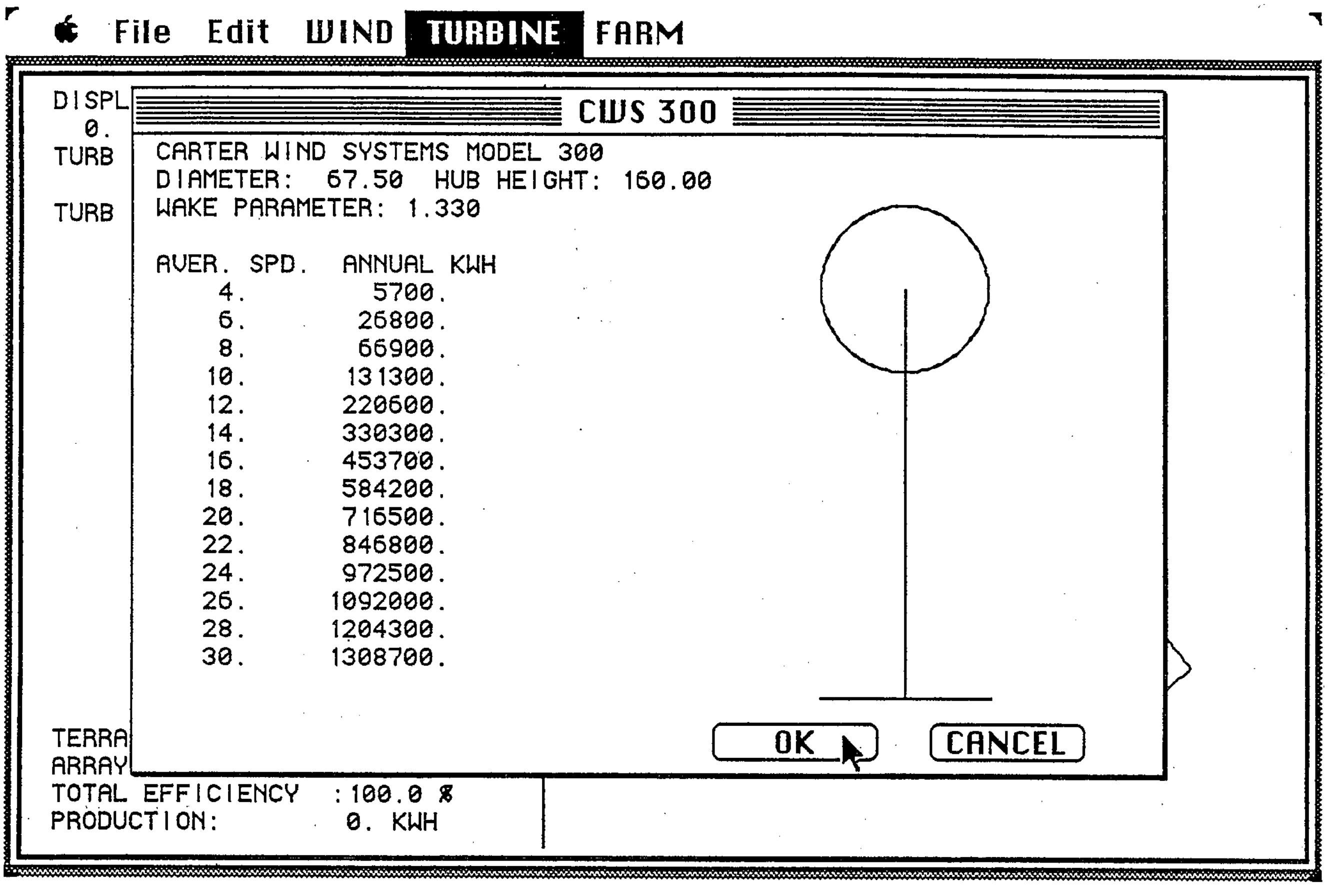
```
DISPLAYED WIND
  0. DEGREES AT  33. FT.
TURBULENCE : 12.0 %

TURBINE    NUM.









TERRAIN EFFICIENCY:100.0 %
ARRAY EFFICIENCY  :100.0 %
TOTAL EFFICIENCY  :100.0 %
PRODUCTION:        0. KWH
```

FIGURE 2-2. Initial blank screen with menu FARM selected for next operation.



```
DISPLAYED WIND
  0. DEGREES AT  33. FT.
TURBULENCE : 12.0 %

TURBINE    NUM.

TERRAIN EFFICIENCY:100.0 %
ARRAY EFFICIENCY  :100.0 %
TOTAL EFFICIENCY  :100.0 %
PRODUCTION:         0. KWH
```

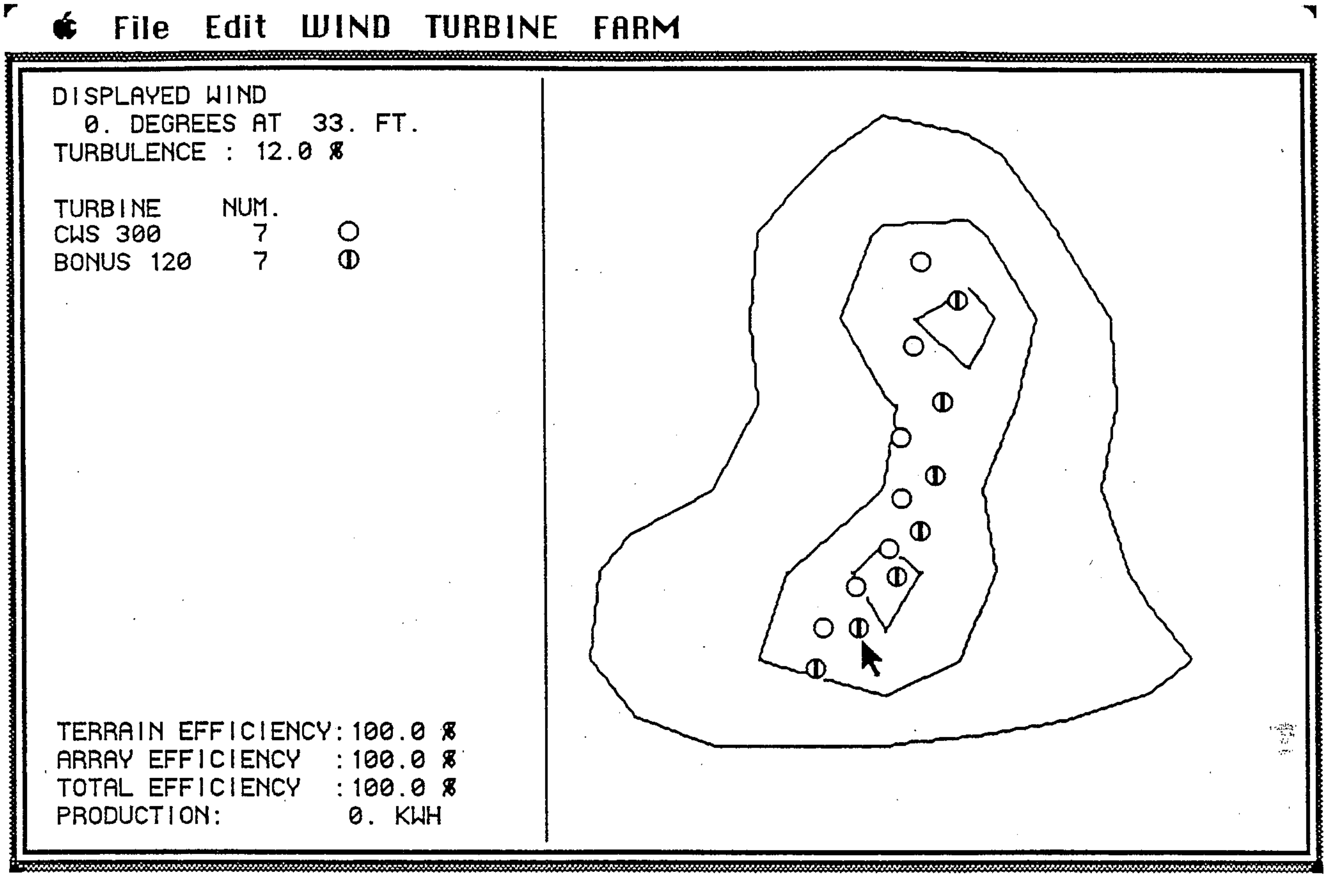
FIGURE 2-3. Contour map of terrain shown with menu TURBINE selected for next operation.



```
CARTER WIND SYSTEMS MODEL 300
DIAMETER:  67.50  HUB HEIGHT: 160.00
WAKE PARAMETER: 1.330

AVER. SPD.  ANNUAL KWH
    4.          5700.
    6.         26800.
    8.         66900.
   10.        131300.
   12.        220600.
   14.        330300.
   16.        453700.
   18.        584200.
   20.        716500.
   22.        846800.
   24.        972500.
   26.       1092000.
   28.       1204300.
   30.       1308700.
```

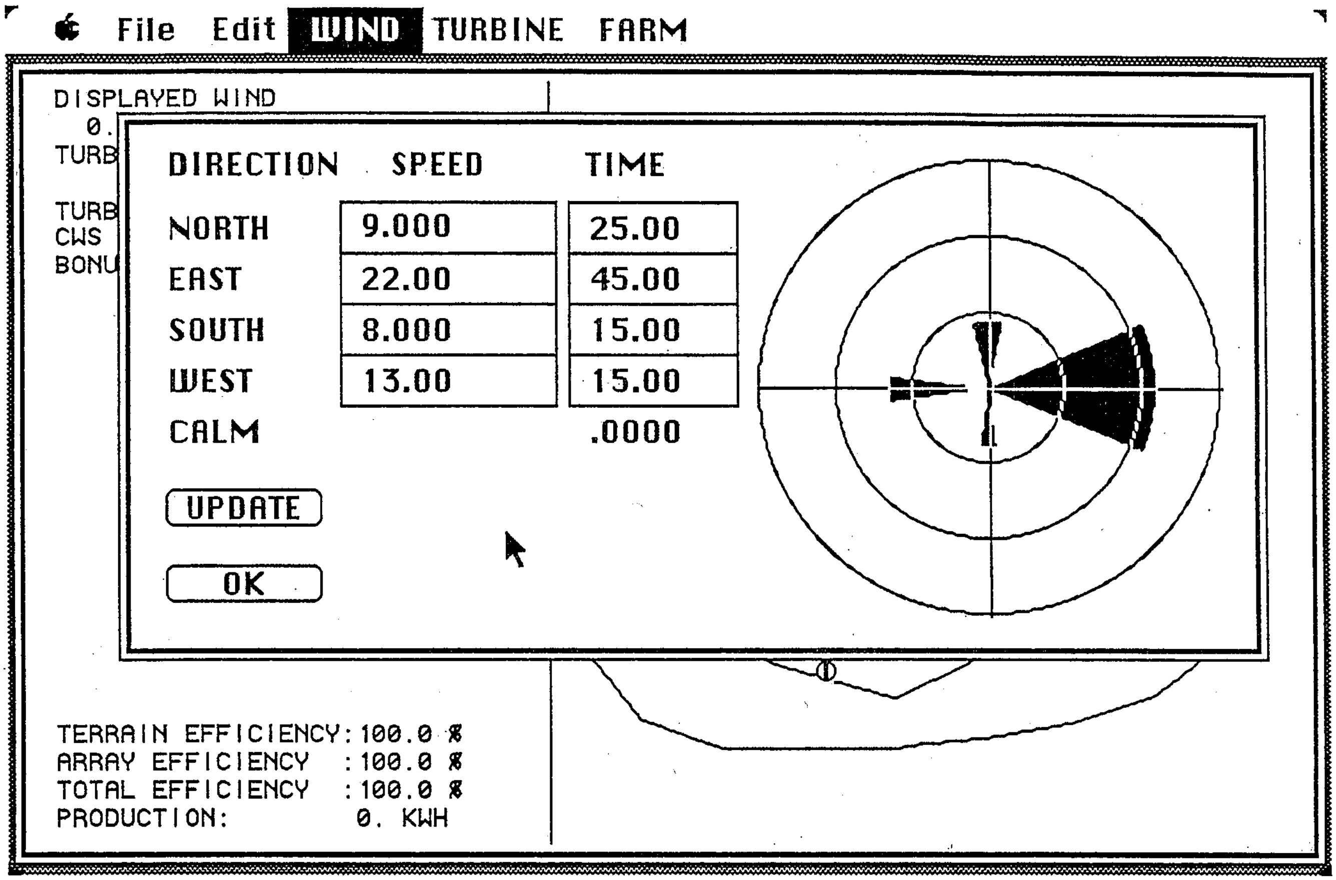
```
TOTAL EFFICIENCY  :100.0 %
PRODUCTION:         0. KWH
```

FIGURE 2-4. Output of TURBINE menu showing proportions and characteristics of the CWS 300 WTG.



```
DISPLAYED WIND
  0. DEGREES AT  33. FT.
TURBULENCE : 12.0 %

TURBINE     NUM.
CWS 300       7     ○
BONUS 120     7     ⦶

TERRAIN EFFICIENCY:100.0 %
ARRAY EFFICIENCY  :100.0 %
TOTAL EFFICIENCY  :100.0 %
PRODUCTION:         0. KWH
```

FIGURE 2-5. Placement of 7 CWS 300 units and 7 BONUS 120 units on site.



