**Annual Report of the Wind
Characteristics Program
Element for the Period April
1976 Through June 1977**

**C.E. Elderkin - Program Administrator
J. V. Ramsdell - Principal Investigator**

July 1977

**Prepared for the Energy Research
and Development Administration
under Contract EY-76-C-06-1830**

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.50
026-050	\$5.00
051-075	\$5.50
076-100	\$6.00
101-125	\$6.50
126-150	\$7.00
151-175	\$7.75
176-200	\$8.50
201-225	\$9.25
226-250	\$10.00
251-275	\$10.75
276-300	\$11.50

ANNUAL REPORT OF THE WIND CHARACTERISTICS
PROGRAM ELEMENT FOR THE PERIOD APRIL 1976
THROUGH JUNE 1977

by
Battelle, Pacific Northwest Laboratories
C. E. Elderkin - Program Administrator
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July 1977

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SUMMARY

The Wind Characteristics Program Element (WCPE) is a service element to provide meteorological information to other parts of the Wind Energy Conversion Program. In this role, the WCPE has as its general objective acceleration of the development, commercialization and utilization of reliable and economically viable wind energy conversion systems (WECS). To accomplish this objective, four technical program areas have been established within the WCPE.

These are:

- Wind Characteristics for WECS Design and Performance Evaluation
- Wind Characteristics for WECS Site Selection
- Wind Characteristics for WECS Presiting Evaluation
- Wind Characteristics for WECS Planning and Operations.

This report discusses the work undertaken in the first three of the Program Areas from April 1976 through June 1977. Work is not scheduled to start in the Planning and Operations Area until FY-1978, but several studies in the other areas will contribute to it. In addition to the technical areas listed above, a fifth Program Area, Special Studies, was established to provide assistance to the Wind Systems Branch as requested.

A systematic evaluation of wind descriptors has begun in the Design and Performance Evaluation Program Areas and is leading to the preparation of handbooks of meteorological information for use in design and performance evaluation. During the current reporting period, the following activities were particularly noteworthy.

- The Rayleigh distribution was examined and found acceptable for the description of the distribution of hourly mean wind speeds for use in preliminary WECS design applications (3.1.1).*
- Using the Rayleigh distribution, generic performance curves were derived to relate average WECS output to annual mean wind speed and WECS cut-in, rated and cut-out speeds (3.1.2 and 3.1.3).

*Report Section discussing the pertinent technical task.

- A meteorological field experiment was conducted to obtain wind information in a reference system directly associated with horizontal axis WECS (3.1.6).

A conceptual framework has been established within the Site Selection Program Area that clearly defines the relationships between siting tools. In general, the siting tools under development consist of: systematic methodologies using numerical nonstandard information and handbooks. Significant developments in the Site Selection Program Area during the reporting period included the following items:

- An Eigenvector analysis technique for vector fields is being developed which may result in significant reductions in the number of simulations required in siting methodologies using numerical and physical modeling (3.2.2 and 3.2.3).
- Preparations have started for the validation and comparison of numerical models for use in site selection methodologies (3.2.5 and 3.2.6).
- Site Selection Handbooks have been prepared for siting of both small and large WECS (3.2.14 and 3.2.15).

The Presiting Evaluation Program Area is involved in the identification of large areas of high wind energy potential throughout the United States, and in the determination of wind characteristics related to the economic viability of wind energy conversion within these areas. The progress toward these objectives during the reporting period includes the following highlights:

- A synthesis of three National Wind Energy Assessments has produced maps showing the annual and seasonal distribution of wind energy in the contiguous United States (3.3.1).
- A Prototype Regional Evaluation has been initiated to develop and test criteria for future studies to refine the National Assessment and extend the number of wind characteristics treated (3.3.2).
- Two studies were completed that significantly increase the amount of existing wind data that is readily available for use in wind energy studies (3.3.9 and 3.3.10).

During the reporting period there were several requests from the Wind Systems Branch that led to Special Studies. Two of these "studies" required significant effort. They were:

- the preparation of preliminary plans for potential International Cooperative studies
- the description of 13 of the Candidate Sites and analysis of the data from all of the Candidate Sites.

During the coming year the WCPE intends to continue in the general directions established during the current reporting period. Work will start in the Planning and Operations Area. New work and directions will be entered as needs are identified.

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ANNUAL REPORT
FOR THE
WIND CHARACTERISTICS PROGRAM ELEMENT

1.0 INTRODUCTION

Battelle, Pacific Northwest Laboratories (PNL), has been providing technical and management support for the Wind Characteristics Program Element (WCPE) of the Wind Energy Conversion Program since April 1976. This first annual report to the Wind Systems Branch (WSB) of ERDA's Division of Solar Energy describes the technical progress within the Program Element from April 1976 through June 1977. Progress during the period from April 1976 through December 1976 has been reported in the Semi-Annual Report of the Wind Characteristics Program Element, BNWL-2220 WIND-2. This Annual Report incorporates the salient features of the semi-annual report.

Within the Wind Energy Conversion Program, the WCPE is a service element to provide information on wind characteristics to those involved in: energy program planning, design and evaluation of performance of wind energy conversion systems (WECS), selection of sites for installation of WECS, and operation of WECS. To identify pertinent wind characteristics and collect and present that information in formats that are usable, the WCPE has been divided into four technical areas:

- Wind Characteristics for WECS Design and Performance Evaluation
- Wind Characteristics for WECS Site Selection
- Wind Characteristics for WECS Presiting Evaluation
- Wind Characteristics for Planning and Operations.

These areas are commonly referred to as Design and Performance Evaluation, Site Selection, Presiting Evaluation, and Planning and Operation.

The distinctions between the Program Areas are not clear-cut; there are significant overlaps. The distinctions that exist are best illustrated by considering the time and space scales of the wind. Figure 1.1 shows the Program Areas in their approximate positions with respect to these scales. The

FIGURE 1.1 Time and Space Scale Relationship of the WCPE Technical Program Areas

boundaries of the areas are vague rather than sharp which, when combined with the overlaps, occasionally makes the placement of tasks in a specific program area arbitrary.

The Design and Performance Evaluation Program Area is concerned with wind information on the smallest time and space scales. It is to provide information on those meteorological characteristics that directly relate to the functioning of the WECS hardware. Meteorological information on these scales can frequently be treated in a generic manner. It is not necessary to have extensive meteorological data at each potential WECS site to provide the needed information. Rather, information can be provided for classes of sites on the basis of detailed measurements made at a few well-chosen sites.

The Presiting Evaluation Program Area, which grew out of the Resource Assessment Area, is concerned with meteorological information at the other extreme of the time and space scales. The goal of this Program Area is to provide information for use in National and regional energy program planning and for use in preliminary planning of specific wind energy conversion applications. The Program Area is more interested in generalizations and trends than in the fine details of wind energy potential at specific sites. In most cases, it

is impractical to make additional meteorological measurements to support work in the Presiting Evaluation Program Area. Needed information must be drawn from existing data and indirect evaluation techniques. Efforts to expand the number of readily available data sets for use in this area are important.

The Program Areas of Site Selection and Planning and Operations occupy an intermediate position in time and space scales. In this position neither the generic, small-scale data nor the readily available, large-scale data are adequate. As a result, these Program Areas must rely on interpolation of meteorological characteristics between locations where data are available to estimate characteristics at potential WECS installation sites. This extrapolation is complicated by distance and complex terrain in many scenarios.

The difference between Site Selection and Planning and Operations is one of emphasis. Site Selection is concerned primarily with the identification of favorable wind energy conversion sites. This is a ranking process in which relative merits of potential sites must be determined accurately. Accuracy in estimates of characteristics at specific sites is an important but secondary concern. Wind characteristics of interest in site selection include: annual mean wind speed, diurnal and seasonal variations in mean wind speeds, persistence of winds, and turbulence.

In the Planning and Operations Program Area the emphasis will be on providing wind characteristics information for detailed planning of a specific WECS installation and for operation of the system on a routine basis. Specifics of the Planning and Operations Program Area have not been defined, but it is likely that it will deal with providing information for use in detailed economic studies for specific installations, studies that could lead to capacity credit for the WECS system. The Program Area may also deal with providing information for use in day-to-day planning of WECS operations.

In addition to the four technical program areas just defined, there is a Program Area entitled Special Studies. This Program Area has been established to satisfy specific needs of the WSB as they arise. Generally the work conducted in this area is of the short-term, fast-response variety. It may cover tasks that would normally fall within any of the four technical Program Areas.

When tasks of a recurring nature are identified, they are transferred to the appropriate Program Area and included in planning of that Area.

The technical work covered in this report includes that done by PNL, other ERDA laboratories (Lawrence Livermore Laboratory and Sandia Laboratories), and other contractors funded directly by ERDA or through PNL. The remainder of the report is divided into two distinct parts. The first describes the overall progress of each of the Program Areas. In it the reader can obtain an integrated view of the progress during the past year and the expected progress in the year to come.

The second part contains the details of progress in the individual tasks within the technical Program Areas. Each major subdivision in this part corresponds to a Program Area. The discussion at the beginning of each subdivision provides a guide to the organization of the tasks within the Program Area and identifies interrelationships between tasks. A reader may use these introductory discussions, skipping the following detailed task discussions, to get a detailed view of the organization and direction of the Program Area. Or, the reader may use them to identify specific detailed discussions in which he is interested.

2.0 PROGRESS IN RESEARCH AREAS

PNL has provided the WSB with technical and management support for the WCPE for 14 months. The progress of the Program Element during that period is described in Section 2.1. Planning for the future is part of PNL's responsibilities. Section 2.2 discusses the WCPE progress expected during the coming year.

2.1 PROGRESS DURING REPORTING PERIOD

The WCPE has maintained a steady, controlled growth during the reporting period. When PNL assumed its responsibilities there were nine WCPE contractors with additional proposals under consideration. Several of these proposals were subsequently funded. Emphasis of the WCPE was clearly on providing wind information for planning of national energy policy and siting of WECS.

Upon assuming its responsibilities, PNL began the process of evaluation of the Wind Energy Conversion Program, and matching existing contracts with those needs. An invitational workshop was held in Boston, Massachusetts, June 2-4, 1976, with the objectives of: 1) introduction of PNL to WCPE contractors, 2) obtaining input for program planning, and 3) encouraging communications between WCPE contractors and wind information users in the rest of the Wind Energy Conversion Program.

By the end of September, the number of contractors working for the WCPE had increased to 17, and the general division of the WCPE technical work into program areas related to phases of the process of implementation was established. The new contracts filled some of the voids in the Program Areas now designated Site Selection and Presiting Evaluation. An approved program development plan for the WCPE for FY-1977 was formally submitted to the WSB on November 15, 1976.

A second invitational workshop was held in Seattle, Washington, in November to assess the roles of numerical and physical modeling in site selection. In addition to reaffirming that modeling has a place in site selection and delineating its proper roles, the Seattle workshop clarified the distinctions

between Presiting Evaluation and Site Selection. It also clarified the various stages in the site selection process.

By the end of December the division of the WCPE into the current Technical Program Areas was solidified. The WCPE Semi-Annual Report, covering the period through December 1976, showed work underway on 19 tasks. Of these tasks, 2 were related to Design and Performance Evaluation, 11 to Site Selection, and the remaining 6 to Presiting Evaluation.

In early January, an invitational mini-workshop was held in Richland to provide direction for the work in the Presiting Evaluation Area.

PNL has continued to adjust the organization of the WCPE to meet the changing needs of the Wind Energy Conversion Program. Since the January mini-workshop, planning inputs have been gained through direct contact with other program elements and through informal contacts with groups and individuals interested in the implementation of wind energy conversion.

The input from these various sources has been used to prepare a program development plan for the WCPE for 1978. This plan was submitted to the WSB for initial review in April 1977.