DIRECTION	SPEED	TIME
NORTH	9.000	25.00
EAST	22.00	45.00
SOUTH	8.000	15.00
WEST	13.00	15.00
CALM		.0000

TERRAIN EFFICIENCY: 100.0 %
ARRAY EFFICIENCY : 100.0 %
TOTAL EFFICIENCY : 100.0 %
PRODUCTION: 0. KWH

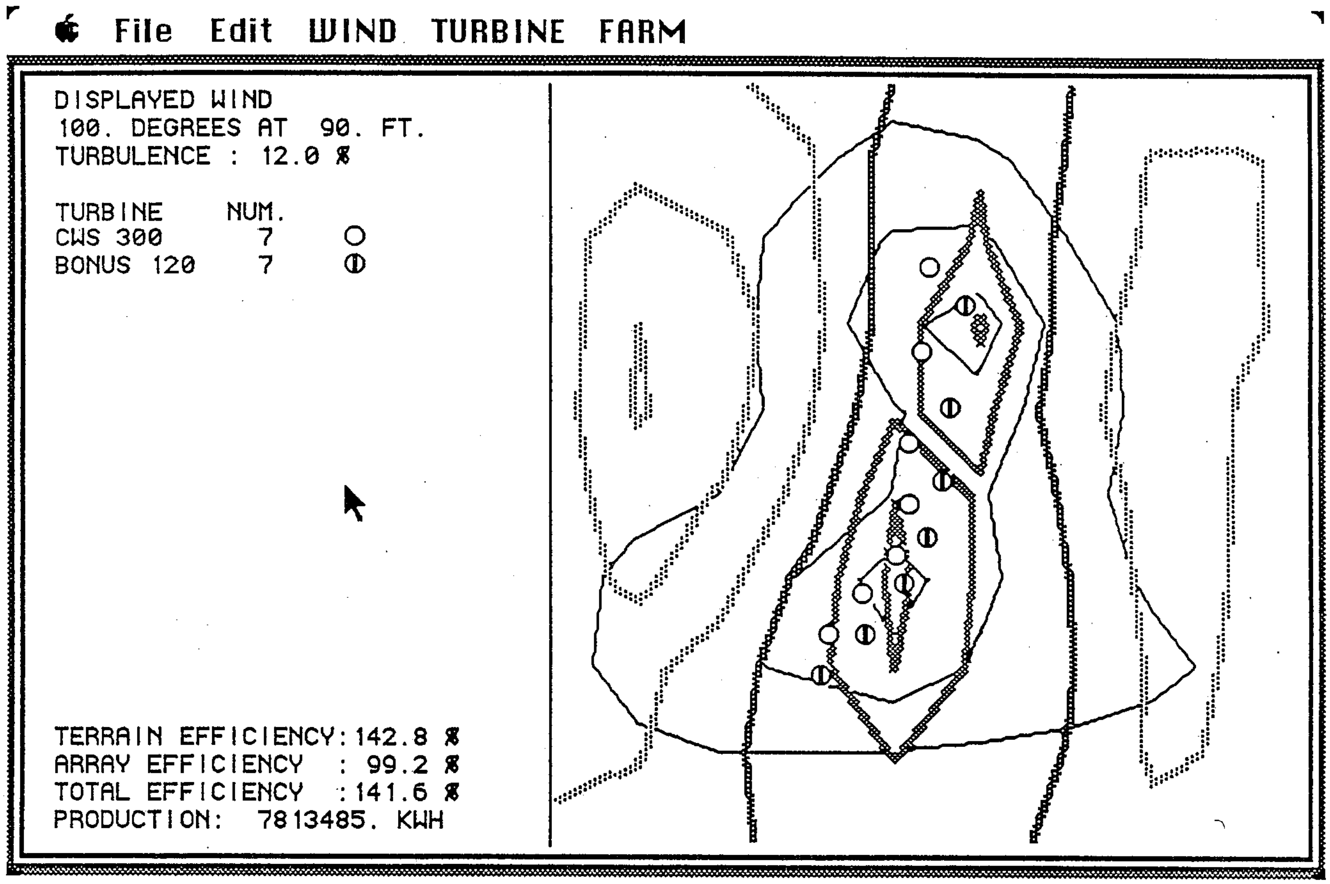
FIGURE 2-6. Wind rose at control station for a particular period.

the pie-shaped sector, while speed is indicated by its radius. The wind flow program calculates the isovents in the form of speed-up factors, the array program is entered for a given wind direction, magnitude and turbulence and calculates the interference and the production of each unit and of the total array. As an aid in optimizing the layout, various efficiencies are calculated and displayed.

The terrain efficiency is defined as the output of each turbine at its site without interference compared with its output if it were located at the reference station. The terrain efficiency is a measure of how well the high energy areas of the site are being used. For the case shown in Figure 2-7, this terrain efficiency is 142.8 percent, the high level indicating that the turbines are all placed in an area where the wind flow is significantly higher than the speed at the reference station. The array efficiency is defined as the actual output of a particular array compared with that for the same array with no interference. It will not exceed 100 percent. For the example shown, the array efficiency is given as 99.2 percent, indicating less than one percent interference, which is appropriate for the case under consideration, an easterly flow with turbines in a north-south line on a north-south ridge. Finally, the total efficiency is calculated (also shown in Figure 2-7 as 141.6 percent). It is the ratio of the output of the actual array to the baseline output for noninterfering units all situated at the reference station.

To optimize the array, the turbines can be dragged by the mouse to different locations while the screen indicates almost instantaneously the new efficiency values. This provides an extremely rapid method of rearranging or adding units, or changing the turbine equipment. After an arrangement has been selected, this process is then automatically conducted for all the prescribed wind directions and frequencies to provide similar information for the complete wind rose for any given period.

Finally, spread sheets will be generated displaying the performance of each turbine or turbine group for different time periods. Arbitrary situations can be input here to increase visibility of the performance of the array. For example, the output for unidirectional flows can be determined by using a wind rose having 100 percent flow from the required direction.



```
DISPLAYED WIND
100. DEGREES AT  90. FT.
TURBULENCE : 12.0 %

TURBINE     NUM.
CWS 300      7     ○
BONUS 120    7     ⦶

TERRAIN EFFICIENCY:142.8 %
ARRAY EFFICIENCY  : 99.2 %
TOTAL EFFICIENCY  :141.6 %
PRODUCTION:  7813485. KWH
```

FIGURE 2-7. Display of speed-up factors at 90 feet above ground and for wind from 100° with various efficiencies for the array.

At its current level of development, the terrain/wind flow interaction has not yet been coded. A modification of the Jackson/Hunt procedure will be used as is discussed at length in Section 3.2. At present, the computer program simply uses a read-in table of the speed-up factors for the particular terrain so that the rest of the code can be operated. Another element which has not yet been coded is the final spread sheet array layout showing the outputs of each turbine and the array for various conditions of wind or time periods. These spread sheets will be designed after consultation with various windfarm operators to determine the most convenient and appropriate schemes of presentation. This step does not require analytical fluid mechanical algorithms but is a matter only of software and display development, which will be accomplished without theoretical difficulty.

3. TECHNICAL ALGORITHMS

3.1 General Discussion of Technical Algorithms

The code referred to in Section 2 requires a number of different operations. In essence these are data input, technical algorithms, and output software. The data input software accepts data descriptive of topography, meteorology and WTG characteristics. The technical software involves engineering calculations of wind flow, array interference, and WTG energy production with statistical variations due to natural fluctuations and mechanical reliability factors. The output software enables results to be displayed in suitable forms. In this section, we discuss only the technical algorithms, which require fluid physics and applied statistics.

The technical algorithms are divided into the four groups listed below followed by a discussion of each.

- Wind Flow Over Nonuniform Terrain -- For which the Jackson and Hunt model has been selected as a base.
- Array Interference in Nonuniform Terrain -- Based on the Lissaman model expanded to include analysis of variable types and sizes of WTGs on complex terrain.
- Effects of Turbulence on WTG Performance and Structural Life --Based on the PROP code.
- Statistical Analysis

3.2 Wind Flow Over Nonuniform Terrain

The wind flow over irregular terrain is very complex. For typical WTG sites with moderate hills and ridges, speed and turbulence variations of the order of 10% to 50% about the mean occur over relatively short distances. This is sufficient to cause significant differences in the output of WTGs in different locations.

Generally speaking, the wind speed is higher near the top of hills and lower in the valleys. In extreme cases of relatively large slope and the associated strong adverse pressure gradient, a separated zone or bubble can occur with strong large-scale turbulent eddies and a relatively quiescent flow state in the bubble. Usually the separation does not extend to the WTG disk, but the turbulence due to the separation does interact with the disk and can produce strong turbulence at the rotor, with the associated possibility of structural damage due to excessive unsteady loadings or fatigue. In extreme cases of a vertically extended separation region enveloping the rotor, the flow speed can be sufficiently reduced that it drops below cut-in speed for the WTG.

The principles of the fluid mechanics of the flow are well understood, although accurate calculation methods have only recently been developed. Figure 3-1 shows the geometry of wind flow over irregular terrain. It has been drawn approximately to scale in the vertical and horizontal dimensions. Generally speaking, the terrain is immersed in a turbulent boundary layer of the order of 600 m in depth, but beyond this region the flow behaves as an inviscid irrotational fluid and thus, for the barotropic case, the potential equation is satisfied. Nonbarotropic situations, associated with flow statification, do not frequently occur with continuous flows of sufficient energy to be important in wind turbine operation. For example, Pasquill (1962) in his classic method of estimation of stability classes by considering insolation and wind speed (p. 209) notes that the wind flow is essentially neutrally stratified for surface (10m) wind speeds in excess of 11 mph (5 m/s) for all insolation and cloud cover cases except for very strong insolation. The relatively high speed of energetic flows causes strong turbulence and mixing, which prevents the layering associated with stratified flow.

The outer potential flow responds to the kinematic boundary conditions imposed by the terrain contour according to the usual well-known characteristics of potential flow about bodies. This can be visualized by considering the effect of a single bell-shaped (Gaussian) three-dimensional hill on a relatively flat plain, and noting that, by the exact linearity of potential flows, a general terrain of arbitrary complexity can be constructed by superimposing a collection of hills and valleys of varying size and spatial disposition.

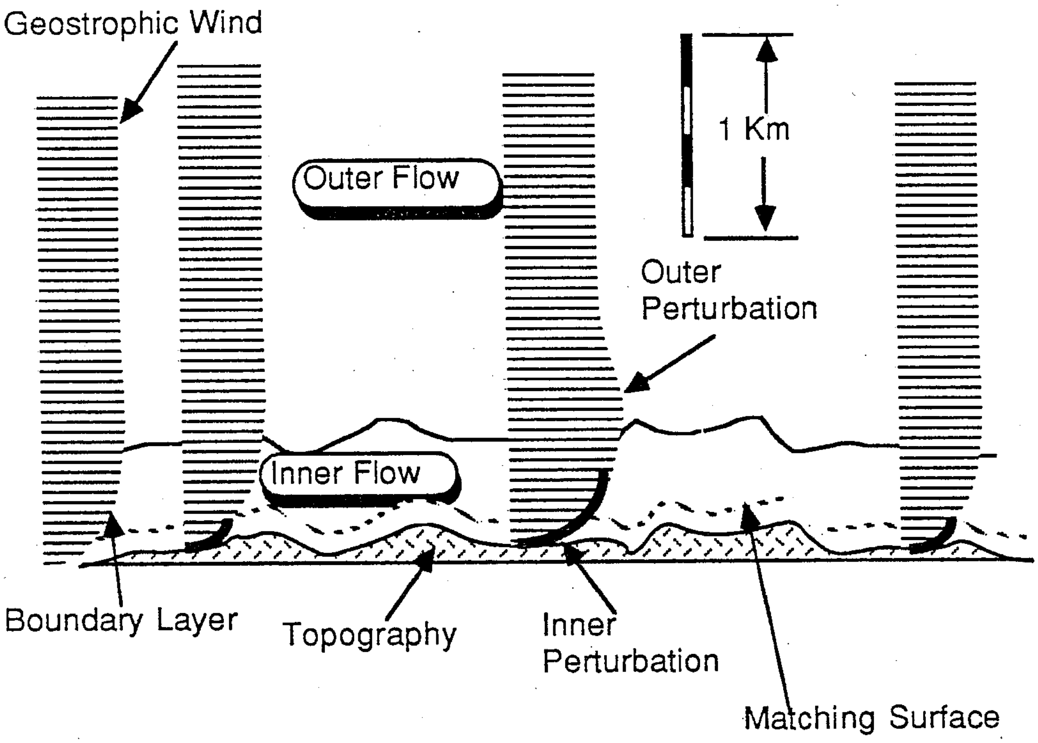


FIGURE 3-1. Geometry for wind flow over irregular terrain.

It can be shown that such a hill has a high speed, low pressure region in the outer flow above the hilltop, with a lower-than-free-speed region above the leeward and windward slopes, the influence being symmetrical upwind and downwind as well as to the left and right of the flow direction. The velocity perturbations are radially symmetrical for a hill having circular contours, but the pressure perturbations are not, because of the coupling with the free stream flow so that the wind rise pressures are different from those at crosswind locations. For a depression or valley, one can show that the velocity perturbations are exactly the reverse of those for the hills. The magnitude of the velocity perturbations in the outer flow is given by U h/L, where U is the undisturbed speed, h the height and L the length scale of the hill. The velocity changes are also reflected in pressure perturbations defined by Bernouillis equation, with the pressure being lower over the peaks of the terrain and the pressure changes more pronounced on the windward and lee slopes than on the crosswind slopes.

The boundary layer causes the flow to come to rest at the ground surface and, being turbulent, there is normally a strong velocity gradient in the first 100 meters above ground level. This is the region in which turbine rotors will normally be located. For most experimental field anemometry this wind shear is technically modeled by a so-called profile exponent, which normally lies between 0.10 and 0.20. This is an adequate approximate representation over a modest height range (less than 100 m). For more rational fluid mechanical modeling it is customary to use the classical logarithmic law, which accommodates the important ground roughness and friction parameters and is theoretically exact for a uniform flow. This logarithmic layer is affected by the perturbation of both the inner terrain boundary profile and the outer flow pressure in the following fashion. The outer pressure perturbation is transferred to the ground almost unchanged, in a way similar to the well-known zero normal pressure gradient behavior of boundary layers over aeronautical and marine vehicles. This pressure perturbation distorts the undisturbed logarithmic boundary layer, and the distorted boundary layer in turn affects the Reynolds shear stresses associated with the interaction of the turbulence and the velocity gradients. Thus the flow response here responds to the effects of the combined pressure and Reynolds stress gradients.

This creates an inner perturbation which is a turbulent boundary layer within a turbulent layer. The perturbation equation, like that of the typical boundary layer, is parabolic in this region, characterized by the well-known increase in thickness of the perturbation region as the flow proceeds from the origin or initial condition. It is this effect that creates the unsymmetrical effect in the low-level wind flow over a symmetrical hill, causing the flow speed at a given height above ground level to be slightly higher to windward of the crest than it is at the same distance to the lee. This effect causes the separation that may occur on a steep lee slope and also contributes to the occasional situation in which a velocity overshoot occurs, i.e., the flow does not increase monotonically with distance above the terrain. This case is sometimes referred to as reverse shear or negative flow gradient. An additional effect of the perturbation of the inner layer is the perturbation of turbulence and shear stress within this layer, associated with the change in profile.

The above paragraphs describe in qualitative fluid mechanical terms the effect of irregular terrain on wind flow in the nappe of the earth. Various mathematical models have been developed to quantify this effect. Before discussing them it is helpful to define what is required from a wind flow model, bearing in mind that the appropriateness of any model is a function of the purpose for which it will be used. The requirements of a wind flow model are that it must be:

- Consistently accurate with respect to the input precision of topography, meteorology and WTG characteristics. In other words, the model should not require topographical and meteorological inputs an order of magnitude of detail different from the accuracy of the calculated wind field, nor should the model provide a wind field of higher precision than justified by the required speed inputs to the WTG.

- Capable of operating with a coarse topographical input. In other words, the model should not call for a more detailed topographical input than can conveniently be provided and should be capable of interpolating topographical data if required.

- Applicable to a very sparse spatial wind input data field. In other words, if only one or two locations of field anemometer data are provided, the model should be able to calculate the flow over the entire field.

- Capable of matching field data to some degree. That is, it should be possible to adjust the model to match field data at a number of points. Note that field data can be incorrect and unvalidated just as theoretical model data can, and it may be sensible, in some circumstances, not to try to match them exactly.

- Able to provide wind vector and turbulence level estimates over the site up to the height of normal rotors. In other words, the model should provide both necessary and sufficient information, giving wind fields only where needed, not, for example, above rotor height.

- Consistent in the numerical structure of the input and output, i.e., it should not be necessary to use a fine scale input if only a coarse scale output is needed.

- Able to run rapidly and to require input and output only once for a given site. In other words, the isovents should be stored for all meteorological conditions.

A description of wind flow models suitable for estimating isovents for wind energy application is given by Lalas (1985). He describes a process of stages, defined as follows: 1st stage (200 km detail), 2nd stage (1 km detail) and 3rd stage (10 m detail). The 3rd stage is often referred to as micrositing and is the scale applicable to our model. At this scale, the incoming geostrophic wind must be separately defined by what we call here the meteorology of the site; in other words, the incoming wind at the reference station is taken as input data. The flow over the rest of the wind farm site is then calculated by the wind flow methods discussed below.

Lalas divides models into two classes, kinematic and dynamic. The kinematic models are those that satisfy only the surface boundary conditions and the continuity equation. This does not provide enough constraints to solve the equations, so other assumptions must be made, sometimes a variational approach is taken or sometimes an irrotationality assumption which provides a LaPlace equation is made. The dynamic models theoretically incorporate the appropriate form of the Navier-Stokes equations as well as the boundary conditions and continuity and thus permit the boundary layer character of the flow to be expressed in a rational manner, using an appropriate model for the turbulent effects. Generally, dynamic models are more complicated than the simple kinematic or mass-consistent models, with the notable exception of variants of the method of Jackson and Hunt (1975), which incorporates dynamic effects in a simple but theoretically satisfactory fashion. A number of modern models taken from Lalas are shown in Table 3-1.

We have decided to use the method of Jackson and Hunt, possibly with some modifications to simplify the three-dimensional effects and to approximately incorporate a separated flow model. These modifications will be described later in this section. The current three-dimensional version of Jackson and Hunt is incorporated in a computer model designated MS3DJH, which is discussed in detail by Taylor, Walmsley and Salmon (1983).

The model analytically directly incorporates the qualitative flow concepts described earlier in this section. It assumes the flow can be divided into an outer inviscid flow region and an inner viscous layer with turbulent shear stresses determined by a very simple mixing length/gradient model, in which the mixing length at a point is taken as the height from the ground level and the gradient as the slope of the wind shear profile at that point. These assumptions, when properly scaled according to an inner/outer matched asymptotic process (described in Jackson and Hunt, 1975), lead to a Laplace equation for the outer flow perturbation and a parabolic boundary layer equation for the inner flow perturbation. The inner flow perturbation is, in effect, driven by the pressure perturbations developed in the outer flow. If only the zero order terms of each of the inner and outer expansions are required, only two simple equations need to be solved. The outer

Table 3-1. Wind flow models listed in chronological order.

KINEMATIC	DYNAMIC
NOABL (1977)	Pielke (1977)
Yocke et al	SIGMET
MATHEW	PSU
Goodin et al	Lee et al
COMPLEX (1982)	Lee, Kaw and Kao
	MS3DJH (1982)
	Yamada (1983)

Capitals indicate model code names.

flow satisfies the three-dimensional potential equation with the actual physical kinematic terrain boundary conditions. This solution provides the velocity and pressure perturbation at the outer edge of the boundary layer. The pressure is communicated directly to the ground, since the normal pressure gradient is zero to first order. The inner flow perturbation is then calculated by solving a pair of simple parabolic equations having an exact solution in the form of a Bessel function. The inner flow solution also provides a method of computing the surface shear stress and the local turbulence.

Expressed in the above form, the combined flow solution has the same simplicity and physical interpretations as was originally provided by Prandtl in his development of the concept of a thin boundary layer on a body in a moving fluid. This appears to be very advantageous because one can now modify the model with a clear physical understanding of what is happening to the fluid mechanics.

The computational requirements of Jackson/Hunt-type formulation are very modest. Taylor et al. (1983) note that a three-dimensional Jackson/Hunt code ran in about four seconds on a CYBER 176, compared with 250 seconds for a standard finite difference method, with the Jackson/Hunt procedure having four times better spatial resolution. Although the comparison is not exact, Lalas (1984) notes that another finite difference dynamic model, on a modest 35 x 25 x 10 grid point method, took approximately 1200 seconds to reach steady state. Even kinematic models require relatively long run times. Lalas indicates the model NOABL for a 40 x 100 x 10 grid point mesh required 150 seconds to run. In a recent paper, Walmsley and Salmon (1984) note that Jackson/Hunt is in general two orders of magnitude faster in operation than finite difference schemes of comparable resolution.

There are additional computational time-saving features related to this specific application. The wind field must be determined for all wind directions. Jackson/Hunt has the very great merit of being linear and vectorial in the outer flow field, as is exactly the case for the outer potential flow. Because of the linearization procedure, the inner equation is also linear. Thus it is necessary only to determine the flow for unit velocities from west and south and these can then be superimposed for any other magnitude or direction. This implies that, in a given wind flow, the speed at any point is linearly related to the speed at some particular reference station, the basis of the method of speed-up ratios in field anemometry.

An interesting theoretical point arises here: if the total flow is fully linear, then the upwind/downwind differentiation noted in a previous section cannot be achieved simply by reversing the onset velocity from +U to -U. Although the field equations are linear, the boundary condition for the inner perturbation is set by taking the unperturbed state to be at the upstream end of the flow. The outer flow having assumed zero perturbation at both extremities is linear for normal and reversed flows. Thus, for a westerly flow, although the pressure field is strictly reversible, the inner perturbation is zero at the western extremity or the boundary layer develops towards the east. This can be taken into account by calculating the inner perturbation with its origin at the upstream flow extremity -- a slight adjustment to the procedure that can be incorporated approximately in a number of different ways. For example, inner flows for each of the four quadrants can be computed and then a northwest flow, for example, by the vertical superposition of a north and a west flow, but a northeast flow by superportion of a north and east flow rather than a north flow plus a 'negative' west flow. At a small extra expense for computing effort, one can actually integrate the inner flow from an arbitrary direction exactly by taking the zero state to be at the proper upwind extremity.

Excellent correlation of the Jackson/Hunt model with detailed field measurements are reported by Taylor et al (1983), who quote good results over real terrain, and by Walmsley and Salmon (1984) from an extensive measurement program over a very good test site, the island Askervein in the outer Hebrides of Scotland. Because we have proposed modifications to the Jackson/Hunt model, these modifications will need to be evaluated numerically to determine whether they degrade the accuracy. We plan to have Dr. Peter S. Jackson, developer of the Jackson/Hunt model, serve as a consultant to AV in these Phase II efforts.

Thus, the Jackson/Hunt procedure has the following desirable characteristics. It is:

- Mass consistent in that it exactly satisfies the continuity equation
- Navier-Stokes consistent in that it incorporates pressure fields, the Reynolds' stresses and ground roughness in a form defining an excellent model of a turbulent planetary boundary layer.
- Analytic in that speed at any point may be determined without having to calculate the entire flow field numerically.
- Rapidly executable in that it does not require three-dimensional grids and requires only surface integrals for the outer flow and line integrals for the inner. The method is reported to be two orders of magnitude more rapid than even the simple finite difference procedures. In addition, the outer flow solution is linear, thus the basic pressure solution is applicable for all directions.
- Rational in the fluid physics in that because of the sound physical basis refinements, approximations, and parameter adjustments may be made as required with a sound understanding of the physical modifications they make. This feature permits one to approximate separated flows as well as the influence of the terrain beyond the boundaries of the calculation.

Finally, it is noted that Jackson/Hunt contains automatically all the features of a mass consistent model like NOABL but, unlike mass-consistent models actually rationally models the boundary layer flow and performs this two orders magnitude faster than the less accurate mass-consistent-only procedures.

3.3 Array Interference in Nonuniform Terrain

3.3.1 Approach

The original array interference model was written in 1977. A full description of the theory and concepts used in the original model has been given by Lissaman (1977) and Lissaman and Bate (1977). The approach which was taken is summarized below.

The air passing through the WTG provides energy to the rotor, thus causing the wake flow to slow down immediately behind the rotor. A shear layer develops between the outer flow and the wake flow, and the subsequent entrainment re-energizes the inner flow and tends to restore the wake velocity deficit. The entrainment is a function of the velocity difference across the shear layer as well as of the ambient turbulence. In the Lissaman model four different regimes have been identified as the flow progresses downstream, and the kinematics have been arranged so that they blend smoothly into each other. The model indicates that turbulence and power coefficient are the main factors affecting rotor wake development -- a theoretical prediction which has been supported by numerous experiments in the field and in wind tunnels.

A key closure condition of the model is that the total momentum deficit in the wake is conserved downstream, a consequence of the fact that for flat terrain only the turbine can exert a streamwise force on the flow if the ground shear is assumed to be balanced by the Reynolds stresses. Although momentum is conserved, energy is not, and the model predicts the continuous wake dissipation due to turbulence which is always observed.

The model has been widely referenced both in the U.S. and Europe and the basic fluid mechanical theory, as well as the turbulence constants, have been generally accepted.

In 1982, after five years of extensive use of the model, AV made some modifications to the model for Battelle Pacific Northwest Laboratory (Lissaman, 1982), using both theoretical and empirical techniques. The resulting model has shown good correlation with experiment. This version of the array model is the last one published by AV. It is an industry standard: many other WTG array analysis programs written by other researchers use this code as their basis, with additions added to it as needed. However, the code as it stands has some limitations. It can directly handle only one type of WTG. If an array consists of two or more WTG types, the input files must be modified.

AV has made many changes and improvements to this model. These have not been published but have been used for more than three years for many clients. The model as it now exists allows several different types of turbines in a single array. Each WTG is defined by its diameter, hub height and a wake parameter. The wake parameter is the ratio of the flow velocity outside the wake to the velocity inside, measured just behind the turbine. It is equal to or greater than one. The array model finds the ratio of the flow velocity at each turbine to the undisturbed velocity. This ratio, along with the turbine power curve and the wind speed frequency distribution, can then be used to find the turbine's ideal energy production. The model also outputs the velocity ratio averaged over each turbine type and the entire array.