The continuing growth of the WCPE is further demonstrated by the number of tasks discussed in this report. Progress is reported in 33 tasks. This compares with 19 tasks covered in the Semi-Annual Report. The distribution of tasks among the Program Areas has also improved. The tasks discussed in this report are distributed as follows: Design and Performance Evaluation, 8; Site Selection, 15; and Presiting Evaluation, 10.

2.1.1 Design and Performance Evaluation

The objectives of the Design and Performance Evaluation Program Area of the WCPE are: to describe the wind and other meteorological characteristics for use in WECS design, to continually upgrade the quantity, quality and type of wind characteristics available to designers, and to transfer this information to other parts of the Wind Energy Conversion Program. To accomplish these objectives, the Design and Performance Evaluation Program Area must be aware of the current needs and anticipate the future needs of the WECS designers. It must be aware of existing wind characteristics information and research,

foster additional research, and it must present the information in a usable format.

During this initial period, the WCPE Design and Performance Evaluation Program Area has established viable goals. The goals are the preparation of wind characteristics handbooks for both design and performance evaluation supplemented by detailed technical reports. The handbooks will be addressed to the preliminary, final, and verification stages of design, as well as to WECS/site optimization. Information will be presented for application to the engineering considerations of ultimate strength, structural fatigue, WECS performance, and control system design.

Wind descriptors that are considered potentially important include: hourly mean wind speeds and their frequency distribution, statistical moments of the wind fluctuations, temporal and spatial correlations and spectra of the fluctuations, mean wind shear and wind shear fluctuations, wind direction variability, and peak wind gusts. Other meteorological factors of known or potential importance include: air temperature, pressure, humidity, icing, hail, lightning, and severe storms.

The Design and Performance Evaluation Program Area has begun a systematic evaluation of these factors. The mean wind speed is the simplest wind descriptor. It was the principal wind descriptor used in design at the beginning of the reporting period and continues to be the most important wind descriptor used in estimating WECS performance.

If the wind experienced by a WECS during its lifetime is described by a sequence of hourly mean speeds, a number of performance estimates can be made based on the frequency distribution of the hourly mean speeds. A number of forms have been suggested for this distribution. The Rayleigh distribution is a particularly convenient form because it is fully defined when the long-term (annual) mean wind speed is specified. The distribution has been evaluated for wind energy applications and has been found to be acceptable (3.1.1).^{*} However, there are systematic differences between the Rayleigh distribution and

^{*}Section in which progress or finding is discussed in detail.

actual wind speed distributions. These differences tend toward underestimating wind power at low wind speed sites and overestimating at high speed sites. Introduction of WECS operating characteristics into the power estimates reduces these errors. The systematic overestimate of wind power at high wind speed sites is the result of overestimation of the probability of extreme wind speeds. Thus, the use of the Rayleigh distribution in structural design problems would be conservative, that is, lead to over design.

Typical WECS characteristics, as embodied in the coefficient of performance, C_p , have been combined with hourly mean wind speeds following a Rayleigh distribution to examine the sensitivity of WECS performance to the WECS design parameters of cut-in rated and cut-out speed as a function of annual mean wind speed (3.1.2 and 3.1.3). The ratio of the long-term average power output of a WECS to its rated power is a function of the ratios between annual mean and rated speed, and cut-out and rated speed. For a given ratio between annual and rated speeds, the power ratio increases with the ratio of cut-out to rated speed until a limiting value is approached. Further increases in the cut-out to rated speed ratio have little effect on the power ratio. For a given ratio between cut-out and rated speed, there is an optimum range for the ratio of annual mean to rated speed. Departure from this range will result in a decrease in the ratio of average output power to rated power.

The next level of complexity in description of the wind is to include the vertical shear of the mean wind speed and to assume that the wind speed varies with time. The mean wind speed shear can be adequately described with either a power law or logarithmic relationship at this level of sophistication. The time variation of the wind speed is generally treated by dividing the speed into mean and fluctuating parts. The fluctuations are then assumed to be random. The Design and Performance Evaluation Program Area has begun the description of these fluctuations. A gust is defined as a departure from the long term (10 min to 1 hr) mean speed. It lasts from the time the speed rises above or falls below the mean until it returns to the mean and has an amplitude that is equal to the maximum departure from the mean. There are both positive and negative gusts.

Data analysis shows that positive and negative gusts have different characteristics (3.1.4). Large amplitude positive gusts are more frequent than

negative gust of equal amplitude. The number of gusts per hour exceeding a given value has been modeled for both positive and negative gusts. The models have been combined with Rayleigh distributions of hourly mean wind speeds to provide initial estimates of the number of gusts exceeding a given magnitude per year as a function of annual mean wind speed and terrain. For a site in moderately hilly terrain with an annual mean wind speed of 8 m/s, it is estimated that there will be 10^4 positive gusts with amplitudes exceeding 10 m/s. At the same site, it is estimated that there will be 3×10^3 negative gusts with amplitudes exceeding 10 m/s.

The detail included in wind description can be further increased by considering time fluctuations of the wind shear. Initial study of wind shear fluctuations has been completed using available data (3.1.5). Wind shear fluctuations, both horizontal and vertical, can be larger than the vertical shear of the mean wind. Models have been developed for the frequency distributions of the shear fluctuations.

The detailed description of the wind, including its time and spatial variations, for use in WECS design and performance evaluation requires numerous assumptions. Among these is the assumption that wind measurement at fixed points can represent the wind experienced by a moving blade. A field experiment has been conducted to provide wind measurements that can be used to estimate the wind experienced by a blade more closely than previously possible (3.1.6). Preliminary data analysis has begun.

The WCPE, through the Design and Performance Evaluation Program Area, has begun the development of procedures for evaluating the efficiencies of WECS control strategies with respect to anticipating or following wind fluctuations (3.1.7). The research has two parts. In the first part actual wind records are combined with explicit or implicit control strategies to determine statistics describing control system operations. Both the number of changes in control system operating modes and the amount of time spent in each mode per hour are computed. In the second part of the program, wind records are analyzed to determine the WECS azimuthal tracking policy that would minimize the variance between the wind direction and the WECS orientation. These optimum

tracking policies will provide a basis for estimating the efficiencies of actual or proposed tracking policies.

Remote sensing of the wind for application to wind energy studies is being evaluated. A Doppler acoustic radar system has been deployed at three locations with mixed results (3.1.8).

Liaison with program elements provides the WCPE with information on wind characteristics needs and permits transfer of existing information to designers. Significant inputs to the WCPE have come from the NASA Lewis Research Center. Large WECS programs, the Sandia Laboratories Vertical Axis Wind Turbine program, and the Rocky Flats Plant small WECS test center. Liaison with small WECS manufacturers has been established through the American Wind Energy Association.

2.1.2 Site Selection

The objectives of the Site Selection Program Area are the development and demonstration of techniques and strategies for identifying favorable wind sites. To achieve these objectives, a variety of tools for extrapolating and augmenting existing wind data are being studied. The specific tools potentially applicable to a given siting problem depend upon the scenario and its constraints. Typically, the scenario and constraints consist of: the size area under consideration and its topographic features, the available meteorological data, the capital investment being considered, the economic resources available for site evaluation, and the specific energy application.

During the reporting period a conceptual framework has been established which can be used to identify the relationships between potential site selection tools. This framework is related to the time and space scale of the site selection process. Figure 1.1 indicates that time scales of meteorological variability of interest in site selection range from a few years to a few minutes, and that length scales range from several hundred kilometers to about 10 m. Various potential site selection tools and their ranges of applicability are shown within the overall site selection time and length scales in Figure 2.1.

FIGURE 2.1. The Relationships Between the Tools and the Important Time and Space Scales for Site Selection

In any site selection scenario, the goal is to move from larger length scales to smaller scales in a timely and economical fashion. The tools chosen depend on the length scale starting point and the time scales of importance.

For systematically screening large areas for favorable wind energy conversion sites, the most appropriate tools currently being evaluated are numerical models and geological indicators. As localization occurs and for small areas, physical models, biological indicators and handbooks containing generic wind flow information become useful.

If temporal variations in wind energy are important in the energy application, the time scale of importance should be considered in selecting siting tools. Geological indicators provide little information on temporal variations, and biological indicators are not likely to provide information on variations of the wind that are more frequent than seasonal. Physical models may provide seasonal wind information, but it is not likely that they can provide much

useful information on diurnal variations of the wind. For small-scale time variations in the wind, it is necessary to rely on time-dependent numerical models, physical models, and generic information. Predictions of these tools should be confirmed by onsite measurements prior to final selection of a site.

A survey of historical practices in selection of sites for small WECS has been completed (3.2.1). In general, the locations for installation of small WECS were governed by use of the energy. Water pumping systems were constrained by the location of water, and electrical generating systems were installed near batteries. Meteorological factors involved in site selection were dealt with on intuitive bases supported by manufacturer's guidelines.

Development of siting methodologies utilizing numerical models has continued. These multi-year studies (3.2.2, 3.2.3, and 3.2.4) are all maturing to the point where it is possible to discern their relative merits and to associate the tools with specific scenarios. The steady-state models of Lawrence Livermore Laboratory (3.2.2) and Science Applications (3.2.3) generally fit into an iterative site screening and localization procedure. A typical application of these models would start with the use of readily-available wind data to identify generally the favorable wind regions within the initial area and to identify locations for wind measurements needed to refine the definition of the favorable regions. Wind measurements would be made to obtain a set of simultaneous, concurrent wind observations in a variety of meteorological conditions. The model would then be used to better define the favorable regions and provide a basis for localization in one or more of the regions. Locations for further wind observations would be identified and another set of measurements would be made. Finally the model would be used to identify the areas of highest winds in the selected regions. The time required to complete the screening and localization process would depend on the number of iterations and could vary from one to several years.

Both Lawrence Livermore Laboratory and Science Applications have made significant progress in developing techniques to reduce the number of model computations required for site selection. The reduction in computations is accomplished through recognition of air flow patterns and making computations for each pattern rather than on an hour-by-hour basis.

The approach taken by Research Triangle Institute (3.2.4) is to extrapolate from wind measurements at a single location using a numerical model. The simulated winds are then related statistically to those at the measurement point. Initial results of the application of this technique to sites in the St. Louis, Missouri, area indicate the need for thorough review prior to continuation.

To be effective tools in the site selection process, numerical models must be reliable, accurate, efficient and relatively easy to use. On these bases, a model effective in one scenario may not be effective in another. As a result, the WCPE has initiated two programs to validate and compare numerical models for use as siting tools (3.2.5 and 3.2.6). Statistical decision theory is being used to develop a family of statistics that can determine the accuracy with which numerical models predict wind fields (3.2.5). The initial work on estimating probability distributions for wind velocities in a modeled region has been completed. A survey of existing meteorological data sets that might be used for the validation and comparison tests has been completed (3.2.6). A total of 139 data sets were identified, and the details of these sets have been published in Survey of Wind Measurement Field Programs, BNWL-2220 WIND-3.

In addition to supporting the development of numerical modeling tools for site selection, the WCPE has supported studies to produce generic wind information for use in siting. There are currently four studies that fall into this category. Poseidon Research is evaluating the effects of atmospheric density stratification (stability) on the air flow over two- and three-dimensional mountains (3.2.7), and the University of Virginia is studying surface winds in coastal zones along the Atlantic and Gulf coasts (3.2.8). Both studies involve the use of numerical models. Colorado State University is using a wind tunnel to examine the influence of terrain shape, surface roughness and atmospheric stability on air flow (3.2.9), and the University of Oklahoma has completed a field measurement program to identify empirical relationships between air flow in the boundary layer and the underlying terrain (3.2.10).