3.3.2 New Model

In the new model to be developed for this project, the only major change needed is the inclusion of the effects of terrain as well as the array interference. The array model as it now stands works well for flat terrain with a uniform wind. The Jackson/Hunt model will be able to find the wind speed at any point in complex terrain. It remains to combine the effects of the array interference with those of the terrain.

The most obvious way to combine the effects of terrain with those of turbine wakes is to use superposition. Here, the wind speed at any point in the array is found by first determining the wind speed due to the terrain alone from Jackson/Hunt, and then decreasing this speed by the velocity ratio determined by the array model, where the array model values were calculated under the assumption of flat terrain. This is the way the existing array model combines the effects of several WTGs when finding the net wind speed at a particular downwind WTG. Superposition does conserves momentum at a linear level. For the case of flat terrain, the wake momentum deficit does not change as the wake develops and its total energy deficit increases gradually as it spreads out. Due to the spreading, the energy deficit measured over a given area decreases, even though the total increases. In complex terrain, the flow in the wake is subjected to the pressure forces developed on the hills and valleys it flows over.

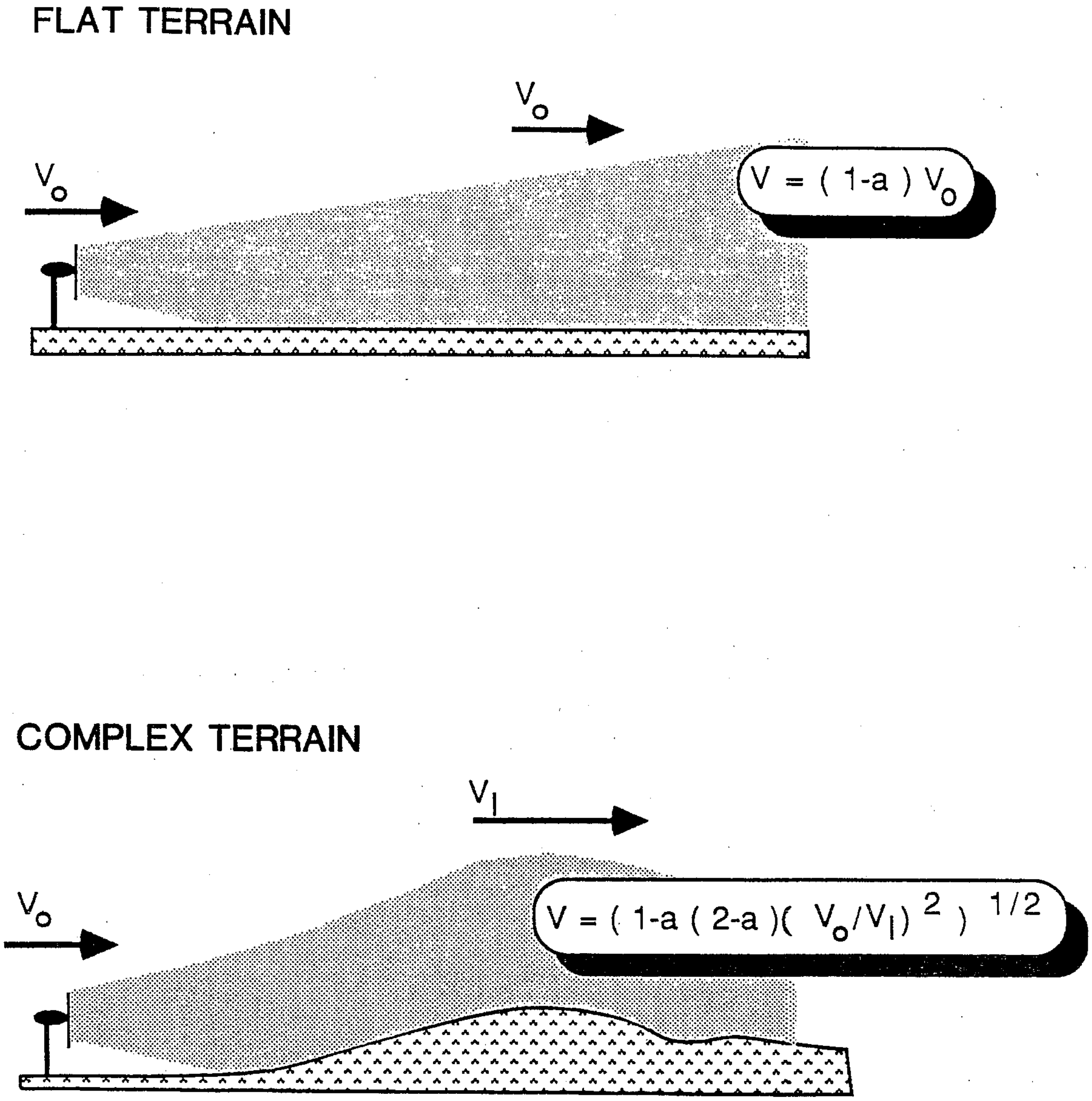
However, it is noted that in an inviscid nonuniform flow energy is conserved. Now, the wake flow is highly dissipative, but this dissipation, due to turbulent fluctuations, has already been taken into account in the uniform flow wake development. We now assume for the nonuniform flow that the pressure changes result in velocity changes according to the energy conservation expressed by Bernoullis Equation. Thus, we do not assume a homenergetic flow, but assume that the rate of dissipation in the energy equation is the same in uniform as in nonuniform flows. It will be noted that this model properly matches both limits; in the uniform turbulent case the standard array solution occurs while in the nonuniform nonturbulent case the standard homenergetic solution occurs.

In light of the above, the following was chosen as an appropriate method for finding the flow velocity at any arbitrary point in the array of turbines First, the velocity is found at that point in the wake using the existing flat terrain model. Then this velocity is transformed to the complex terrain so that the total head of the flow remains unchanged.

The flat terrain model expresses the factor that relates the velocity, V, in the wake to the velocity of the undisturbed freestream flow, V_0, by:

$$V = (1-a)V_0.$$

Here a is the normalized wake deficit, shown in the upper diagram of Figure 3-2. The complex terrain case is shown in the lower diagram. Here the undisturbed flow velocity is V_0 at the turbine and V_1 at some point downstream. The head H, of the flow at the turbine, but just outside its wake, is:


FLAT TERRAIN

COMPLEX TERRAIN

FIGURE 3-2. Basic algorithum for array-terrain interaction in flat and complex terrain.

$$H = (1/2)\rho V_0^{\ 2}$$

This is equal to the head of the outer flow at the downstream point:

$$H = (1/2)\rho V_1^{\ 2} + \Delta P$$

where ΔP is the pressure difference between Point 1 and Point 2. Thus:

$$\Delta P/\rho = (1/2)V_0^{\ 2} - (1/2)V_1^{\ 2}$$

Similar relations hold for the flow inside the wake. Here the velocity in the wake is given by the parameter b:

$$V = V_1(1-b)$$

The parameters a and b are related by assuming constant head:

$$(1/2)V_0^{\ 2}(1-a)^2 = (1/2)V_1^{\ 2}(1-b)^2 + \Delta P/\rho$$

Using the above relation for $\Delta P/\rho$ and after some manipulation a relation for the wake deficit, b is found to be:

$$b = 1-(1-(V_0/V_1)^2 a(2-a))^{1/2}$$

If there are several upwind turbines, the factor b must be found for each of them. Each upwind turbine may have a different V_0 and a different a. The total effect of all of them is found by summing the b's from each.

3.3.3 Simplifications

The array program as it now stands is somewhat slow. On the Apple Macintosh computer an array of thirty WTGs takes 15 seconds to analyze for one direction and wind speed. The model will probably need to be run for 16 directions and three to four wind speeds. (Different wind speeds result in different ratios between the initial wake velocity and the freestream velocity. Generally, the ratio is larger in light winds, resulting in greater array losses in low winds.) The array losses at other wind speeds will be found by interpolation. Thus, the current code would take about 15 minutes to analyze a 30-WTG array completely on the Macintosh. Note that finding the terrain interference will also take some time, but it need be found only once, whereas the array effects need to be found every time the array configuration is changed.

There are three ways to speed the process. First, the algorithms can be simplified and increased in efficiency wherever possible. Second, any modeling detail that will have a small effect on the results can be ignored. Finally, hardware that allows for a faster run time should be investigated.

The run time can be reduced via several improvements and simplifications to the computer code. The code sorts the turbines by their relative distance to windward for each wind direction to determine which WTGs are in the wakes of other units. The current sorting method is slow; a more efficient method can be used. The calculation of the wake effect can also be sped up. The program finds the velocity at the rotor disc of each turbine due to all of the upwind WTGs by averaging the calculation results over five points on the disc. For most cases, the variation of wake velocity in the plane of the rotor is so small that only one point is really needed. Only when the distance between two WTGs is small (less than about 15 diameters) are the entire calculations justified.

There are some modeling details that can be included in the calculations that have a small effect on the result. These details, if correctly modeled, would greatly increase run time for little gain in accuracy. Thus they should not be included. One of these is the effect of the wake trajectory. In flat terrain, the wake simply drifts downwind in a straight line; that is, the wake follows the local streamlines. In complex terrain, the local streamlines are not straight, so the wake convects downstream in a nonstraight line. However, the wake is spreading quite rapidly due to the freestream turbulence, with a spreading angle of near 30 degrees measured at its edge. Compared to these large angles, the wake's drift off a straight line is small and can be ignored. The resulting errors will be so small as to be swamped by other effects.

Another modeling detail is the effect of the turbines on the flow over the terrain. The orientation of the streamlines will be affected not only by the terrain, but also by the turbine wakes. The air must slow down and thus spread out as it approaches a WTG. In the wake, the streamlines gradually move back in toward the wake's centerline as it spreads and weakens. This will have a small effect on the wind flow over the terrain. The terrain can move the streamlines up and down over distances of over one hundred meters, whereas the turbines will have an effect of only a fraction of their diameter, a few meters. Even this will drop off very fast as points more distant from the turbine are considered. Ignoring this effect is the same as saying that the turbines only slow the flow down, but do not change the direction that it is flowing. This violates continuity, but the amount is so small compared to other effects that it can be safely ignored.

The effect of winds from nonprevailing directions can also be ignored. These winds are, at most sites, weak and infrequent. Their effects can be ignored simply by not analyzing the array for those directions. In fact, the program as currently envisioned will simply skip over any direction for which there is no wind data input. We expect that only 4 of the 16 directions need be considered, which will quarter the needed execution time.

These modifications and simplifications of the array interference algorithms will also need to be validated. Limited data of field wake measurements from single WTGs and wind tunnel tests of a single unit and small arrays are available. AeroVironment has examined all available wake and array interference data and has adjusted the variable parameters of the current uniform-flow array interference model to fit existing wind tunnel data, which we believe to be accurate. To date, we know of no reliable field test data from large arrays.

However, our experience with commercial wind farm clients indicates that array losses estimated by the AV model are certainly not incorrect.

In Phase II the array interference model will be modified to account for nonuniform wind flow. We know of no wind tunnel data against which these modifications can be checked. Experiments could be conducted by operating a WTG model in the plenum (low-speed end) of the contraction zone of a wind tunnel and measuring the wake as the flow accelerates into the working section. A field validation of wake development in nonuniform flow would be very difficult to conduct, as our work for Batelle Pacific Northwest Laboratory with the DOE-MOD-2s at Goodnoe Hills (Zambrano and Gyatt, 1983) has shown. During this test, which was on nearly flat terrain (and thus did not have strong nonuniformity), it was found difficult to obtain any conclusive wake interference measurements. Array interference in the nonuniform wind model might be obtained theoretically from a detailed, three-dimensional, finite difference, Navier-Stokes solution. This solution could then be compared with the model's results. We will do this in Phase II if promising and theoretically acceptable finite difference methods are available.

If all of the simplifications and improvements are incorporated, and as faster computer equipment becomes available, then the execution time for large arrays will be reduced by two orders of magnitude.

3.4 Effect of Turbulence on Machine Performance and Structural Life

Wind turbines must by necessity operate in a turbulent environment. In most cases, the majority of the turbulence comes from wind shear, the increase in wind speed with height above the ground. The surface roughness also contributes: rough areas generate more turbulence than flat areas. In complex terrain, the flow over the terrain will also generate turbulence. Finally, in a wind farm, the turbines themselves generate turbulence that can affect turbines downwind.

Turbulence is defined as the ratio of the magnitude of the wind fluctuations to the average wind speed. An appropriate measure of the fluctuations is the standard deviation of the wind speed, σ_u, the turbulence intensity, α_u, is given by:

$$\alpha_u = \sigma_u/U$$

where U is the average wind speed.

The turbulence intensity, α_u, is only one component of the turbulence, the along-wind component. There are also the crosswind component, α_v, and the vertical component, α_w. Their definitions are similar to that of α_u;

$$\alpha_v = \sigma_v/U$$

$$\alpha_w = \sigma_w/U$$

Usually, the crosswind component is less than the along-wind component, and the vertical component is smaller than the crosswind component.

Turbulence has two major effects on a wind turbine. First, the power output can be reduced. Second, the turbine can be damaged by the turbulence.

3.4.1 Turbulence-Induced Power Loss

In a turbulent environment, the power output of a turbine will be different from what it would be in a nonturbulent environment. Here the effects of the crosswind component and the along-wind component of the turbulence will be considered. The effects of the vertical component are similar to those of the crosswind component. The effect on turbines will be investigated by analyzing a typical turbine with the AeroVironment PROP computer code. This code finds the expected power output of a turbine given the blade geometry and other turbine characteristics, the airfoil performance, and the wind characteristics.

The turbulence component that is along the wind results in the turbine experiencing a time-varying wind speed. This turbulence can have any frequency. Very low frequencies result in slow changes in wind speed with time and can be handled simply by assuming the turbine power output is only a function of the total wind speed. This is known as a quasi-steady assumption. Under this assumption, the turbulence does not change the turbine's power output. For higher frequencies, unsteady effects could become important. The PROP code in its current form handles these unsteady cases by modeling one of the major unsteady effects, dynamic stall. The rotor is assumed to be rigid, so PROP does not consider the aeroelastic effects.

The effects of turbulence can be judged by an example. Figure 3-3 shows the power output for an Enertech 44/25 in nonturbulent conditions and in turbulent conditions (Hibbs, 1985). For the turbulent case, results are shown for the quasi-steady approximation and with the unsteady effects included. The turbulence was assumed to be sinusoidal with a peak magnitude of 20% of the average wind speed. The frequency was taken to be equal to twice the rotation rate of the rotor. It has been found in previous work on turbulence as experienced by a rotating blade that the frequencies that contain the most turbulent energy are integer multiples of the rotation rate.

As can be seen from the figure, including the unsteady effects causes a small change in the predicted power curve, much smaller than the change caused by the introduction of turbulence itself. The change in the power curve due to turbulence for the quasi-steady case is just what would be expected; the power output is equal to the steady-flow power curve averaged over a small range of wind speeds. The turbulence level chosen for this example (20%) is quite high if it is all concentrated at one frequency. For lower turbulence levels,the inclusion of unsteady effects results in an insignificant change in the power curve.

Crosswind turbulence also affects the power curve. The main effect is to cause the turbine to operate with a yaw error. This is because no turbine can perfectly follow the changes in wind direction in the horizontal plane, and no turbine follows the changes in wind direction in the vertical plane at all.

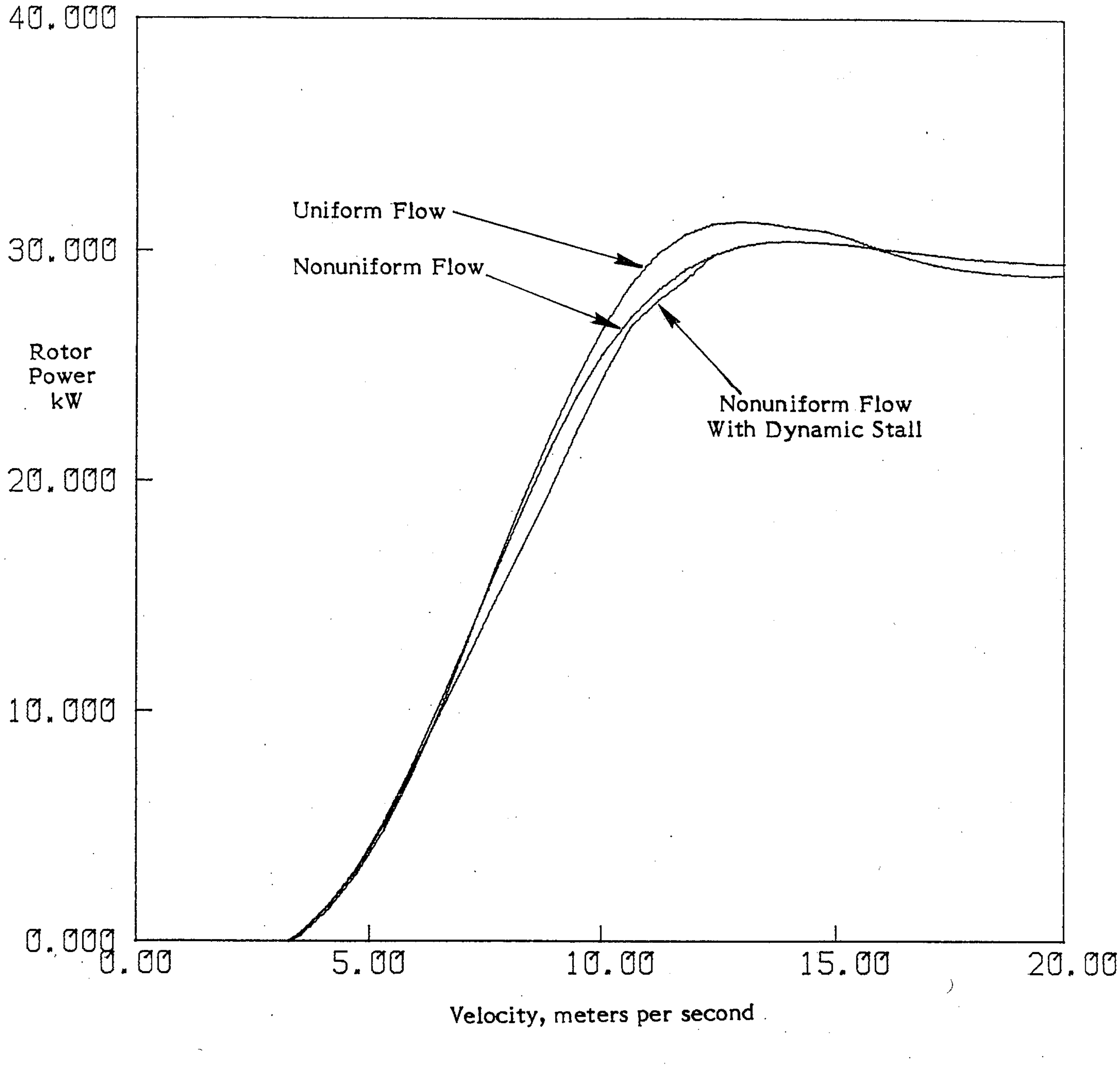


FIGURE 3-3. Enertech 44/25 performance in two cycles per revolution turbulence (turbulence intensity ≈ 20%).

Figure 3-4 shows the Enertech 44/25 in uniform flow and with a 20 degree yaw error (Hibbs, 1985). Normally, the effect of yaw error on power output is described as following a cosine, cosine-squared, or a cosine-cubed rule. Here it can be seen that the effect of the yaw error is to shift the power curve to the right A good approximation is that the wind speed needed to achieve a given power output is increased by the reciprocal of the cosine of the yaw error angle

Another way to state how turbulence affects turbine power output is to first divide the incoming wind into two components: a component parallel to the rotor plane and a component normal to the rotor plane. The turbine's power output is approximately a function of the normal component of the wind; the parallel component is of small importance but will reduce the magnitude of the normal wind component. In nonturbulent flow, the normal component is equal to the total wind speed (assuming the turbine can accurately track a uniform wind). In turbulent winds the normal component will be smaller than the total wind speed. Thus the effects of turbulence on power output can be closely approximated by modeling it as a reduction of the wind speed as seen by the rotor.

3.4.2 Turbulence Effects on Turbine Structure

The form of the loads as seen by a component of a wind turbine operating in a turbulent environment is shown in Figure 3-5. This is a time series plot for an arbitrary WTG (Waldon 1980). There is an average load level, about which the total load varies. The load can be characterized by three values: the average load, the magnitude of the variations about the average, and the frequency that the load crosses the average (the crossing frequency). The crossing frequency may be near the natural frequency of oscillation of the component in question. For instance, if the load shown in the figure was for some part of the tower, then the crossing frequency could be about equal to the tower's first bending frequency, with the other modes of vibration making a small perturbation on it. Any material that is subjected to oscillatory loads can fail due to fatigue. The magnitude of the load can be quite low, less than half of the load needed to make the material fail under steady load conditions (yield strength). The lower the oscillatory load, the more cycles that are required to make the material fail. For example, a material may

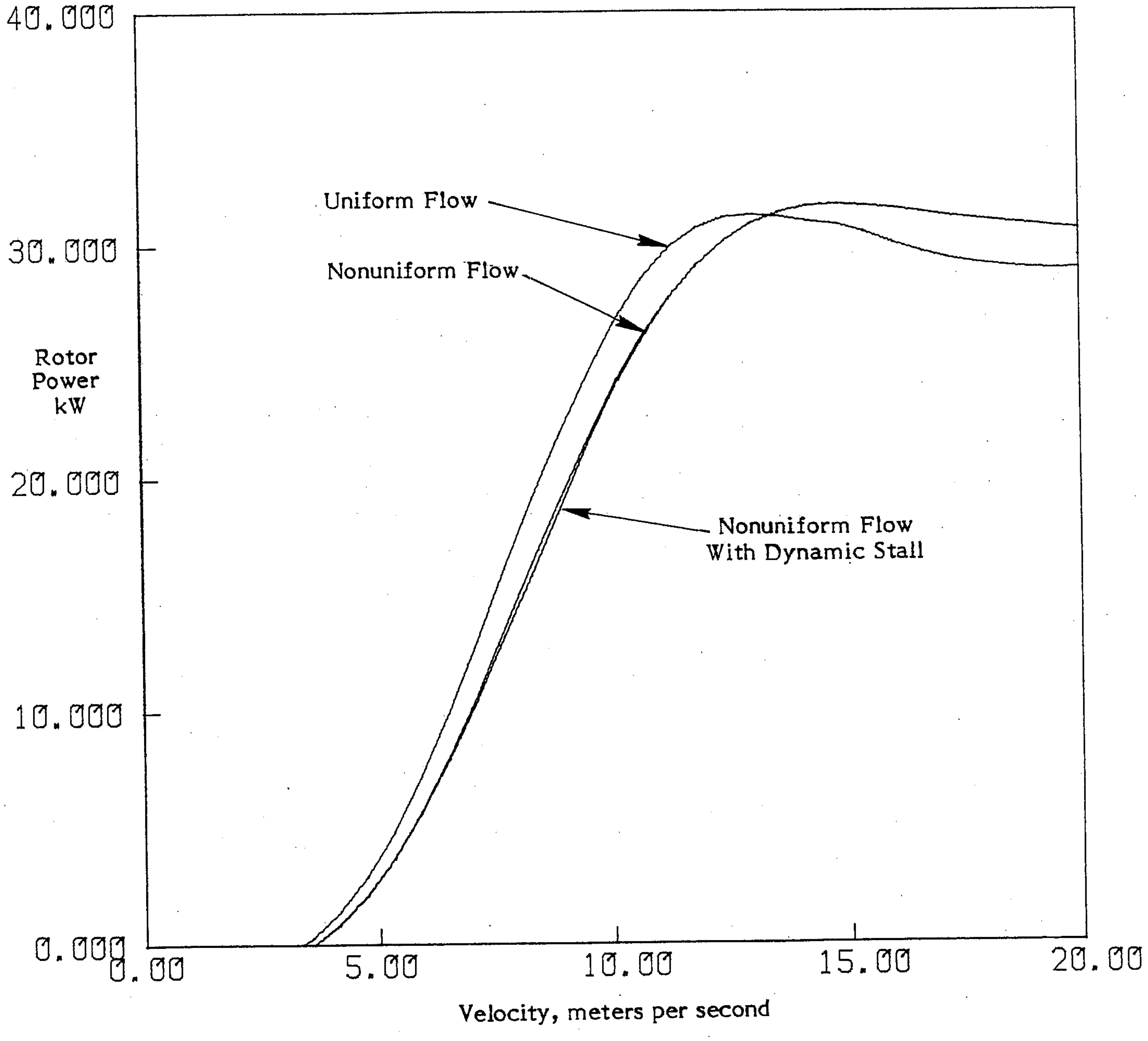


FIGURE 3-4. Enertech 44/25 performance with 20° yaw error.