Poseidon Research is using Fourier integrals to solve a mass-conserving set of hydrodynamic equations. The integrals are computed by use of Fast-Fourier transformations. Results of computations for both two- and

three-dimensional mountains show that in neutral atmospheric conditions, surface wind maximums occur at the mountain peaks. For stably stratified atmospheric conditions, these maxima move off the peaks; to the lee of the mountain in the two-dimensional case, and to the side in the three-dimensional case.

Colorado State University has completed a set of measurements over hills with five different shapes. The same flow parameters were used for all terrain configurations. The measurements indicate that the fractional speedup of the flow is independent of shape if the hills have slopes less than 1/3 or 1/4. Tabulated data were published for experiments completed earlier in the program.

The United States coastline from New England to Mexico has been divided into five regions for evaluation of wind energy potential by the University of Virginia. Data for use in modeling the air flow within 1 km of the coast have been acquired and compiled. Preliminary analysis has begun to delineate both annual cycles and regional differences in winds.

A draft of a final report on the measurement of air flows in valleys has been received from the University of Oklahoma. The work, funded by NSF, generally agrees with expectations based on physical understanding of atmospheric processes.

Nonstandard sources of wind information offer the potential of augmenting readily-available wind data in the site selection process. The WCPE has supported two studies that are evaluating nonstandard data sources. It has also initiated a procurement action to identify and evaluate several additional studies.

Oregon State University is evaluating the use of vegetation as an indicator of areas of high wind velocities (3.2.11). Its studies are focused on conifer deformation in the Columbia River Gorge and the depth of salal at the Oregon Coast. Cameras and recording anemometers have been deployed at the experimental sites.

LANDSAT imagery is available for many regions of the United States. The University of Wyoming is evaluating the potential use of this information to identify high wind energy regions by inferring wind characteristics from

aeolian geomorphological features (3.2.12). Work to determine the utility of stabilized features, develop techniques for quantitatively estimating wind characteristics, and assess regional applicability of LANDSAT imagery is underway. However, results have not been attained in any area.

The ultimate goal of the Site Selection Program Area is the documentation of siting tools in usable formats. The remaining three tasks in this Program Area are directed toward that documentation.

FWG Associates has undertaken the preparation of a Design Manual describing the effects of terrain features on the wind at a WECS site (3.2.13). The Table of Contents of the manual as outlined in the WCPE Semi-Annual Report contains major sections dealing with: 1) General Wind Characteristics, 2) Engineering Philosophy, 3) Portfolio of Terrain Features, and 4) Site Selection Criteria Relative to Winds Over Terrain Features. Available information on the effects of flat and two-dimensional small scale terrain features has been collected, and a sample chapter of the Manual has been prepared. This chapter is being reviewed for form and content.

Interim handbooks have been prepared for use in siting small and large WECS (3.2.14 and 3.2.15). These handbooks combine the work of the contractors in the Site Selection Program Area with other readily available meteorological information and present the results in usable formats. The small system handbook presents siting techniques that require a minimum of mathematics and are based on rules of thumb (3.2.14). The large system handbook assumes a greater level of sophistication on the part of the user (3.2.15). The handbooks are currently being reviewed.

2.1.3 Presiting Evaluations

The Presiting Evaluation Program Area has two primary objectives: 1) the identification of large areas of high wind energy potential, and 2) the determination of wind characteristics which are related to economic viability of wind energy conversion in these areas. To accomplish these objectives for large scale areas, the Presiting Evaluation Program Area must rely primarily on existing information and interpolation techniques.

The wind energy conversion program and its NSF predecessor have funded three separate National Wind Energy Assessments. The results of these assessments, while having many features in common, were not entirely consistent. Inconsistencies were found in both the estimated magnitude and geographical distribution of wind power. The information used in the original assessments, supplemented by data from selected additional sources, was used to prepare a synthesized national assessment (3.3.1). Maps prepared in the synthesis show the annual and seasonal distributions of wind energy for the contiguous United States. The results have been published as a PNL report.

One of the conclusions of the synthesis, and of the January mini-workshop, was that significant refinement of the National Assessments could best be accomplished through a series of Regional Evaluations. To establish criteria for Regional Evaluations, work has begun on a prototype (3.3.2). In the initial phase of the Prototype Regional Evaluation, the United States has been divided into multi-state regions utilizing state boundaries except for Alaska and Hawaii which are considered complete regions. The Northwest United States was selected for the prototype evaluation because of its topographical and climatological diversity.

The WCPE inherited two research programs in February 1977 that will contribute to the regional evaluations. The first, conducted by the University of Alaska (3.3.3) was transferred to the WCPE from the Farm and Rural Use (Small) Systems Program Element, and the second, conducted by the University of Hawaii (3.3.4), was transferred for technical monitoring purposes from the National Science Foundation.

During the reporting period the University of Alaska has analyzed wind data from 28 sites. Wind power predictions were made for selected areas. The University of Hawaii has used historical data and mobile data sampling programs to identify areas of high wind power potential on the Islands of Hawaii, Maui and Oahu. The mobile data sampling program also contributed in the selection of permanent wind measurement sites in areas of potentially high wind power.

Unlike the National Assessments, which concentrated on available wind power, the Regional Evaluations will consider a variety of wind characteristics.

Among these are: extractable power, the timing and variation of power, the probability of obtaining power at a given time, the probability that wind will be available continuously for m hours, and the probability that no wind power will be available for n consecutive hours. Developing this information for each area would require excessive data analysis. The WCPE Presiting Evaluation Program Area funds supplementary studies that seek to provide more realistic approaches to obtain the needed information. Eight studies currently fall within the supplementary study category.

Georgia Institute of Technology has been evaluating the power production characteristics of large arrays of WECS (3.3.5). During the past year, simulated arrays of 0.5, 1.5 and 2.0 MW wind systems have been studied for the Great Lakes and Pacific Coast regions. These studies, combined with earlier studies of the New England and Central United States regions, have been used to develop a simplified array simulation model. A second, simple model was developed for incorporation of density variations, wind shear, gusts and wind directional changes in WECS power estimates.

The stochastic modeling studies of Northwestern University (3.3.6) have examined data collection requirements obtain accurate wind statistics. The duration of wind measurement programs to obtain an estimate of average wind speed and power within specified accuracy and confidence limits has been determined. Additional data analysis has led to the development of a run duration model based upon mean wind speed. Run duration is the length of time the wind stays above or below a given value.

The effects of sampling frequency and data averaging on wind power estimates have been examined at PNL (3.3.7). Wind observations averaged for 1 min and recorded every other minute, formed the fundamental data set. Power estimates based on reduced data sets were compared with those obtained from the fundamental set. Power estimated from 1 min average observations taken each hour was about the same as that estimated from the full set. Further reduction of the sampling frequency to once every 3 hours had little effect on power estimates. When power was estimated from hourly average wind speeds, about a 10% reduction was noted. This study is currently evaluating the extrapolation of parameters for wind speed frequency distributions.

At Sandia Laboratories wind data from selected sites are being used to examine optimization of WECS output on the basis of climatology and WECS characteristics (3.3.8). These data have been used to compare seasonal and interannual variability of wind power. Interannual variability is indicated to be larger than seasonal variability.

The remaining four studies, not discussed in Section 3, have just begun. These studies involve the estimation of wind characteristics at a remote location without the use of any onsite wind data. These studies are part of an overall project to determine the accuracy of existing wind interpolation techniques in a variety of topographic settings. The techniques under evaluation range from relatively simple weighted-interpolation schemes to the use of numerical models. The topographic settings which have been selected for the test range from flat plains to mountains. Contractors for these studies are Meteorology Research, Inc.; the Center for the Environment and Man; Geomet, Inc.; and Stanford Research Institute.

The success of most studies in the Presiting Evaluation Program Area depends upon the availability of existing data sets. Two studies were undertaken and completed by the WCPE to increase the number of data sets readily available for use in its programs. The National Climatic Center has prepared an index of all summarized wind data available through it (3.3.9). The index lists the period of record and summary format for the available data. It is divided into two parts. The first is a listing of available data by location, and the second is a listing of available data by summary format.

Wind data collected at nuclear power plant sites throughout the United States were compiled at PNL, and the compilation has been published. The data were collected at 107 sites; many of the sites have more than one measurement level. Velocity duration curves and power estimates for each level are included with the published data. The data have been used in several of the tasks discussed under the Design and Performance Evaluation Program Area (e.g., 3.1.1, 3.1.3).

2.1.4 Planning and Operations

The identification of the area of wind characteristics for detailed planning of WECS installations and for operational employment of WECS occurred in about December 1976, although many of the required tasks were recognized as early as the Boston Workshop. None of the current technical tasks are assigned to this Program Area. However, current tasks in the other three technical Program Areas are developing information that will apply to the needs in this area. Specifically, the work on array reliability (3.3.5) and stochastic modeling of site wind characteristics (3.3.6) is related to large scale (long time) predictability of the wind. Work on wind characteristics for design of turbine blade control and tracking strategies (3.1.7) is related to small scale (short time) predictability. In addition, the Site Selection studies using numerical modeling (3.2.2 and 3.2.3) and the new Presiting Evaluation studies to determine the accuracy of wind interpolation schemes will contribute to detailed planning studies.

Outside of the Wind Energy Conversion Program, the National Weather Service and the Federal Aviation Administration are currently involved in research on short-range weather forecasting techniques. This work should contribute to the day-to-day and hour-to-hour employment of WECS in large power systems.

2.1.5 Special Studies

During the reporting period PNL responded to numerous requests from the WSB. In general, these requests can be grouped into three categories: International Cooperative Studies, Meteorological Assistance with respect to Candidate Site for Experimental WECS, and Reviews of Reports and Programs of other Wind Energy Conversion Program Elements.

The WSB requested that PNL identify and develop preliminary plans for possible International Cooperative Studies on Wind Characteristics. Of the studies initially suggested, three were selected for further development. Completion descriptions of the three studies were prepared and submitted to WSB in October 1976. The studies selected were: Validation of Models for Wind System Siting, Predictability/Uncertainty Analysis to Assess Dispatching Algorithms, and Remote Sensing for Determining Surface Winds. These

were ultimately submitted to the Wind Working Party of the International Energy Agency. In January, C. E. Elderkin attended meetings of IEA in Paris, France, to discuss the suggested studies and seven additional studies suggested by other countries.

The largest of the Special Request categories deals with the Candidate Sites. At the request of NASA Lewis Research Center and the WSB, PNL staff members visited 13 of the 17 Candidate Sites during the period January through March 1977. Detailed descriptions were prepared for each site visited. The descriptions included discussions of meteorological tower locations, possible topographical effects on data collected at the site, representativeness of the tower location with respect to the proposed WECS location, and potential problems in WECS installation at the site.

In addition to visiting the Candidate Sites, the PNL staff has been directly involved with wind data collected at the sites. Recommendations on wind data summarization and presentation were made to NASA Lewis, and wind data collected at the Candidate Sites are being sent to PNL for analysis.

In April an analysis of Candidate Site wind data, both newly collected and historical, was presented to the Phase II Evaluation Panel. The analysis included performance estimates for the NASA/ERDA MOD 1 turbine. At the same time, the Site Review Board was briefed on the results of the site visits.

Finally, there have been discussions between NASA Lewis and PNL with respect to meteorological instrumentation and measurements for evaluation of the performance of the NASA/ERDA WECS.

The third general area of Special Studies is the review of work by other elements of the Wind Energy Conversion Program. These reviews contribute to the growth of the WCPE by providing firsthand information on wind characteristics needed. Through these contacts the WCPE identifies adjustments needed in its own work.

2.2 EXPECTED PROGRESS DURING NEXT REPORTING PERIOD

Progress in the WCPE is an iterative process. Needs of the Wind Energy Conversion Program must be identified or anticipated; wind characteristics

information must be assembled to meet the needs, and the information must be transferred to users. Progress requires each of these steps. The expected progress described in this Section is based upon current work and planned additions. Increased contact with other parts of the Wind Energy Conversion Program during the coming year may lead to an acceleration in WCPE progress.

2.2.1 Design and Performance Evaluation

The primary products of the Design and Performance Evaluation Program Area have been identified as handbooks. Interim versions of these handbooks are to be prepared during the coming year. Preparation of the handbook of meteorological information for use in WECS design will be closely coordinated with NASA Lewis' contractor working in the same area.

To achieve this goal, the WCPE will continue the systematic evaluation of wind descriptors that has been started. Simple descriptors will be evaluated first, followed by more complex descriptors. The results of the individual tasks in this effort will be published in technical reports and summarized in the handbooks.

In instances where data analysis is necessary, preliminary analysis will be conducted on readily available data and tentative results published. Additional data from a variety of locations will then be analyzed. Results will be compared and the tentative results revised as necessary to provide generally applicable design information.

The field experiment simulating WECS will continue. A new instrument array will be installed to simulate a 160 ft diameter WECS.

The evaluation of extremely short-range predictability of the wind for use in design and evaluation of WECS control systems will continue.

The interactions between the WCPE and the Small Systems Testing program at Rocky Flats will increase during the coming year, and will contribute to the preparation of a handbook on meteorological considerations in WECS performance evaluation. Topics to be included in the handbook include: the selection and positioning of wind instruments, as well as data collection and analysis. Continued liaison with NASA Lewis on its mobile data van and plans for evaluation of the performance of the large experimental WECS will also contribute to the handbook.

2.2.2 Site Selection

Preparation of interim siting handbooks at the conclusion of the current reporting period marked the beginning of an iterative process designed to result in final siting handbooks in FY-1980. The first revision of the interim handbooks will take place during the coming reporting period. At that time new information pertinent to siting will be included and changes will be made to improve the utility of the handbooks.

The emphasis in development of systematic siting strategies will continue to shift from the development of methodologies using numerical models to the validation and comparison of the models. Transfer of siting technology to potential users will assume greater importance.

Work in the development and application of nonstandard techniques for estimating wind characteristics will expand. Several new studies will be initiated early in the reporting period.

The WCPE will continue to support the development of generic wind-information for use in siting.

It is anticipated that analysis of meteorological data from the Candidate Site will be a continuing WCPE requirement. As a result, this task has been assigned to the Site Selection Program Area. The task of development of criteria for prequalification of future Candidate Sites will be shared by the Site Selection and Presiting Evaluation Program Areas.

2.2.3 Presiting Evaluations

In the coming year the priority tasks of the Presiting Evaluation Program Area will be preparation of Regional Evaluations. Initial emphasis will be on completion of the prototype evaluation and the development of criteria for subsequent regional evaluations. Toward the end of the year, the emphasis will shift to work on evaluations in high priority regions. A workshop is planned for contractors selected to assist in Regional Evaluations. Contractors will be selected via a competitive procurement.

The WCPE will continue to support studies to supplement the Regional Evaluation effort. Prediction of site wind characteristics in the absence

of on-site data will continue to be evaluated. The accuracies of techniques employed in the prediction will be evaluated by comparison of predicted and observed characteristics. The range of applicability of the techniques will be determined on the basis of accuracy and cost for various topographic settings.

2.2.4 Planning and Operations

The initial task assigned directly to the Planning and Operations Program Area is an invitational workshop to define the directions and goals of the Area. The workshop, planned for early FY-1978, will also recommend appropriate tasks for support. There may be problems in defining specific end products for the area because of the number of considerations that require detailed information about each individual WECS application. However, it should be possible to define tasks to develop techniques for presenting available meteorological data for use in detailed planning studies and for routine operation of WECS within utility power grids.

2.2.5 Special Studies

PNL and the WCPE will continue to give priority to requests from the WSB. It is anticipated that the WSB will continue to request assistance in the review of the work of other parts of the Wind Energy Conversion Program. It is also anticipated that International Cooperative Studies may also be the subject of future requests.

3.0 PROGRESS IN TECHNICAL TASKS

This section describes the progress in the major technical tasks. Tasks are identified by contract title and task number from the Development Plan for the Wind Characteristics Program Element dated November 15, 1976, when appropriate. Technical tasks being performed by the Universities of Hawaii and Alaska were transferred to the WCPE in February 1977, and several other tasks discussed, including the task on Model Validation and Comparison, were initiated as a result of the continuing review of WCPE needs during the year. The contracting organization and Principal Investigator are identified for each task. In addition, a PNL Contract Monitor or contact is identified.

Technical tasks are generally funded for 12 months at a time. Where completion of a task requires more time, the work is reviewed and evaluated prior to renewal of the funding. Completion dates indicated in this section are dates for completion if the proposed schedule is followed. They neither imply nor guarantee funding beyond the current contract.

3.1 DESIGN AND PERFORMANCE EVALUATION

Progress in Program Area of Wind Characteristics for WECS Design and Performance Evaluation is covered in Sections 3.1.1 through 3.1.8 in detail. The prefatory discussion here will present an overview of the directions of the research.

The general equation relating the wind and power is

$$P = 1/2 \rho V^3 A C_p \quad (1)$$

where:

P = power generated by a wind energy conversion system

ρ = density of air

V = wind velocity at the hub

A = frontal area of the system

C_p = coefficient that describes the WECS operation.

The combination of terms $1/2 \rho V^3 A$ describes the power available in the wind. The aerodynamics and efficiencies of the WECS are all included in C_p , which is a function of the wind velocity.

As a zero-order approximation, when using this equation it is assumed that V is the mean wind speed, and that it is uniform in space. This approximation represents the conditions that are found in a wind tunnel. To apply the approximation to the atmosphere, it is further assumed that the wind in a given period can be described as a sequence of steady-state conditions, each described by a mean wind speed. If the frequency distribution of these short-term mean wind speeds is specified, Equation (1) and the frequency distribution can be used to provide estimates of average power during a year, percent operating time, etc., when WECS characteristics (C_p) are given.

The work described in Section 3.1.1 evaluates a theoretical distribution that may be used to describe the frequency distribution of hourly mean wind speeds given an annual mean speed. The work described in Sections 3.1.2 and 3.1.3 uses that frequency distribution to examine the sensitivity of predicted WECS performance to variations in the design parameters cut-in speed, rated speed, and cut-out speed.

The wind in the atmosphere is not a steady, rather it is continuously varying. The first order approximation which incorporates this fluctuating nature in Equation (1) is to let

$$V(t) = \bar{V} + v(t)$$

where:

$V(t)$ = wind speed at time t

$\bar{V}$ = mean wind speed

$v(t)$ = departure of $V(t)$ from $\bar{V}$ at time t .

To specify the wind it is now necessary to provide information on the mean speed and the fluctuations. By definition the average of $v(t)$ is zero, so it is necessary to choose a different parameter to characterize the fluctuations. The parameter generally chosen is the standard deviation of the fluctuations (root-mean-square fluctuation) denoted by σ_v .

In return for the increased complexity of the first-order approximation, it is possible to begin to examine the effects of wind gusts on WECS. The V^3 in Equation (1) now becomes

$$(\overline{v^3} = 3\overline{v} \overline{v^2} + \overline{v}^3)$$

Thus, it is seen that the fluctuations contribute to the power available in the wind. However, gustiness may also affect the performance of the WECS embodied in C_p . In addition, gustiness causes varying loads on the WECS and may contribute to fatigue. Evaluation of these effects requires more detailed mathematical description of the WECS than is given by C_p .

In the work described in Section 3.1.4, the frequency of gusts of a given amplitude is examined for use in design. When combined with a frequency distribution of hourly mean wind speeds (Section 3.1.1), the number of gusts exceeding a given amplitude that will be experienced by a WECS during a period of time is estimated.

More realistic description of the wind for use in design requires that the spatial variation of wind speed be accounted for. It is necessary to specify wind at a point on the blade of a WECS as well as that at an instant in time. One way to describe the wind in this detail is to use a spatial Taylor series expansion about the wind at the hub. Thus V in Equation (1) becomes:

$$V = V(r,t) = \overline{V}(h) + \frac{\partial \overline{V}}{\partial z} \Delta z + v(h,t) + \frac{\partial v(t)}{\partial y} \Delta y + \frac{\partial v(t)}{\partial z} \Delta z \quad (2)$$

where:

r = distance from the hub to the point of interest on the blade

h = hub height

$\Delta y = r \sin \Omega$

$\Delta z = r \cos \Omega$.

In the last two expressions, Ω is the angular position of the blade, defined with $\Omega = 0$ when the blade is vertical and up.

The last two terms on the right side of Equation (2) describe random variations of wind in time and space. Section 3.1.5 describes work done to evaluate the size of these terms, both in absolute terms and relative to the mean wind shear described by the second term on the right. Information on the shear fluctuation terms is limited; however, the available information has been used to develop statistical descriptions of the terms.

The description of the wind can be further expanded by treating the full velocity vector rather than just speed.

Meteorologists have consistently measured the spatial variation of the wind using arrays of instruments set up in lines. This arrangement is appropriate for evaluating the terms in Equation (2), but a more useful arrangement for use in gaining wind information for use in WECS design is a circular array. Section 3.1.6 describes a field experiment to obtain wind information specifically for application to horizontal axis WECS. The data from this experimental program will contribute to all other parts of this Program Area.

In addition to providing information on wind characteristics, the work in the Program Area applies wind data to specific problems. Section 3.1.7 describes the application of wind data to a potential WECS control system operating strategy, and the development of a technique for estimating the efficiency of a control strategy with respect to wind variability.

Finally, Section 3.1.8 discusses the work in a project to evaluate the use of Doppler acoustic radar systems for remote sensing of wind characteristics in the lowest 100 m of the atmosphere.

3.1.1 Annual Wind Speed Distribution for Design (1d)*

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

J. V. Ramsdell (509) 946-2749

Objective:

To identify and evaluate probability distributions for describing the frequency of occurrence of hourly average wind speeds for use in establishing meteorological criteria for WECS design.

Program Status:

The Rayleigh distribution, a special case of the Weibull distribution, is currently being evaluated for use in WECS design. Its principal advantage is that it is a one parameter distribution which is completely defined when the long term (annual) average wind speed is specified. Differences in estimates of available and extractable wind power made from actual and Rayleigh wind speed distributions are being examined.

Progress During Reporting Period:

Estimates of available wind power have been computed from 197 actual wind speed distributions. Estimates have also been computed from Rayleigh distributions with corresponding mean wind speeds. Ratios between these two estimates have been averaged in 1 m/s bands and plotted as a function long term mean wind speed to examine systematic departures of Rayleigh distribution from actual wind speed distributions. Figure 3.1 shows the result. The solid circles represent the geometric mean ratio between estimates from actual and Rayleigh distributions for each band. The error bars indicate the mean ± 1 standard geometric deviation, and the numbers in parentheses indicate the number of distributions averaged in each band.

*Numbers in parentheses following titles refer to task numbers in the November 15, 1976 Program Development Plan.

FIGURE 3.1. Ratio of Available Wind Power Estimated from a Rayleigh Wind Speed Distribution to that Estimated from Actual Wind Speed Distributions as a Function of Annual Mean Wind Speed

At low annual mean wind speeds, the Raleigh distribution consistently underestimates the available wind power. However, as the annual wind speed approaches speeds generally considered usable for large scale wind energy conversion, the ratio between the two estimates approaches 1, indicating that the distributions are approximately comparable. Finally, the trend of the ratios as a function of mean wind speed indicates that the Raleigh distribution should overestimate available wind power at high wind speed sites.