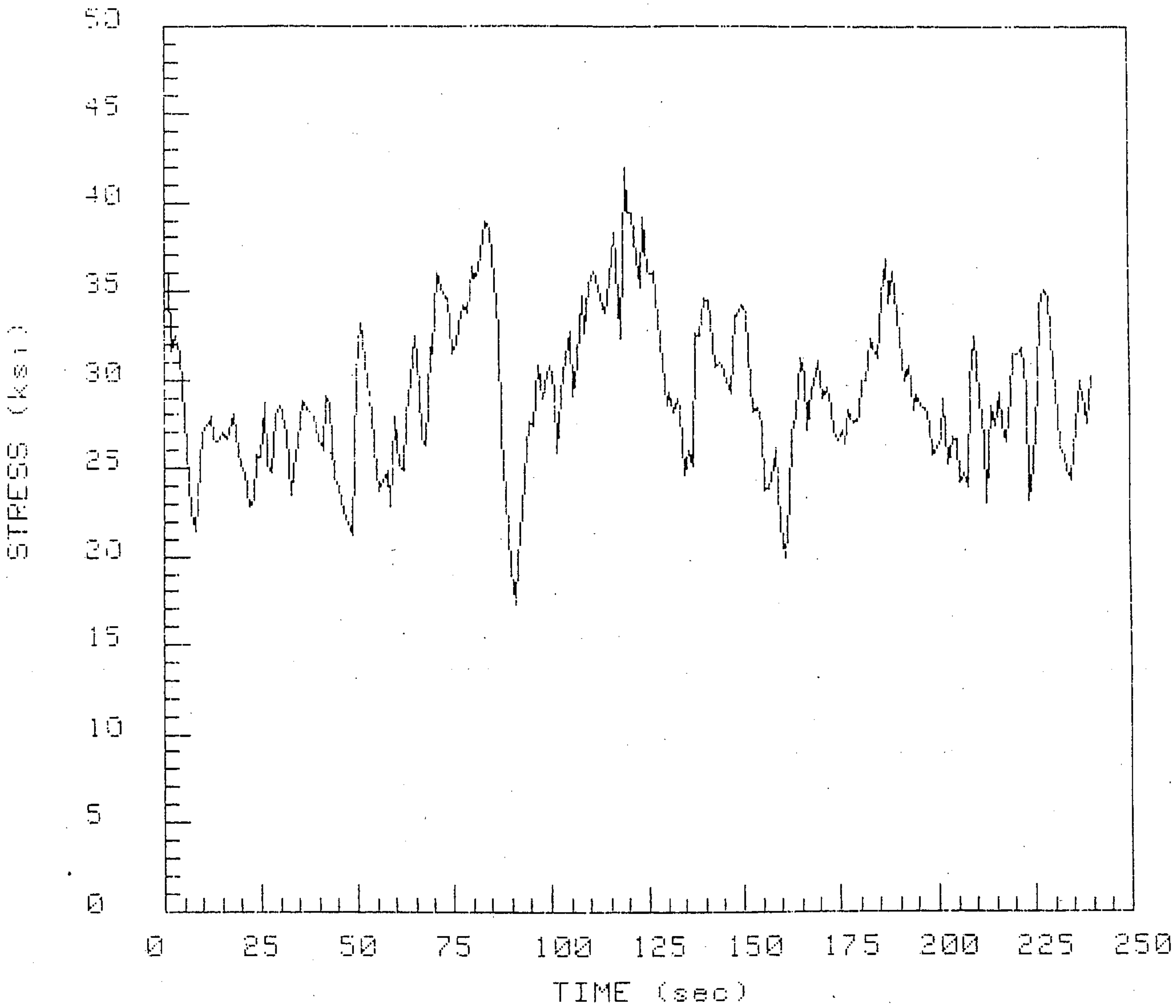


FIGURE 3-5. Example of time-series vesus load plot.

86-9

require 10,000 cycles to fail if the peak load each cycle is half of its yield strength, and 100,000 cycles to fail if the load is only 40% of yield. This strong relation between load and cycles to failure is typical. Other loads result in other cycle to failure limits, forming the fatigue characteristic of the material. With this curve, it is possible to find the lifetime of a part subjected to random loads. For example, if the material described above is subjected to 3,000 cycles at 50% of its yield strength, then it has had 30% of its fatigue lifetime used up. If it also is subjected to 25,000 cycles at 40% of its yield strength, then it has lost another 25% of its lifetime, for a total of 55%. The material can be expected to fail when 100% of its lifetime has been used.

Fatigue can cause problems in two ways. First, fatigue failure of small parts can cause increased downtime for the turbine and increased operating expenses. Second a failure due to fatigue of a major part, such as the tower, can destroy the turbine.

In determining the structural life of a wind turbine operating in a given wind farm environment, several factors must be evaluated. The influence of wind shear, yaw rates, utility interconnect dynamics, braking/stopping loads and tower shadow effects, if any, can be determined analytically with relative ease. The resulting loads and their expected frequency of occurrence can then, in turn, be used. Such techniques as Goodman's method, Miner's rule, etc., provide a good estimate of the fatigue life of the wind turbine's major structural components. The influence of atmospheric turbulence (a non-stationary stochastic process) on the machine's structural life, however, is not as easy to determine but must also be considered in order to determine machine life.

Turbulence levels are influenced by many factors. In a wind turbine array, topography, turbine spacing, wind direction and wind speed all play important roles. While the Jackson/Hunt model will be able to calculate the turbulence intensity, frequency and time of exposure for each unit, it remains to be determined how to use these data to assess the influence of turbulence on a wind turbine's structural life. To date, wind farm developers and operators have in general ignored turbulence, even though they are aware of the potential damage that turbulence can produce over time. In some wind farms, the developers, driven in part to meet certain energy output quotas, have allowed wind turbines to continue to operate even in the worst highly fluctuating wind conditions: for example, high velocity up-row winds. Over the expected 20- to 30-year life expectancy of commercial wind turbines, turbulence effects on turbine component fatigue may, insidiously, be one of the most important factors, given that all other fatigue-inducing actions can be adequately designed for.

The reason for this is that atmospheric turbulence contains a wide spectrum of frequencies and intensities, any of which may pass through a wind turbine system at a given time. Which turbulence intensities and frequencies are most damaging to a particular wind turbine? The answer to that is turbine-specific. Configurations, materials and operating algorithm differences, among other things, will affect the turbine's resistance or vulnerability to turbulence.

A benchmark of potentially damaging turbulence intensity levels can be calculated using the equation:

$$I = \sqrt{\int_{x_1^2}^{x_2} S(n)\, dn / V_o^2}$$

Where I is the turbulence intensity, x is the wave number (and is equal to 1200 n/V_o where V_o is in m/s), S(n) is the spectral density n is the frequency in cycles per second, and V_o is the wind velocity of interest. The equation can be integrated for, say, V_o = 10 m/s and results similar to Table 3-2 (Hibbs, Radkey, 1983) can be generated to show the relationship between turbulence intensity and the turbulence scale.

In this example, possible turbulence intensities of interest could be those on the approximate scale, say, of blade chords. For instance, if a chord-sized turbulent "bubble" passing through a turbine rotor disc and is "sliced" by a blade, a pressure or lift perturbation would be generated on the blade that would translate into a blade-loading transient. This could conceivably, if the blade was not well damped in some vibrational mode, cycle the blade in bending several times thus adding fatigue stress cycles to the system. If these chord-sized turbulence

TABLE 3-2. Turbulence intensity in a 10-meter-per-second wind and 10 meters altitude.

Turbulence Scale	Turbulence Intensity	SWECS Turbine Rotor Scale
100 mm and less	0.57 %	blade boundary layer
0.1 - 1.0 m	1.4 %	blade chord
1.0 - 10.0 m	3.1 %	rotor radius
10 - 100 m	6.7 %	entire turbine
0.1 - 1.0 km	12.8 %	
1.0 - 10.0 km	4.7 %	
10 km and greater	1.2 %	
all sizes	17.3 %	

"bubbles" were present when the wind exceeded a certain level or when it was from a particular direction and if the developer learned from the model output for his wind farm that this condition induced a high rate of fatigue cycle accumulation, he might choose to shut some of this machines off until the damaging condition passed by. Rotor-radius-sized turbulence may be even more detrimental to wind turbines, since a condition known as dynamic stall might be induced. In this case, an entire blade, as it passes through a turbulent eddy, can experience short duration lift forces much larger than the maximum expected when it operates in a smooth air flow. Again, the turbulence scales a wind farm developer should avoid will depend on characteristics of the equipment operating in his wind farm.

Besides the intensity (or scale), the turbulence frequency can have a detrimental effect on turbine structures. If turbulence-induced wind velocity variations have a frequency at or near the natural structural bending frequency of a component, a resonant condition can be set up that can very rapidly add damaging fatigue cycles to it. In the worst case, a condition might arise in a wind farm in which, at a certain wind speed and/or direction, the atmospheric turbulence contains eddies of an undesirable size arriving at the rotor at an undesirable frequency for a given wind turbine. If this condition should occur, high oscillatory stresses could be set up in the machine, causing a reduction in component life due to fatigue.

The oscillatory loads can also cause failure in an entirely different manner. Between every pair of crossings a local minimum or a maximum stress level is reached. The values of these local extrema are not equal, but have a random, approximately Gaussian distribution. Because of this, some of the extrema can be quite large. If one is sufficiently large, then the turbine can fail suddenly, without warning. All that can be done about this type of failure is to design the turbine so that the probability of failure is acceptably small.

3.4.3 Modeling Turbulence Effects

The effects of turbulence on turbines is quite complicated. In order to properly model these effects, it is necessary to know the turbine structural characteristics in detail: the weight and stiffness of each part, the mechanical damping of each part, and so on. In general, these data are not available to a wind farm designer. In fact, it is so difficult to get these data in sufficient detail that even turbine manufacturers often do not have it. Manufacturers usually follow up what calculations they can do with field tests in order to find any potential problems with the operation of their turbine due to turbulence.

Thus the prediction of turbine structural effects due to turbulence is unfeasible for the wind farm designer. However, a turbulence level prediction can be made using the Jackson/Hunt model. The most feasible method appears to be to correlate the turbulence data with existing maintenance data. This can be done both as part of the Phase II program and by users of the program.

There is a large amount of data on the maintenance costs of various types of turbines. Correlating these data to turbulence level should not be difficult. The turbulence model can be run for existing wind farms to determine the turbulence level as seen by each turbine. This can then be compared to the maintenance expenditures for each turbine, allowing any trends to be identified. The turbulence level (in percent) will probably not be the proper term with which to do the correlation, but rather some other term such as the cumulative turbulence energy. This is found by squaring the product of the turbulence level and the wind speed, then integrating over all the winds as seen by the turbine. Software for doing these correlations can be developed as part of Phase II. Using existing data, this software can be exercised, and some results can be obtained for a few types of turbines. The software can also be supplied to the wind farm designer. This will allow the designer to do additional correlations for farms he has worked on previously.

3.5 Statistical Analysis

Wind energy assessments are a critical factor in deciding whether to implement multi-million dollar wind energy projects. Thus it is important when presenting calculated results based on numerous interdependent variables that an estimate of the accuracy of the results be included. This statistical analysis illustrates the large energy production fluctuations possible in wind energy development.

3.5.1 Approach

Once the expected energy production of the WTGs has been calculated, using long accepted methods described by Golding (1955), an additional analysis will determine the variation that this value can experience. The results of this analysis include, among other statistics, the high and the low range of the energy output values, which are the upper and lower bounds of the 70% confidence interval (approximately one standard deviation) symmetrical about the expected value. The analysis can be carried out for a number of specified time periods or confidence levels.

The annual energy output depends on several parameters whose natural variations or estimated approximations can lead to substantial deviation from the expected energy value. These variations are divided into two categories, meteorological variations and system variations. The meteorological variations category includes all those factors that effect the most important meteorological parameter, the expected annual average wind speed at WTG hub height

Measurement Error -- The error caused by the inaccuracy of measurement equipment used to obtain meteorological data. Typically, this error is about 2% of the annual average wind speed.

Extrapolation Error -- The error associated with extrapolating meteorological data from its original location to the location of the WTG; this error can range from 0% to 15% of the annual average wind speed.

Interannual Variations -- Climatic variations occurring from year to year as compared to the meteorological data base. In any given year, this variation may be as high as 12%. Over many years, the variation self-compensates and reduces to about 3% of the annual average wind speed.

System variations are those intrinsic to the wind farm layout and the WTG system's operation. System variations include WTG availability, the wind farm's electric transmission lines efficiency, the WTGs control system efficiency and the array efficiency. These energy loss factors can be calculated or estimated with relatively high levels of confidence.

- **Assumptions**

To calculate the overall variation about the expected annual energy output without having to calculate the convolution of the probability density functions of all the parameters, we have made two assumptions. The two assumptions are as follows:

1. All the parameters (annual average wind speed, control efficiency, etc.) are random variables that can be represented by Gaussian probability density functions.

2. All variations defined above are the standard deviation of the parameter to which they refer and are therefore the upper and lower bounds of the 70% confidence interval symmetrical about the expected value (15% of area below and 15% above). When the variation is specified for values below and above the expected value, we assume that the density function is formed by two "half-Gaussians" with different standard deviations, but joining smoothly.

A general statement as to the accuracy of the results based on these assumptions cannot be made without knowing the sensitivity to the results of both the shape of a skewed distribution and the magnitude relationships between various density functions. Thus, a sensitivity analysis needs to be performed in the Phase II program to quantify the uncertainties. This could be done by using a matrix of possible combinations of the meteorological and system variations and investigating how the results of the calculation procedure changes as skewness is added to each one or several of the variations. The results, in turn, can then be compared to those obtained by using a simple Gaussian density shape for each variation to eliminate those non-Gaussian combinations that do not produce significant error in order to simplify computational requirements in the uncertainty analysis model. The results would identify which variables can affect energy production and the investor's economic return.

3.5.2 Procedure

The procedure for calculating the uncertainty in wind energy production can be divided into five steps:

1. The calculation of the overall variation (σ_m^+, σ_m^-) of the annual average wind speed due to the meteorological variations (σ_{mi}) is done separately for positive and negative variations by summation of the squares.

$$\sigma_m^+ = \sqrt{\Sigma_i(\sigma_{mi}^+)^2} \quad \text{and} \quad \sigma_m^- = \sqrt{\Sigma_i(\sigma_{mi}^-)^2}$$

2. In the conversion of the annual average wind speed variation into annual energy output variation by using the convolution of the WTG power curve and the wind speed frequency distribution (CAPFAC), the wind speed frequency distribution is rebinned to the annual average wind speeds determined using the variations found in Step 1.

3. In the conversion of the system variations into ratios, each variation is divided by the expected value of the corresponding parameter. This gives the variation (positive and negative) as a percent of this parameter.

4. The calculation of the overall variation of the annual energy output includes both meteorological and system variations as they appear in Steps 2 and 3. The calculation is carried out as in Step 1, considering separately the propagation of the squares of the positive and negative variations.

5. The upper and lower bounds for the 70% confidence interval of annual energy output are calculated according to the formulae:

$$E^{-} = IEQ(\eta - \sigma^{-}) \qquad E^{+} = IEO(\eta + \sigma^{+})$$

where:

IEO = Ideal Energy Output (calculated for expected annual average wind speed and no losses)

η = System Efficiency (includes all the efficiency and availability parameters)

σ = Overall Variation (from Step 4)

o **Effects of Approximating the Skewness**

The assumptions made in this method introduce some inaccuracy in the estimate which is discussed below.

1. Average

Some of the random variables are probably non-Gaussian. If this is taken into account, the expected value of the joint density function would appear shifted below or above that of the all-Gaussian assumption. The direction and magnitude of the shift depends on the non-Gaussian density shape and its magnitude relations with the others. There is no general rule and the shift cannot be easily predicted without knowing the analytical description.

2. Variation

The same problem is found in attempting to compare the variation estimate provided by the outlined procedure with that ideally obtainable by following the complete analysis using a known analytical description with some of the variables skewed. In the case of a variable with a skewed density function, the (+) and (-) variations are still assumed to be those values defining the symmetrical 70% confidence level about the average (even though it has no simple relation to the variance, as the Gaussian case does), and the calculation follows these steps:

- convolution of all the density functions (including the skewed one)
- identification of the average for the resulting joint density function
- calculation of the 70% confidence interval bounds (by area measurement)

After these steps, the upper and lower bounds found are compared with those resulting from the procedure outlined above.

4. SOFTWARE DEVELOPMENT

This chapter discusses the software requirements of the computer program and the approach to meeting these requirements. Early in this Phase I project it was realized that the best method for designing certain portions of the software capabilities was to experiment and to develop a test program. This experimental version of the program has been successful enough to present with reasonable certainty the expected requirements and format of the final program. In the following sections this experimental version of the software is referred to as the test program, and the complete version to be developed during the Phase II project is referred to as the final program.

4.1 General Design Considerations

For this computer program to be practical and widely applied, it must be easy to use, accurate and fast. To that end, several features to ease data input are planned. These include:

1. Standard preprogrammed default values wherever possible. Thus if the user lacks certain information required as an input, the program automatically makes reasonable assumptions to fill in the missing data.

2. Explanatory notes displayed during data input routines to clarify what is being asked for, to display the standard default value and to indicate the acceptable range of input data.

3. A large library of data pertaining to WTG specifications readily accessible at appropriate times. The user needs only to select the name and model of the WTG to be used. The program automatically displays its critical characteristics as confirmation.

4. An edit mode to allow quick and easy changes to any of the input parameters, or to create and evaluate new WTG designs.

5. User option to work in English or S.I. units.

An additional characteristic of the program is its modularity. In its final form, the computer program will consist of several modules. Each module, actually a program in itself, will handle one part of the job. These include modules for topography, meteorology, WTG characteristics, and analysis. Essentially, the first three modules prepare input data for analysis in the fourth module.

Several of the algorithms used in this program have been developed by AV over the past decade of wind energy assessment. Each of the modules is discussed in the following sections.

4.2 Topographical Module

The topographical module characterizes the land being considered for wind energy development.

4.2.1 Input Parameters

Topographical data describing the major terrain features of the site are a one-time, initial input. Once the data are input, either manually or by digitizing, the data will be permanently stored for subsequent calculations. The program user will be required to input the following information:

- wind farm site boundaries
- terrain contours
- terrain blocks excluded from development for any reason (e.g., setbacks, right-of-ways, land rights, etc.)
- maximum slope acceptable for WTG placement

The topographical module will allow contour maps to be input to the computer. Topographical data are stored as a two-dimensional array of height data. Each array element gives the height of the terrain at a particular point on a rectangular grid over the region of interest. The size of the array may be quite large. If the user wishes to plan a wind farm on an area two miles on a side and terrain features of 100 feet in size are important, then a 100 by 100 element array is needed. Inputting the 10,000 numbers needed to describe the terrain by hand is far too cumbersome. Two other methods appear to be convenient and feasible. First, the data can be purchased from the United States Geological Service (U.S.G.S.) in a computer-readable format. Then the topographical module needs only to read the data and store it in a format appropriate for the design module. The U.S.G.S. data has a reasonable degree of resolution: the distance between points is 30 meters. When greater resolution is needed, or U.S.G.S. data are not available for the area of interest, terrain data can be obtained from a contour map using a digitizing pad.

Most likely for any area that is being considered for a wind farm there will be a contour map available. Such a map would be required for proper planning of a wind farm even in the absence of this design program. Thus, the ability to enter terrain data directly from a contour map is desirable. This will require a digitizing pad, and the software will have to be written to handle this task. One of the methods should be sufficient to define the terrain for the design and analysis module.

4.2.2 Graphical Output

Following the topographical data input, the program will display a scaled map of the site on the computer screen. Figure 2-3 shows a simple example of the topographical output from the test program. This is a plan view showing the land's contour and major terrain features. Any land on the parcel that is excluded from development will be shaded.

A graphical display of the terrain showing the entire map at once, has been implemented in the test program. Because of the large area some wind farms cover, the final program will have to allow the user to "zoom in" to view small regions of the wind farm site and to move about on the map.

At the bottom of the computer screen the user is given the opportunity to approve the topographical portion of the program, after which the program goes on to the meteorological module or modifies any topographical input values as instructed.

4.2.3 Sensitivity

It is believed that a fairly coarse representation of the topography will be adequate for this application, because the terrain features will have a relatively low impact on the final results as compared with the meteorology. At present it is envisioned requiring input of vertical gradient data in increments of 10 feet. A considerable portion of the Phase II testing and validation of the program will involve a detailed sensitivity study to determine the minimum level of resolution required for accurate results.

4.3 Meteorological Module

4.3.1 Input

The wind data entry can be handled in several different ways. First, it is necessary to examine the form of the data that will be most convenient for the design program.

In order to find the expected energy production of a WTG, it is necessary to know the power curve of the turbine and the wind speed frequency curve. The latter curve gives the amount of time the wind blows at each speed. Normally, the wind speed range is divided into increments of one mile per hour or one-half meter per second. If terrain and array effects are to be considered, then it is necessary to have a frequency curve for each direction. Typically, 8 or 16 directions equally spaced about the compass are used.

It may be necessary to have separate frequency curves for different time periods, for example, one for each month. Each frequency curve consists of about 60 frequencies, one for each mile per hour. If 16 directions and 12 time periods are to be considered, then the total data to be input is about 10,000 values. Again, it will probably be too cumbersome to enter this data by hand, although provisions for doing so will be part of the meteorology module. Fortunately, most of the wind data collection equipment currently being used by the industry is designed to interface with computers. Generally, a program provided by the manufacturer of the data collection equipment reads the data from collection equipment and stores it on the computer in a more readily accessible format. Thus, the meteorological module needs only to handle such data formats.

The meteorology input module must have a great deal of flexibility built into it. For example, it may be desirable to use the data from one site, but only after it has been scaled up by some factor to better represent the site being studied. It may be desirable to combine the data from several sites so as to cover gaps in the data, or to get an average distribution. The division of the data into various time periods must be provided for. If these periods are different months or seasons, then the task is easy. If they are electric utility time of purchase periods (i.e. summer on-peak, winter mid-peak, etc.) then the task is more difficult. Provisions must be made for the definition of the times of purchase, as they differ for utility to utility, and even from year to year. AV has already developed programs with these capabilities, so it only remains to integrate them into the module.

This module also requires the location of the meteorological reference station. This is the location on the terrain that most closely experiences the input wind flow conditions. In cases where on-site data are input into the model, the data source location is the reference station location. Results from the analysis module will be reported with respect to this reference station location.

4.3.2 Graphical Output

There are many ways to display the meteorology data. Figure 2-6 shows the wind rose display used in the program. It consists of a pie-shaped wedge for each direction with the width of the wedge corresponding to the portion of time the wind comes from that direction and the length corresponding to the average wind speed from that direction. In the test program, the wind speed frequency distribution was taken to be a Rayleigh distribution. In the final program, the frequency distribution will be user defined.

Other, less graphical, methods of displaying the input meteorological data are possible, including standard tabular format. These other formats will be examined and, if appropriate, be included as additional user options in the final program.

The meteorological module will also display the effect of the terrain on the wind. The user selects a wind direction and a height above ground level, the program displays wind speed contours (isovents) superimposed over the terrain map defined in the previous module. Since most high wind sites have a prevailing wind direction, displaying the effect of the terrain on the wind flow for one direction at a time will be sufficient to allow the user to place WTGs in preferred locations.

4.3.3 Sensitivity

Meteorology is the most critical of the input values. A minor variation in wind speed can have a large effect on WTG energy output and a minor variation in wind direction can greatly affect array effectiveness. Unfortunately, meteorological data can often be misinterpreted, not representative of the site, or inaccurate. Based on hundreds of wind farm energy production calculations, AV has found that the most sensitive input value is the average wind speed. Wind speed frequency distribution variations are secondary in affecting long-term energy results. Array effectiveness depends primarily on wind direction, minor shifts in direction can have large effects on the typical wind farm array's effectiveness. Turbulence intensity variations have considerably less effect on energy production.

4.4 WTG Module

4.4.1 Input Parameters

The WTG module will require the simplest input. Few parameters need to be defined; these are:

- the WTG power output versus wind speed curve, commonly known as the WTG power curve
- the rotor diameter of the WTG
- the hub height of the WTG

These data will be typed in by the user. The module will display the data both graphically and numerically so that errors can be seen and corrected. Provisions will be included to correct power curves to air densities other than sea level. Once all data have been input, the module will store it in a file for later reference by the analysis module. Several commercially-available WTG's data files will be supplied with the program.

4.4.2 Graphical Outputs

The WTG data are normally displayed at the time the user selects which WTG types to use. The display consists of a simplified drawing of the WTG, its rotor diameter, hub height, and power curve (in tabular format). The user can then either accept or reject the WTG for inclusion in the current design session.

Figure 2-4 illustrates the graphical output following the WTG type selection. This figure is an output from the test program and differs from the final program in that it shows a table of average wind speed versus annual energy output rather than the power curve.

After all the WTG types to be used have been selected and their specifications accepted, the WTGs must be placed within the topographical display. This will be done by using the mouse to "drag" the WTGs to the user's desired location. Figure 2-5 shows an example, from the test program, of WTGs placed on the map.

Provisions are also included for moving WTGs already placed on the map. The final program will have to have provisions for placing WTGs in regular rows with uniform spacing, and for moving groups of WTGs. This is not expected to be a problem.

Once all the WTGs are sited, a summary spread sheet will be displayed, as discussed in the analysis module section. The user may then go through WTG placement iterations to optimize the energy output of the array. Strategy and software requirements to optimize the array are discussed in Chapter 5.

4.4.3 Sensitivity

To determine long-term energy output the WTG input parameters must be accurate. Given the shortfalls experienced to date in WTGs attaining their projected energy output, there has been some question about whether the WTG power curve data are accurate and reliable. AV's experience, based on theoretical and actual measurement analyses, has been that WTGs in general do conform to their published power curve. Shortfalls occur when natural energy losses (e.g., array losses and turbulence losses) have not been reasonably accounted for, or more critically, when the resource has been overestimated. Thus, it is believed the WTG performance parameters used in the program (specifically the WTG power curve) will be sufficiently accurate in determining long-term energy output, assuming that other standard site-specific energy losses are accounted for and that good operations and maintenance (O&M) practices are followed, one of the most critical of which is keeping airfoil surfaces clean.

4.5 Analysis Module

The analysis module is the heart of the entire wind farm design and analysis program. The topographical, meteorological, and WTG modules simply provide the data to be analyzed in this module. A simplified version of this module was written and tested to evaluate the operation of several of the algorithms and to determine how the user might interact with them. This section discusses the development of the analysis module.

4.5.1 Interactive Logic

Analysis of the wind farm can be done anytime after the input data files have been defined and the WTGs have been placed on the topographical map. The first function of the analysis module is to input all of the data prepared by the other modules. In a typical situation each of the modules will have several files, and the user, with instructions from the program, will direct the selection of the appropriate files.

The analysis module will calculate and report the expected power output of each WTG, taking into account the terrain, meteorology, array effects, and other standard losses (e.g., WTG availability, line losses) as set by the user. This is accomplished by extrapolating the meteorological data over the wind farm, accounting for flow variations over the terrain by the method described in the previous chapter, then adjusting the wind speed at each WTG using the results of the array interference model. Finally, with the array- and terrain-adjusted wind speed at each WTG calculated, the net energy output of each WTG is calculated using a subroutine AV has previously developed and incorporated in the analysis module. Portions of the analysis module have been implemented in the simplified test program with satisfactory results in accuracy and speed.