In terms of wind speed frequency, the Raleigh distribution underestimates the number of occurrences of low speeds, and in particular it does not indicate the occurrence of any calms. For low mean wind speed distributions it overestimates the frequency of occurrence of moderate speeds and underestimates the frequency of high speeds. This combination

of under and over predictions results in an under prediction of available power because of the cubic relationship between wind speed and power. For moderate mean wind speeds there is a slight overprediction of moderate and high speeds which approximately compensates for the underprediction of low speeds. At high mean speeds the Raleigh distribution over prediction of high wind speeds is dominant and power estimate significantly exceed estimates based on actual wind speed distributions.

Use of the Rayleigh distribution for establishing meteorological criteria for WECS design is considered to be conservative. That is, the distribution tends to over predict the frequency of occurrence of high hourly average wind speeds and as a result design criteria based on the distribution will tend to be more stringent than if they were based on actual wind speed distributions.

In terms of extractable power, the incorporation of WECS characteristics, such as cut in, rated and cut out speed, in power estimation should reduce the discrepancies between power estimates from actual and Rayleigh wind speed distributions for the range of annual mean wind speed of interest for wind energy conversion. In particular, the estimates of extractable power at high wind speed sites should be very comparable. The results of preliminary analysis of extractable power for standard ERDA/NASA WECS are shown in Figure 3.2. For locations with annual mean wind speeds greater than 5 m/s the use of Rayleigh distribution gives very good estimates of the extractable power. The power underestimates caused by use of the Rayleigh distribution at low annual mean wind speeds are related to turbine cut in speed.

FIGURE 3.2. Ratio of Extractable Wind Power Estimated from a Rayleigh Wind Speed Distribution to that Estimated from Actual Wind Speed Distributions as a Function of Annual Mean Wind Speed

Expected Progress During the Next Period:

The use of the Rayleigh distribution in estimation of both available and extractable wind power will be completed, and a technical report will be prepared on the Rayleigh distribution and its application to the WECS design criteria.

Reports and Publications:

None

3.1.2 Sensitivity of WECS Performance to Cut Out Speed (1d)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

William C. Cliff (509) 942-5066

Objective:

Estimate the sensitivity of expected power output and percent downtime of a standard ERDA/NASA wind turbine to various cut out speeds for design and performance evaluation considerations.

Program Status:

The technical analysis is complete. A formal report is being written.

Progress During Report Period:

An analysis to estimate the sensitivity of the expected power output and percent downtime of a standard ERDA/NASA wind turbine was performed using the present wind turbine performance characteristics for steady state wind conditions. A Rayleigh probability density distribution was then used to describe the frequency distribution of hourly mean wind speeds. The Rayleigh distribution was selected because of its closeness to the general shape of the high annual wind speed frequency distributions observed at present ERDA/NASA candidate wind turbine sites. (See Section 3.1.1 for a discussion of the use of the Rayleigh distribution for design.)

Figures 3.3 and 3.4 present expected extractable power and percent downtime as functions of annual average wind speed and cut out speed.

For wind energy conversion sites with annual mean wind speeds up to 10 m/s, Figure 3.3 shows that reduction of cut out speed from 29 to 22.4 mph has little effect on the average extractable power. At sites with annual average wind speeds of 7 m/s

FIGURE 3.3. Average Extractable Power for a Standard ERDA/NASA Wind Turbine as a Function of Annual Mean Wind Speed and Cut Out Velocity

FIGURE 3.4. Percent Downtime of a Standard ERDA/NASA Wind Turbine as a Function of Average Annual Wind Speed and Cut Out Velocity

and less the cut out speed may be reduced to 17.9 m/s without a significant decrease in power output. Figure 3.2 shows the increases in downtime which correspond to decreases in cut out speed. For sites with average speeds below 10 m/s there is little increase in downtime if the cut out speed is reduced to 22.4 from 29 m/s. Similarly for lower wind speed sites (7 m/s and less) the cut out speed can be reduced to 17.9 m/s without increasing the downtime significantly.

Expected Progress During the Next Period:

The results of the analysis will be documented.

Reports and Publications:

None.

3.1.3 Generic Performance Estimates for WECS (1d)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

W. C. Cliff (509) 942-5066

Objective:

To provide guidance in estimating the performance of WECS with limited meteorological data.

Program Status:

The program to provide general performance estimates was begun in May 1977. Preliminary guidelines for estimating the average power produced and percent of time operating, on the basis of annual mean wind speed and WECS cut in, rated, and cut out speeds have been completed.

Progress During Reporting Period:

In response to numerous requests for information on wind energy, a small task was undertaken to provide general guidelines relating simple meteorological descriptions and typical WECS characteristics to expected WECS performance. The results during the current reporting period include two sets of curves. The first, shown in Figure 3.5 provides an estimate of the long term average power, and the second, shown in Figure 3.6, provides an estimate of the percentage of time a WECS will operate. Both figures are based on an assumed Rayleigh distribution for hourly mean wind speeds. As a result of the assumed wind speed distribution and variations in WECS designs, actual performance can be expected to vary somewhat from the predictions.

The nondimensional ratios used in the figures add to their flexibility by permitting one set of figures to be used to provide power and operating time estimates for any number of different WECS if the annual mean wind speed is known.

FIGURE 3.5. The Average Output of a Typical Wind Turbine at a Site Where Only the Yearly Averaged Wind Speed is known

FIGURE 3.6. Percent Operating Time for WECS

The figures may also be used to determine desired WECS characteristics for a given site and power application. An example of the use of Figures 3.5 and 3.6 to estimate WECS performance is as follows. Given a site with a 6 m/s (13.4 mph) annual mean wind speed and a WECS with cut in, rated and cut out speeds of 3.1, 9.8 and 16.7 m/s (7, 22 and 37 mph) rated at 4 kW, the following ratios are computed:

$$\frac{V_a}{V_r} = 0.61; \frac{V_{co}}{V_r} = 1.70$$

and

$$\frac{V_{ci}}{V_a} = 0.52; \frac{V_{co}}{V_a} = 2.78$$

where

V_a = annual mean wind speed

V_{ci} = cut in wind speed

V_r = rated wind speed

V_{co} = cut out wind speed

From Figure 3.5 it is seen (follow the dashed line) that the upper two ratios give a power ratio of 0.34. The average power output estimate is then:

$$P = (0.34) (4 \text{ kW}) = 1.36 \text{ kW},$$

and the expected energy output per year is

$$E = (1.36 \text{ kW}) (8766 \text{ hours/yr}) = 11,900 \frac{\text{kW-hr}}{\text{yr}}$$

Using the lower two ratios and Figure 3.6, it is estimated that the WECS will be operating approximately 92% of the time (see dashed lines). From both figures it is apparent that increasing the cut out speed will not increase the expected performance of the WECS.

The two figures may also be used in designing WECS to operate in a given annual mean wind speed regime or to select optimum WECS characteristics for a site with known mean wind speed.

Expected Progress During the Next Period:

The analysis leading to Figures 3.5 and 3.6 will be completed and the final results will be prepared for publication.

Reports and Publications;

The guidelines shown in Figure 3.5 have been incorporated in R. L. Drake, M. M. Orgill and C. Huang, An Interim Handbook for Siting Small Wind Energy Conversion Systems, BNWL-2220 WIND-7, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1977, in review.

Both sets of guidelines will be included in a separate report and will be submitted to the Wind Technology Journal for publication.

3.1.4 Gust Amplitude Estimates (2b)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

J. V. Ramsdell (509) 946-2749

Objective:

To provide estimates of the number of gusts of a given amplitude that will be experienced by a WECS during a given period.

Program Status:

The study of gust amplitudes was begun in May 1977 as one of several programs to analyze existing wind data and present the results in formats usable for WECS design and the development of design criteria. The analysis of gust data collected downwind of large surface roughness elements in Seattle, WA, has been completed and the results are being compiled for review by WECS designers.

In the present context gusts are defined as the periods of departure of the wind speed from the mean speed. The wind is then a succession of gusts. A positive gust begins when the speed increases above the mean and ends when it next falls to the mean. The amplitude of the gust is the maximum difference between the instantaneous and mean speeds. Negative gusts occur when the wind falls below the mean.

Progress During Reporting Period:

Initial data analysis indicated that the number of gusts per kilometer of air passage was inversely related to wind speed. Further examination supported this finding and showed that on the average there were about 1150 positive and negative gusts per hour. This number is independent of wind speed and relatively independent of surface roughness and height above ground.

Analysis of the data showed that the amplitudes of positive gusts were, in general, larger than those of negative gusts. The average number of gusts per hour exceeding a given amplitude is shown in Figure 3.7 for both positive and negative gusts. In Figure 3.7 the gust amplitudes have been normalized to the standard deviation of the wind speed fluctuations. Empirical models developed to fit the data are shown in Figure 3.7.

The number of gusts per hour reaching an amplitude Δu is a function of only Δu and the standard deviation of wind speed fluctuations, σ_u . It is therefore possible to estimate the number of gusts exceeding Δu per year if the annual distribution of σ_u can be determined.

As a first approximation it has been assumed that σ_u is directly proportional to the hourly mean wind speed with the constant of proportionality being a function of terrain roughness. For Seattle the constant of proportionality is about 0.25; for typical WECS installation sites it may be somewhat smaller. This assumption permits the number of gusts/year exceeding Δu to be computed using a wind speed distribution.

The computations described have been carried out for terrain from water to rugged mountains and for sites with annual mean wind speeds ranging from 4 to 14 m/s. The annual distributions of hourly mean wind speeds were assumed to be Rayleigh distributions. (See Section 3.1.1 for a discussion of the use of the Rayleigh distributions for hourly mean speeds.) Typical results are shown in Figure 3.8 for moderately hilly terrain with annual mean wind speeds of 4 to 12 m/s.

Expected Progress During the Next Period:

During the next period of the analysis of wind speed gusts will be completed and documented. The analysis will be extended to examine wind direction shifts using the same data set.

FIGURE 3.7. Number of Gusts per Hour (positive and negative) Exceeding a Given Amplitude

FIGURE 3.8. Estimated Number of Gusts/Year (positive and negative) Exceeding a Given Amplitude as a Function of Annual Mean Wind Speed for Moderately Hilly Terrain

Additional data sets will be evaluated for gust amplitude studies. Analysis of selected data sets will be initiated to determine whether the Seattle results are general or not.

Analysis of gust shapes will be started. Gust amplitude information does not describe the rate of change of wind speed or direction.

Reports and Publications:

None.

3.1.5 Analysis of Wind Shear Fluctuation Data (1c)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

J. V. Ramsdell (509) 946-2749

Objective:

To provide information on the magnitude and frequency of occurrence of wind shear fluctuations for use in Wind Energy Conversion System Design.

Program Status:

The program, which was started in August 1977, is complete. Further development and application of the wind shear fluctuation models will be undertaken as part of a systematic description of temporal and spatial decomposition of the wind vector as applied to WECS.

Progress During Reporting Period:

The data analysis was completed and the interpretation of the preliminary analysis was revised. The following conclusions were reached for component of the wind vector parallel to the mean wind direction:

1. The vertical and lateral shear fluctuations downstream of large roughness elements can be described by a Pearson Type IV distribution.
2. The parameters of the distribution can be predicted by simple relationships involving the mean wind speed and several easily determined physical variables. In general the distribution of the vertical shear fluctuations is positively skewed and more peaked than the Gaussian. These characteristics indicate that the instantaneous vertical shear will be less than the mean shear more than 50% of the time. They also indicate that large positive departures from the mean vertical

shear will occur more frequently than large negative ones. The lateral shear distributions also are skewed, but the skew may be of either sign. Thus large lateral shears can be expected more frequently than if a Gaussian distribution of equal variance is assumed, but their sign cannot be predicted.

3. The time scales for shear fluctuations can be predicted using the mean wind speed and easily evaluated physical parameters. Typical dimensions and operating wind speeds for WECS are associated with shear fluctuation time scales of the order of 1 to 10 δ .
4. Comparison of data for Seattle with those for Cape Kennedy shows very similar results. This similarity provides a basis for hope that "universal" relationships may exist.
5. There is a rather large scatter of data on all relationships. If WECS performance and durability are significantly affected by shear fluctuations additional research is needed.