Once this array configuration's results have been output for the user's consideration, the values are stored for subsequent comparisons with later iterations of the array. The results are calculated and stored in a manner that minimizes the required calculations on iterations of the model. For instance, if only a few WTGs are relocated on a second iteration, the program does not recalculate the terrain-affected wind flow because it will not change. Processing time will also be saved by creating an output file for the results of each iteration, thus allowing quick comparisons between tested array configurations. These files will be easy to recall for review or printing. Such processing-time saving features will be critical in making the program a practical tool.

4.5.2 Output of Analysis Results

Program versatility for a wide range of users being a key concern, the final program will allow the analysis results to be output in various formats on several output devices. Graphical displays will be useful for optimization iterations of WTG placement. Printed tabular results will be useful for reporting and further economic assessments. It may also be desirable to save the results on computer disk for future reference.

To suit the output to his purposes, the user will select the time period of the analysis and the desired groupings of the WTGs from a menu of options. For planning new wind farms, and for comparing WTG types and array configurations, annual time periods would be acceptable. If, on the other hand, energy-sales revenue is being assessed, the appropriate time periods would be the time-of-purchase periods of purchasing utility companies. Note that the shorter the time periods being analyzed, the more detail is required in the input meteorological data.

The results broken down by groups of turbines will also be important: some WTGs may be owned by one investor, and some by another. The definition of which WTGs belong to which group will be under the control of the user. Thus he will be able to determine the expected production for each investor. In some cases, it will be necessary to account for turbines that are not on the wind farm being analyzed. The wake effects of turbines on a neighboring wind farm just upwind must be included, but their energy production is of little interest.

After specifying the time period and WTG groupings, the user will select what results he would like to see displayed or printed from a menu. The following lists, and briefly describes, the results that will be available in the final program. The user's application will determine which results he will need to know.

- **WTG Values**
    - WTG Identification -- A number and/or letter designation by which the user can identify the WTG's location.
    - WTG Type -- An additional clarifier of the WTG type and model number, which will be useful when the array being analyzed contains a number of different types of WTG.
    - WTG Coordinates -- X,Y coordinates from topographical map identifying the location of each WTG.
- **Energy Production**
    - Net Energy Production -- Energy output per WTG accounting for <u>all</u> losses.
    - Terrain Energy Output -- Energy output per WTG accounting for terrain and turbulence effects only.
    - Array Energy Output -- Energy output per WTG accounting for array interference effects only.
- **Average Wind Speed**
    - Net Average Wind Speed -- Hub height wind speed at each WTG, accounting for all effects of the terrain and array.

- Terrain Average Wind Speed -- Hub height wind speed at each WTG, accounting for only terrain and turbulence effects.
- Array Average Wind Speed -- Hub height wind speed at each WTG, accounting for only the array interference effects.

- **Efficiency**

Note efficiencies listed below are ratio of energy production to energy production that would occur with only the specific parameter (e.g., terrain, array, turbulence) considered.

- Net Efficiency -- Energy efficiency of each WTG, accounting for all factors (terrain, turbulence, array, and WTG).
- Site Efficiency -- Energy efficiency of each WTG with respect to the reference station, accounting for terrain effects only.
- Array Efficiency -- Efficiency of each WTG, accounting for only the effects of array interference of energy production.
- Turbulence Efficiency -- Measure of the turbulence effects only on energy production of each WTG, derived from turbulence intensity values predicted by wind flow model.
- Turbulence Intensity -- Measure of wind speed fluctuation with respect to the mean wind speed at each WTG.

5. DESIGN OPTIMIZATION STRATEGIES

5.1 General

The optimization of the wind farm array in order to maximize energy production is an important goal of this research project and subsequent computer program development. We have defined three levels of sophistication that the computer program can employ to optimize WTG placement. Trade-offs between user ease and versatility and program complexity must be evaluated in selecting the most appropriate choice of array optimization strategies.

5.2 Potential Strategies

5.2.1 Strategy 1

The simplest approach from a programming perspective is to depend on the user to make sound decisions in striving to select optimum locations within the array. This is an iteration strategy, as array layout would be optimized by trial and error placement of individual WTGs. With experience, the users would learn what layout schemes are optimum, thus this approach is not unreasonable.

The user will get some guidance in placing WTGs by the display of wind speed contours. These will only be displayed for one direction, but as this can be selected to coincide with the site's prevailing wind direction, it will be good enough to show the user which areas are windy and which are not, due to the terrain.

Another aid to the user would be to display a region on the terrain map surrounding each WTG sited that should be avoided in order to avoid excessive array losses. The region would have a user-defined width and length for the crosswind and downwind directions, respectively. The program will allow WTGs to be placed in such areas (as would be necessary for wind farms with WTGs with different hub heights), but the visual display of the wind farm would allow the user to avoid doing so as needed.

5.2.2 Strategy 2

The mid-level approach would still require the user to select the locations of each WTG by dragging the WTG symbol onto the terrain map. The quality of each site selected would be gauged by a display after each WTG is sited of its total efficiency relative to the other WTG sites.

One method to indicate the efficiency of each turbine is to change how each is displayed on the screen. Figure 5-1 shows an example of how this may be done. The symbols are displayed for turbines with efficiencies ranging from a low of 80% to a high of 120%, with 100% being defined as equal to the expected output of the turbine if it was located at the base station. Efficiencies can be higher than 100% for areas where the wind speed is greater, due to terrain effects, than it is at the base station. The definitions of the symbols will be under user control. In addition, the user can select which efficiency factor to display: the efficiency due to terrain effects alone, the efficiency due to array effects alone, or the combined efficiency. With this information, the user can rearrange the array to improve its performance and thus move toward an optimum configuration.

5.2.3 Strategy 3

The third approach, and the one with the most programming complexity and sophistication, would make the selection process more automatic. The user would select the initial location of each WTG; then, if any WTG was in a location that has a (predetermined) low array efficiency, the computer program would automatically relocate the WTG to a better location.

One way to implement an automatic, optimal array routine is to first have the user define a grid. This grid would have three parameters: a cross-wind spacing, an along-wind spacing, and an orientation. Normally, the orientation would be chosen to coincide with the prevailing wind direction. The user would then place the desired number of WTGs in initial locations that looked acceptable. Then the array would be analyzed. The grid points that did not have turbines would also need to be analyzed to see how a turbine would perform at each location. The

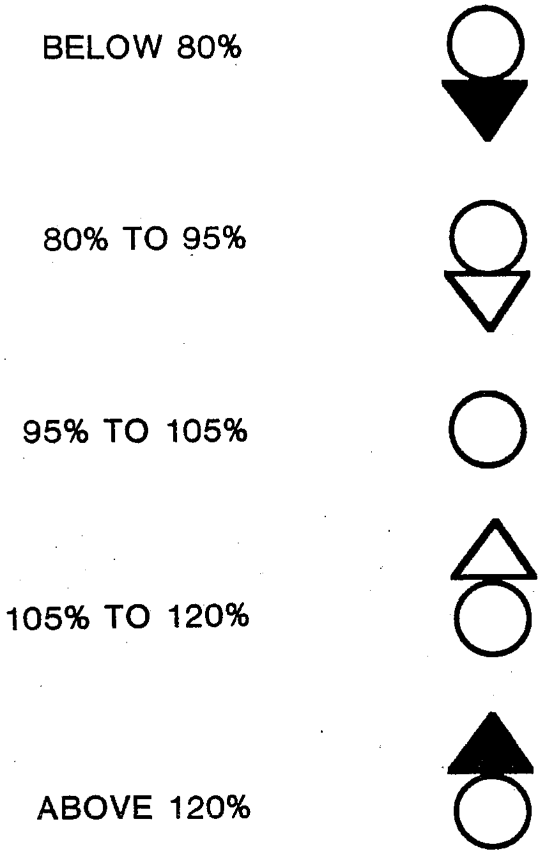


FIGURE 5-1. Symbols indicating WTG's total efficiency.

optimization routine would then move all the WTGs that would benefit by a move, and the routine would repeat to evaluate the change in array effects from the move. A spot that looked preferrable in one analysis may not be so good in the next after some of the other WTGs had been moved. Because of this, this routine would probably not select a single "best" configuration, but would instead cycle between several good configurations. This cycling can be prevented by storing each configuration and comparing a new configuration with each of the previous ones. When a repeat is found, the routine stops and outputs the best configuration found.

There is no guarantee that this method will yield the best possible array, it can only be expected to give a good array. Other methods will be examined to determine whether better optimization can be found. For example, it may be fruitful to move upwind WTGs to other, almost as good locations elsewhere on the site. The WTG moved may have reduced output, but the array as a whole may improve, since the wake of the WTG that was moved may affect the rest of the WTGs less. Other methods could involve making small changes in the grid size, adding extra WTGs, or changing the WTG type. We will examine all of these ideas to determine which gives the best results.

6. SELECTION OF COMPUTER EQUIPMENT

Now that the technical approach for modeling wind farm performance in complex terrain has been determined and the software requirements identified, we will discuss in this chapter the selection of the computer equipment that will run the program.

6.1 General Criteria

Advancements in the quality and capabilities of computer equipment are proceeding at a tremendous rate. Because computer equipment is evolving so rapidly it is difficult and impractical to evaluate computer equipment on a features-available-today basis. A better method is to evaluate computer equipment from a program application perspective. That is, what equipment best facilitates achieving the goals of the project. This approach allows us to derive general criteria for evaluating computer equipment.

Because this computer program is intended for a wide variety of users, none of whom would necessarily be computer specialists, the computer and its associated software, must be easy to use. The development of the software will take this into account and that effort would be in vain if the equipment itself did not facilitate easy operation by the user. To contribute to the ease of use, the equipment should have very good graphics capabilities, as the presentation of multiple overlaid graphics will make the WTG placement and results more understandable. The equipment should have logical commands that are easy to learn and use. Also, the computer's processing speed must be relatively fast, particularly for running optimization routines.

The second main criterion is that the equipment be readily available to potential users. Many of the users will be in small businesses, consequently the equipment must be affordable. Ideally, the potential users would already have the computer equipment in their offices.

6.2 Computer Equipment Recommendation

Given the general criteria for the equipment, two popular, reasonably priced, microcomputers were considered: the IBM PC and the Apple MacIntosh. Table 6-1 shows a comparison of the two computers. These two computers are comparable in cost, less than $4,000 for the basic units. And while IBM has about five times the market share of Apple, that advantage is more than offset by the excellent graphics capabilities and menu-driven ease of use of the Apple MacIntosh.

Although both computers have relatively fast processing speeds, the Apple Fortran (the programming language to be used) compiler is four to five times as fast as comparable compilers for the IBM computer. Also, indications are that Apple will soon make available Macintosh systems using 68020 microprocessors that will further reduce the processing time by a factor of five.

We considered proposing to develop the software so that it would operate on either the IBM or Apple Computer, but this would be costly since the majority of the computer programming requirements involve formatting of data input and output, which are different for the two systems. All things considered, the Apple Macintosh computer system was selected as the computer to use for this project. Its exceptional graphics capabilities, which allow multiple overlays, and its easy to use menu-driven routines make the Apple an excellent choice.

We have been in contact with technical and business representatives of Apple; they have been very supportive of our effort. It is our plan to include Apple consultants in our Phase II proposal.

TABLE 6-1. Relative comparison of IBM-PC and Apple Macintosh.

Criteria	IBM-PC	Apple Macintosh
Cost	<$4000	<$4000
Market Leader	X	
Compiling Speed		X
Computational Speed	X	
Ease of Use		X
Graphics Capabilities		X

X indicates equipment with advantage.

7. CONCLUSIONS AND RECOMMENDATIONS

It has been established that there is a need to replace the labor- and judgment-intensive process of planning and analyzing the design of a wind farm 'by hand' and that this has been shown to be feasible with a user interactive computer program operating on an inexpensive personal computer. It is noted that this Phase I project has accomplished a demonstration of feasibility as intended, but in addition, it has been possible to progress further than expected and to actually implement major portions of the program code. One major technical algorithm still remains to be developed, and it is recommended that this be accomplished and an operational wind farm optimization program be developed in further work.

The specific conclusions are listed below:

1. A need exists to develop an accurate and easy to use computer program to permit rapid automated design and optimization of wind farm arrays.

2. Main software and algorithmic elements of the system described above have been implemented on a Apple Macintosh Plus computer. The Macintosh computer with its excellent graphics capabilities and customized pull-down menus is an excellent system for the proposed application. It has been shown that the system runs very rapidly with delay times between changes and major updates of less than a few seconds.

3. The Lissaman array interference model has been expanded to allow combinations of WTG-types on complex terrain to be analyzed. The modifications have been implemented and can readily be integrated with the nonuniform wind flow model in the final computer program.

4. The only major technical algorithm which remains to be implemented is the wind flow model. An excellent method by Jackson and Hunt has been researched and deemed highly suitable for inclusion in the final computer program.

5. The interactive computer code designed for use by nonspecialists is feasible and quite readily implementable.

6. The project met and exceeded its goals.

Listed below are the recommendations:

1. That the computer program technical algorithms be extended and completed to incorporate the selected wind flow model and a turbulence damage model.

2. That the computer program be extended to include a spread sheet type output.

3. That a study of the commercial applications of marketing and utilizing an optimal wind farm design program be commenced.

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