The results of this program have been submitted to the Journal of Applied Meteorology for publication.

Expected Progress During the Next Period:

The results should be published.

Reports and Publications:

J. V. Ramsdell, "Wind Shear Downwind of Large Surface Roughness Elements," Preprint Volume: Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites. November 16-19, 1976; Melbourne, FL, American Meteorological Society, Boston, MA, p. 22-27.

J. V. Ramsdell, "Wind Shear Fluctuations Downwind of Large Surface Roughness Elements," submitted to Journal of Applied Meteorology.

3.1.6 Wind Flow Through a Vertical Plane (1e)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

M. Gary Verholek (509) 942-0712

Objective:

To produce data on the wind field experienced by a simulated blade of a horizontal-axis turbine.

Program Status:

Data have been taken using an 80-ft diameter circular anemometer array. Preliminary analysis of the data has been performed. The field project is being expanded to include a 160-ft diameter circular array.

Progress During Reporting Period:

Work on Phase I of the field project began in early January. Testing and installation of equipment was completed by the end of February. The tower configuration is depicted in Figure 3.9. After the electronics checkout and evaluation the system was ready by mid-March. Initial data were acquired on March 24, 1977; the final run was on April 14, 1977. Thirty-eight (38) hours of data were taken during which mean winds reached 12 m/s and maximum speeds exceeded 20 m/s.

Some preliminary checkout data analysis has been performed in which we have calculated means and standard deviations, examined maximum and minimum values, calculated auto-correlation and space-correlation coefficients, and developed initial synthetic wind histories (Figure 3.10).

GILL ANEMOMETERS NO. 1-9
TEMPERATURE PROBES NO. 10-12

FIGURE 3.9. Instrument Array for Vertical Plane Field Program (design and performance evaluation)

FIGURE 3.10. Synthetic Wind Field at Blade Radius of 40 ft (RPM = 75)

Expected Progress During the Next Period:

The next 12 months will be used to upgrade the field experiment (Phase II), take additional data and provide more detailed analyses. A new microprocessor will be installed.

Reports and Publications:

To date, there have been no publications or formal reports prepared; however, several will be forthcoming as results of the analysis warrants.

Selected data are stored on 9-track tape and can be made available to other technical organizations for appropriate applications.

3.1.7 WECS Operating Strategy (2b)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

T. C. Kerrigan (509) 942-5038

Objective:

To develop procedures for estimating the efficiencies of WECS operating strategies based on palpable wind statistics.

Program Status:

This program was initiated in mid-January 1977, and will continue through February 1978.

Progress During Reporting Period:

The first product has been a computer program which combines wind velocity data with the particular WECS operating strategy implicit in Figure 3.11 to simulate the WECS performance in the given wind. Statistics about the operation of the WECS in these various modes can then be easily tabulated. Samples of these statistics are given in Tables 3.1 and 3.2 for 6 hours of wind data collected during the field experiments described in Section 3.1.6.

The second product has been a mathematical procedure for summarizing wind velocity data in a tractable analytic form. This form is appropriate for computing the efficiency of WECS operating strategies using the theory of Markov processes.

Expected Progress During the Next Period;

The first product will be generalized for use with a variety of WECS operating strategies. The output from the second product forms the basis for estimating WECS operating efficiencies. The final form will be an expression for operating strategy efficiency based on quantitative measures of gustiness and changeability in wind direction.

Reports and Publications:

None.

*NOTE: NO YAW MANEUVER IN THE SHUTDOWN RANGES

FIGURE 3.11. WECS Control Modes

TABLE 3.1. Distribution of Time Spent in WECS Control Mode(s)

WECS Control Mode	Hour					
	1	2	3	4	5	6
Nonoperating	8	0	0	0	102	907
Normal Operating	1252	1925	1865	2296	1647	1002
Yaw Maneuver	2340	1675	1735	1304	1851	1691
Normal Shutdown	0	0	0	0	0	0
Rapid Shutdown	0	0	0	0	0	0

Hour	Mean Velocity (m/s)	RMS Wind Velocity (m/s)
1	9.1	1.6
2	11.0	1.0
3	10.0	1.0
4	9.7	0.7
5	9.8	2.1
6	5.9	1.2

TABLE 3.2. Number of Times Each WECS Control Mode
Was Occupied

WECS Control Mode	Hour					
	1	2	3	4	5	6
Nonoperating	2	0	0	0	4	15
Normal Operating	48	41	47	55	43	26
Yaw Maneuver	50	41	46	56	45	36
Normal Shutdown	0	0	0	0	0	0
Rapid Shutdown	0	0	0	0	0	0

3.1.8 Assessing the Local Wind Field for Siting of Wind Power Systems (2a)

Contract No.: EY-76 C-06 2441

AeroVironment, Inc.
145 Vista Avenue
Pasadena, CA 91107

Principal Investigator:

J. Worden (213) 449-4392

Contract Monitor:

R. K. Hadlock (509) 946-2961

Objective:

To observe, with dual Doppler acoustic radar systems, the detailed three-dimensional flow to 100 M above ground around complex terrain features in order to establish "meteorologically preferred" sites for wind power systems. Mean profiles will be related to the needs of wind power system designers and evaluators.

Program Status:

This program was initiated in July 1976 and will continue through August 1977.

Progress During Reporting Period:

Work during the past year (July 1, 1976 to June 30, 1977) has been in three general categories: the assembly of a Doppler acoustic radar system (dual array), the laboratory and field testing and calibration of this system, and a measurement program to assess the system performance while sited in complex terrain.

Acoustic enclosures, antennas and drivers, a microcomputer, tape recorder and associated support systems have been integrated into a dual array Doppler acoustic radar system. System buildup and construction was completed prior to December 1976.

Laboratory bench tests were conducted during the several stages of system buildup during November 1976. Installation of the dual system was accomplished at White Sands Missile Range with data acquisition in the period November 30 through December 16, 1976. The system was determined to be operational and reliable in the field; acoustic reflections from the adjacent comparison meteorological tower prevented acquisition of sufficiently accurate data to enable system calibration.

The field calibration, comparison with data obtained from a tethered-balloon profiler, was conducted successfully at Southern California Edison Company's Devers Substation near Palm Springs, California, between February 27 and March 11, 1977. The location essentially coincides with the NASA/ERDA San Geronio site. A formal topical report will be transmitted during July 1977.

Measurements were obtained during June 1977 at a complex terrain site in the mountains near Pasadena at the Tejon Ranch. This location was visited, prior to data acquisition, by BNW and the site was approved as suitable for a program to determine effectiveness of the dual acoustic system as a wind power system siting tool. Approximately 3 weeks of data acquired at this site will form the main basis for discussion and conclusions to be contained in the final report.

Expected Progress During the Next Period:

The work to be accomplished during this period (prior to September 1, 1977) will be solely associated with production of the final report. Reported conclusions will form a basis for consideration of the acoustic technique as a siting tool.

Reports and Publications:

To date, there have been no publications nor formal reports prepared under this contract. However, topical reports on the Devers calibration and the Tejon Ranch measurements will be prepared prior to September 1, 1977.

3.2 SITE SELECTION

In the Introduction, the Program Area entitled Wind Characteristics for WECS Site Selection was related to the extrapolation of existing data for use in identifying favorable wind energy conversion sites. The ranges of time and length scales involved are from a few minutes to a few years and from several hundred kilometers to several meters. The extrapolation tools with the greatest time and length scale versatility are numerical models. Physical models are useful for extrapolation up to a length scale of the order of 10 to 20 km. But, they are limited in time scales to those longer than 2 to 3 weeks, and those less than 1 to 2 hours because of problems in modeling atmospheric stability changes. Geological and biological indicators combined provide information over the full range of length scales, but they have a very limited range of useful time scales, geological indicators of the order of a year and biological indicators of the order of seasons. Finally, siting handbooks provide extrapolation information for both small length and time scales.

Progress in WCPE tasks related most closely to Site Selection is discussed in this Section.

A systematic development of site selection techniques requires the identification and evaluation of historic siting practices. Section 3.2.1 presents the conclusions of a study conducted to provide this information.

Sections 3.2.2 through 3.2.4 discuss progress in the development of siting methodologies using numerical models. The extrapolation tool in the work discussed in Section 3.2.2 is a steady state numerical model, while those used in the tasks discussed in Sections 3.2.3 and 3.2.4 are time-dependent models. In each task statistical techniques are being developed for reduction of the number of computations required.

The final stage in the development of siting methodologies is the comparison of the various tools for extrapolation of wind data. The work described in Sections 3.2.5 and 3.2.6 represents preliminary steps in that direction. Model validation and comparison tests will be used to identify the cost and accuracy of the siting methodologies given a scenario comprised of topography, data availability, and time and monetary constraints. Section 3.2.5 describes

progress in the design of the validation and comparison tests, and Section 3.2.6 describes work done to identify meteorological data sets for use in the tests.

In addition to the development of siting methodologies, the Site Selection Program Area is developing generic wind information for use in siting. Sections 3.2.7 through 3.2.10 describe the generic studies.

The work discussed in Sections 3.2.7 and 3.2.8 involves the use of numerical models to examine the effects of atmospheric stability on flow over mountains and at coastlines, respectively. In Section 3.2.9 the progress of wind tunnel studies examining flow over various terrain features is described. Section 3.2.10 discusses the results of a task in which actual field measurements were made to define empirical relationships between wind speed and direction in boundary layer and the underlying terrain.

There are many potential sources of information on wind speeds and directions that may be of use in WECS siting which do not involve standard meteorological measurements. The work discussed in Sections 3.2.11 and 3.2.12 involves the evaluation of two of these sources. Section 3.2.11 describes the progress in evaluating the usefulness of vegetation deformation, and Section 3.2.12 describes progress in evaluating the use of satellite observation of aeolian features.

To be of value in the development and commercialization of WECS, siting information must be compiled and made generally available in an understandable form. Sections 3.2.13 through 3.2.15 describe the progress in documentation and dissemination of siting information. The work discussed in Section 3.2.13 involves collection, organization and presentation of published information on small scale terrain effects on airflow. The task discussed in Section 3.2.14 involves the preparation of a handbook for siting small WECS, and that in Section 3.2.15 involves preparation of a handbook for siting large WECS. These three tasks distill information from the previously described tasks in the Site Selection Program Area, from other Program Areas within the WCPE, from other elements of the Wind Energy Conversion Program, and from wherever else pertinent information can be found. The products of these tasks are in essence the primary products of the Program Area.

3.2.1 Survey of Historical and Current Site Selection Techniques for the Placement of Small Wind Energy Conversion Systems (3b)

Contract No.: B-36302-A-E

American Wind Energy Association
Ben Wolff, Executive Director
c/o Wind Works
Box 329, Route 3
Mukwonago, WI 53149

Principal Investigator:

Jack Park (916) 675-2478

Contract Monitor:

J. V. Ramsdell (509) 946-2749

Objective:

To compile information on historical and current practices in the selection of sites for installation of small wind energy conversion systems for use in planning in the Wind Energy Conversion Program.

Program Status:

The program is essentially complete. A draft report has been prepared and reviewed. Final revisions are being made in the report.

Progress During Reporting Period:

Results of a survey of individuals with experience with small wind energy conversion systems and a review of literature related to WECS site selection were compiled in a draft report.

The primary findings of the study were:

1. The primary factor in selecting the location for WECS was the application of the power. Locations for water pumping systems were constrained by the availability of water, and locations for electrical generating systems were constrained by proximity to batteries.

2. Historically, when meteorological factors affected the selection of WECS location or tower height, the factors were dealt with on the basis of intuitive understanding based on experience and guidelines supplied by WECS manufacturers.
3. WECS distributors indicated that tower height decisions were often made on the basis of cost, while WECS owners indicated that tower heights were selected to clear obstructions. A widely applied rule of thumb was to select a tower extending 15 to 25 ft above obstructions within a 300 to 500-ft radius.
4. The most frequently cited source of information on site selection was the WECS salesman or dealer.
5. The most frequently cited source of wind information for use in site selection was the National Weather Service. However, it was unclear whether those responding to the survey know: how to obtain information from the National Weather Service, what type of information to request, or how to use pertinent information.

Expected Progress During the Next Period:

The revisions to the final report will be completed, and the report should be published early in the next period.

Reports and Publications:

American Wind Energy Association, Survey of Historical and Current Site Selection Techniques for the Placement of Small Wind Energy Conversion Systems, BNWL-2220 WIND-9, to be published.

3.2.2 Wind Power Studies (5a)

Contract No.: UCRL-50034-76

Lawrence Livermore Laboratory
University of California
Livermore, CA 94550

Principal Investigator:

D. M. Hardy (415) 457-1100, Ext. 3481

Contract Monitor:

R. L. Drake (509) 942-2861

Objective:

To develop and demonstrate a methodology for the assessment of regional wind power in hilly or mountainous areas that are expected to be rich in wind energy. The program is focused, for illustrative purposes, on an area of high potential for early, economically successful development of wind power on a large scale (the Island of Oahu).

Program Status:

This program started at the beginning of FY-76 and is to continue into FY-78. A proven assessment methodology can be achieved in FY-78. Once the methodology has been proved for the Island of Oahu, it will be transferred to other regions. This will be the final step in the development and demonstration of the methodology for the assessment of regional wind power in complex terrain.

Progress During Reporting Period:

A program of field measurements to improve the input data available to the diagnostic model was planned and executed. Automatic wind velocity measuring stations were installed at four remote locations selected for wind-energy purposes. Conventional and space-averaging optical anemometers were used.

Numerical model calculations based on a limited number of historic wind measurements were used to estimate the

three-dimensional velocity field over the topography of the island. Subregions (~10 km in extent) of expected wind enhancement were predicted by these calculations. The field measurements confirmed the presence of a broad spatial area of sustained high wind speeds predicted in the initial numerical calculations.

Operational procedures now in effect provide necessary wind data for numerical analysis. A new series of model calculations based on the field program data has begun.

A principal component analysis of the field program data has also begun. This mathematical procedure was developed to objectively identify predominant wind velocity patterns present in a large set of measured data. It will be used here to define typical tradewind velocity patterns over the island and later to study more anomolous conditions.

Expected Progress During the Next Period:

Concurrent regional and subregional field measurements will be taken and analyzed during the next period. These data will then be used in a validation study of the diagnostic model, in continuing the principal component analysis, and for numerical model and statistical analysis calculations of regional and subregional wind-energy patterns.

Reports and Publications:

The following were prepared during the reporting period:

Hardy, D. M., Wind Power Studies: Field Measurement Priorities for Numerical Analysis of Wind Energy (Progress Report for April through June 1976)

UCRL-50034-76-3, Lawrence Livermore Laboratory, University of California, Livermore, CA 94550, 5 pp., June 1976.

Knox, J. B., D. M. Hardy, C. A. Sherman, T. J. Sullivan, Status Report: Lawrence Livermore Laboratory Wind Energy Studies, UCID-17157-1, June 1976.

Hardy, D. M., Wind Power Studies: Regional Wind Energy Measurements (Progress Report for July through September 1976), UCRL-50034-76-4, Lawrence Livermore Laboratory, University of California, Livermore, CA 94550, 9 pp., November 1976.

Hardy, D. M. and J. J. Walton, "Principal Components Analysis of Vector Wind Measurements," UCRL-78926, December 1976. Prepared for submission to the Journal of Applied Meteorology.

Hardy, D. M., Eigenvector Analysis of Vector Observations, UCRL-79084, January 1977. Submitted for publication of Geophysical Research Letters.

Hardy, D. M., Wind Studies in Complex Terrain, UCLR-79430, May 1977. For presentation at the American Wind Energy Association Conference and Exposition, Boulder, CO, May 11-14, 1977.

The following were prepared prior to the reporting period:

Hardy, D. M., Wind Power Studies: Initial Data and Numerical Calculations (Progress Report for September through December 1975), UCRL-50034-76-1, Lawrence Livermore Laboratory, University of California, Livermore, CA 94550, 39 pp., January 1976.

Hardy, D. M., Wind Power Studies: Initial Regional Applications (Progress Report for January through March 1976), UCRL-50034-76-2, Lawrence Livermore Laboratory, University of California, Livermore, CA 94550, 27 pp., March 1976.

3.2.3 Development of a Wind Energy Site Selection Methodology (5b)

Contract No.: EY-76-C-06-2440

Science Applications, Inc.
1200 Prospect Street
P.O. Box 2351
La Jolla, CA 92038

Principal Investigator:

R. M. Traci (714) 459-0211

Contract Monitor:

R. L. Drake (509) 942-2861

Objective:

To develop and demonstrate a WECS siting methodology for complex terrain. Major elements are the development of mathematical models and analysis techniques. These models and techniques will be validated through the use of field data collected over complex terrain.

Program Status:

The program is in the second year of a 3-year study. The current contract year began in May 1976. The project will be completed in April 1978.

Progress During Reporting Period:

Work to date on a wind energy site selection methodology has concentrated on developing and improving the elements which make up the siting methodology and on systematizing that methodology. The elements include the SIGMET primitive equation mesoscale simulation models, objective analysis (OA) windfield models and collection and reduction procedures for stratifying climatological data. The development and optimization of the SIGMET family (1-D, 2-D, and 3-D versions) of mesoscale meteorology codes are completed. The explicit versions of the SIGMET family and MODMAT have been improved and are now in a production status. The prototype of the models is being used for a preliminary site selection

demonstration. The Yamada-Mellor "level 2-1/2" turbulence formulation has been implemented in the SIGMET family and tested in the 1-D SIGMET code. The use of 1-D model to test the model sensitivity and to obtain the required parameters reduces the computing expense. The information gained from these results will be used to modify the numerical models.

Site screening and field data collection activities are completed. A preliminary methodology demonstration for the region around the Tehachapi Mountains in California has been performed. The Tehachapi site was particularly attractive both because of its wind energy potential and because it has been proposed that aerogenerators could be used to pump aqueduct water over the mountains into the South Coast Basin. The Tehachapi region has a ridgelike structure over which winds from the San Joaquin Valley are funneled.

In wind power evaluation a large volume of meteorological data are needed. Empirical Eigenfunction Expansion (E^3) procedures have been developed to categorize weather patterns and provide a compact data representation. Based on this compacted data, a series of MODMAT simulations (with and without data stratification) will be performed covering a relatively long span of time and selected 3-D SIGMET simulations will be performed.

The numerical simulation of wind field for the Tehachapi Mountain site for a summer and winter day have been performed. Preliminary results show the expected high wind region in the Tehachapi ridge area and in the upper desert.

Model sensitivity studies of the effect on diurnal simulations of surface boundary conditions (surface roughness, soil conductivity and moisture content, albedo, etc.) and of the accuracy of input data are being completed. In order to increase model efficiency, a gravity wave implicitization scheme is being developed.

Significant numerical improvements have recently been effected by code streamlining, boundary condition improvement and optimized relaxation. Test calculations indicate a factor-of-5 improvement in code efficiency has resulted from these activities. The model "fine tuning" is being done by comparing SIGMET and OA calculations and by comparing computed results with wind tunnel test data (Meroney, 1976).

For wind energy siting, it is necessary to obtain wind energy potential for a given region over a period of at least a year. One way of obtaining this data would be to run an objective windfield model twice a day for each day of the entire year. Even for comparatively simple models the expense could be prohibitive. An alternative is to perform an E^3 analysis on observed wind data to obtain the set of associated eigenvectors. By retaining only those eigenvectors contributing to the largest variance and using them, rather than the observational data, as initial conditions to objective windfield models, considerable computational time can be saved. The accuracy of the approach is being examined by comparing windfields calculated using E^3 analysis with the original observational windfield data.

Expected Progress During the Next Period:

The proposed third-year effort will complete model optimization as well as verify and demonstrate the overall siting methodology. A technology transfer program may also be initiated.

Reports and Publications:

The following publications or reports were written under the present project:

Freeman, B. D. and J. R. Taft, "Mathematical Modeling of Topographical Effects on Wind Energy Systems."
Presented at the International Symposium on Wind Energy Systems, held at Cambridge, England, on September 7-9, 1976.

Freeman, B. E., "Development of a Wind Energy Site
Selection Methodology," RLO/2440-76/4, Sci. Appl. Inc.,
La Jolla, CA 92038, December 1976.

3.2.4 Technique for Optimally Locating Wind Energy Systems Based on Predicted Wind Statistics (5c)

Contract No.: EY-76-C-06-2445

Research Triangle Institute
Geosciences Department
Research Triangle Park, NC 27711

Principal Investigator:

F. M. Vukovich (919) 541-6946, Ext. 2657

Contract Monitor:

L. L. Wendell (509) 942-6677

Objective:

To determine the feasibility of using historical wind data from a synoptic weather station, together with simulated wind fields in the vicinity of that station to predict the wind distribution at nearby locations where wind data are not available.

Program Status:

The present contract began on September 20, 1976, and was to continue until September 20, 1977. The work started during the previous year with NSF funding. A no-cost extension on this year's contract will continue the work period until December 20, 1977. A decision to continue work in the development of this technique will be based on the final results of the current efforts.

Progress During Reporting Period:

One of the major accomplishments during this reporting period was to successfully complete the primitive equation model exercises to produce the simulated winds and organize them on a tape for use by the statistical model. Also completed was the development of a statistical model to relate the winds at Lambert Field in St. Louis, Missouri to winds at the selected Regional Air Pollution Study (RAPS) meteorological and air pollution observation stations. It was found that adding

higher order terms to the linear model increased the correlation between the wind speed and direction at Lambert Field and that at any one of the selected RAPS stations from 97% to 99.5%. The 2.5% increase was considered important enough to adopt the higher order model.

Coefficients for the statistical model were generated and the model was applied to 1 year (1976) of wind data from Lambert Field to produce 1 year of predicted wind data at each of the five RAPS sites. Mean observed and predicted wind speeds, observed and predicted power levels, and the correlation coefficients between observed and predicted winds are shown for three of the RAPS stations in Table 3.3. Probably the most striking feature of this table is the 60% over-prediction of power at Station 119. Power at Stations 105 and 106 is under-predicted by 3.5% and 18%, respectively. It is interesting to note that the correlation coefficient for observed and predicted wind speed was higher for the worst power prediction than for the best power prediction. This indicates that use of the correlation coefficient alone should be viewed with caution.

One of the possible causes of the discrepancies between the observed and predicted mean winds and power levels is attributed to different sampling methods at Lambert Field and the RAPS stations. The Lambert Field data are 1-min average readings recorded once every 3 hours. The RAPS data, used in this study, are 1-hour average observations every 3 hours. The suspicion is that the hour averaging tends to produce lower readings in general. This has been shown to be the case in a PNL study, but the discrepancy in the resulting power prediction is only of the order of 10%. (Section 3.3.4 of this report and Section 3.19 of the WCPE Semi-Annual Report describe the PNL study.)

TABLE 3.3. Comparison of Predicted and Observed Quantities
Pertinent to Wind Energy Conversion for Three
RAPS Stations

<u>RAPS Station Number</u>	<u>$\bar{w}$ (m/s)</u>	<u>$\hat{w}$ (m/s)</u>	<u>$\bar{w} - \hat{w}$ (m/s)</u>	<u>RMS Error (m/s)</u>	<u>OBS Power</u>	<u>Predicted Power</u>	<u>R</u>	<u>Average Bias (m/s)</u>
105	4.06	3.90	0.16	1.33	115	111	0.77	0.3
119	3.54	4.18	-0.64	1.44	81	130	0.79	0.7
106	3.72	3.33	0.39	1.12	88	72	0.82	0.1

$\bar{w}$ = mean observed wind speed

$\hat{w}$ = mean predicted wind speed

R = correlation coefficient between observed and predicted
wind speed (a measure of the clustering about a straight
line)

Avg. Bias = the approximate amount the line departed from the origin.

Expected Progress During the Next Period:

The effect of the sampling and averaging differences will be carefully examined in the context of this study. For at least one RAPS station, three hourly, 1-min observations will be obtained for the year 1976. Mean wind speeds, power and frequency distributions will be constructed and compared to those parameters derived from the hourly averaged data.

Wind speed and power predictions will be made based on 10 years of data at Lambert Field. The predicted power will be examined in light of the large data base since it is expected, as a result of previous work, that this will be a better estimate.

The results of this study will be critically examined to determine the advisability of pursuing this technique.

Reports and Publications:

No formal publications or reports have been released under the current contract. A semiannual report has been prepared and is listed below:

Vukovich, F. M., Techniques for Optimally Locating Wind Energy Systems Based on Wind Statistics, Semi-Annual Report under ERDA Contract No. ERDA (45-1)-2445, Research Triangle Institute, April 1977.

3.2.5 Model Validation and Comparison*

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

Thomas C. Kerrigan (509) 942-5038

Objective:

To develop a family of statistics to be used to determine the accuracy with which computer models predict mesoscale wind fields.

Program Status

This program was initiated in early December 1976, and will continue through May 1978.

Progress During Reporting Period:

An analysis based on statistical decision theory has been undertaken. The progress to date has been the development of a computer program which assigns a probability distribution for wind velocity to each point in a modeled region. The assignment is based on actual field data and parameters which embody specific terrain features. The wind field generated by a computer model will then be analyzed by using these probability distributions as the basis for a maximum likelihood test.

Expected Progress During the Next Period:

The analysis will be generalized to account for the time dependence of the wind data, the maximum likelihood test will be constructed and a procedure for parameterizing terrain features based on the field data will be explicated. This work will appear as a Battelle report.

Reports and Publications:

None.

*Planned to start in FY-1978 but initiated early as a result of the November workshop on the role of modeling in site selection.

3.2.6 Survey of Existing Meteorological Data Sets for Model Validation (5j)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

M. M. Orgill (509) 942-3341

Objective:

To identify and describe existing meteorological data sets that might be used for validation of various wind models within the Wind Energy Conversion Program.

Program Status:

This program was initiated in June 1976 and is complete.

Progress During Reporting Period:

A total of 139 existing micro- and meso-scale meteorological sets have been identified that are potentially useful in the wind energy conversion program. Specific details about the data sets have been compiled in tabular form by state. These details include descriptions of the topographical setting of the measurement site, the data collected and the organization or individual to contact for further information about the data set.

The results of the survey have been published as a Battelle, Pacific Northwest Laboratories report.

Expected Progress During the Next Period:

None, program complete.

Reports and Publications:

Orgill, M. M., Survey of Wind Measurement Field Programs, BNWL-2220 WIND-3, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, May 1977, 53 pp.

3.2.7 The Effect of Atmospheric Density Stratification on Wind-Turbine Siting (5d)

Contract No.: EY-76-C-06-2443

Poseidon Research
11777 San Vincente Blvd.
Suite 641
Los Angeles, CA 90049

Principal Investigator:
S. C. Crow (508) 826-5543

Contract Monitor:
R. L. Drake (509) 942-2861

Objective:

To study the effect of atmospheric density stratification on wind turbine siting through the use of a simple and accurate method for computing the locations of maximum wind velocity over a given terrain feature. Areas with adverse pressure gradients, which are expected to be poor wind turbine sites, are also to be identified.

Program Status:

The program is a 1-year effort that was initiated in September 1976. The work is divided into six tasks; the first four have been completed, and a fifth has been started.

Progress During Reporting Period:

One- and two-layer models are being used to investigate the air flow over two- and three-dimensional mountains. The models are mass-conserving systems of the basic hydrodynamic equations. The method of Fourier integrals is employed to solve the equations; Fast-Fourier transformation is used to evaluate the integrals.

During the reporting period, tasks on atmospheric modeling, two-dimensional computations, theory of air flow over three-dimensional mountains, and a code for three-dimensional computations have been completed.

For flow over a two-dimensional mountain in neutral atmospheric conditions, a wind speed maximum is located at the peak of the mountain. During stable atmospheric conditions, the wind speed maximum moves to the lee side of the mountain. Preliminary computations of flow over three-dimensional mountains also show the wind speed maximum displaced from the mountain peaks for stable atmospheric conditions.

Expected Progress During the Next Period:

During the remaining portion of the contract, computation of wind fields and development of separation criteria for the identification of adverse wind areas will be completed.

Reports and Publications:

Agopian, K. G. and S. C. Crow, The Effect of Atmospheric Density Stratification on Wind Turbine Siting, draft Progress Report for the period October 1976 through March 1977.
Poseidon Research, Los Angeles, CA, 83 pp.

3.2.8 Coastal Zone Wind Energy (5e)

Contract No.: EY-76-S-06-2344

University of Virginia
Dept. of Environmental Sciences
Charlottesville, VA 22903

Principal Investigator:

M. Garstang (804) 977-3733

Contract Monitor:

R. L. Drake (509) 942-2861

Objective:

To evaluate near surface winds in coastal zones for wind energy potential utilizing a sea breeze mesoscale circulation model. The effects of land/sea temperature differences, the large scale velocity field and surface roughness will be explored as they vary along the coastal zones from Mexico to New England.

Program Status:

This program was initiated in September 1976 and will continue through August 1977. A second year program is currently under consideration.

Progress During Reporting Period:

The coastline from New England to Mexico has been subdivided, on a climatological basis, into five coastal regions for separate wind energy potential evaluation. The wind variability over a year is considered in separate time periods, which are established for the regions on the basis of atmospheric circulation patterns and the temperature regimes of land and water.

Meteorological data for both the modeling analyses and statistical analyses have been acquired and compiled. These consist of the following:

1. High frequency wind measurements from NASA Wallops Flight Facilities towers from the surface to 300 ft at 50 ft intervals.
2. Medium frequency wind measurements from NASA Wallops 10 m towers (island and mainland) for 1 year at 5-min intervals.
3. Low frequency wind measurements from 50 coastal stations together with surface meteorological variables.
4. Complete Coast Guard station and ocean station data.

Preliminary analysis of the Coast Guard station data has begun to delineate annual cycles and regional differences. Calculation of power duration curves and preliminary wind power calculations for a typical WECS have begun. The coastal climatology for wind energy consideration is nearing completion.

In the modeling area, a two-dimensional model has been tested and is now operational, which produces predictions of wind distribution as a function of height (first 100 m) and distance from shore (1 km landward and seaward). The locations of maximum wind energy are easily identified in resulting predicted fields. Verification of the results with available data is the next order of business. Sensitivity testing will be performed before the full-scale model predictions are carried out.

Expected Progress During the Next Period:

The major accomplishments for this project will include:
1) detailed climatology of the East and Gulf Coasts based on more than 50 stations for a period of 10 years. This climatology will be tailored for the purpose of coastal wind power evaluations; 2) annual power curves and power predictions for a typical WECS in each of the coastal regions will be completed.

Additionally, results from the 2-D numerical model will provide estimates of the wind speed distribution as a function of height and distance (+ and -) from the shore for limited conditions and locations. Spectral analyses of wind speed and direction covering all but the highest frequencies (2 sec^{-1}) will be completed for one location (Wallops Island, VA). Estimates of the contribution of the gustiness of the wind to the power duration curve will also be made.

Reports and Publications:

To date, there have been no publications or formal reports prepared under this contract. However, the two publications listed below describe the 3-D mesoscale model being used in this study:

Mahrer, Y. and R. A. Pielke, "Numerical Simulation of the Airflow over Barbados," Monthly Weather Review, (104(11)), 1392-1402, 1976.

Pielke, R. A. and Y. Mahrer, Verification Analysis of a Three-Dimensional Mesoscale Model Prediction Over South Florida for July 1, 1973, Rep. No. UVA-ENV SCI-MESO-1976-1, Dept. of Environ. Sci., University of Virginia, Charlottesville, VA 22903, December 1976.

3.2.9 Sites for Wind Power Installations (5g)

Contract No.: EY-76-S-06-2438

Colorado State University
Department of Civil Engineering
Fort Collins, CO 80523

Principal Investigators:

R. N. Meroney (303) 491-8572*

V. A. Sandborn (303) 491-8551

Contract Monitor:

R. L. Drake (509) 942-2861

Objective:

To verify wind tunnel techniques for determining the influence of topography and to examine the influence of topographic profile, surface roughness, insolation and stratification.

Program Status:

This program was initiated in June 1975 and will continue through May 1978.

Progress During Reporting Period:

A laboratory wind tunnel is being used to study air flow over various terrain features for the purpose of locating optimum sites which have high wind speeds and low turbulence. The study assesses the effects of surface roughness, solar heating of the ground, vertical temperature structure, and stratification, and upstream velocity on the wind characteristics at potential sites for wind systems.

During the first part of this reporting period, the data collected from measurements of wind speed, static pressure variation, and turbulence intensity over two-dimensional triangular, Gaussian, and sinusoidal-shaped hills were analyzed and organized in tabular and graphical forms. A description

*Prof. Meroney is in New Zeland from July through December 1977, Prof. Sandborn is acting as principal investigator.

of the data reduction activity and some of the features of the analyses is given in the PNL semi-annual report for April through December 1976. Progress during the last part of the reporting period is as follows:

1. Measurements of velocities, pressure distributions, turbulent intensities, and temperature fluctuations for stratified flow over several types of ridges have been completed. Velocities of 10, 20 and 30 ft-sec⁻¹ for constant temperature flow have been used. Three different triangular hills, with 1/3, 1/4, and 1/6 slopes have been tested.
2. Measurements on five different types of hills, using the same flow parameters for each, have been completed. These tests were designed to examine the shape effect of hills, and included triangular, ramp, complex ramp with a flat top, and escarpment features. Results of these tests show that the fractional speedup of flow along hills with slopes less than 1/3 or 1/4 is essentially the same regardless of the shape of the hill.
3. A report is in preparation reviewing the turbulence data, shear stresses, correlations, and spectra for the different tests.

Expected Progress During the Next Period:

During the next period, data will be collected on three-dimensional conical-shaped hills using 1/2 sin and Gaussian slopes for neutral and stratified flow. A field site is being selected for validation of the model flow measurements. Several sets of data, including those summarized by Orgill,* are currently being examined to make the selection. Validation of the flow measurements made on the three-dimensional hill with actual field data will be completed by Spring, 1978.

*Orgill, M. M., Survey of Wind Measurement Field Programs, BNWL-2220 WIND-3, Battelle, Pacific Northwest Laboratories, Richland, WA 99352.

Reports and Publications:

Reports and publications during the reporting period are given below:

Meroney, R. N., V. A. Sanborn, R. J. B. Bouwmeester, and M. A. Rider, Sites for Wind Power Installations: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence, Rep. No. ERDA/NSF-00702/75/T1, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523, 80 pp., July 1976.

Meroney, R. N., V. A. Sanborn, R. J. B. Bouwmeester, and M. A. Rider, "Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence," Paper A6 at the Intern. Sym. on Wind Energy Systems, held at St. John's College, Cambridge, England, September 7-9, 1976.

Meroney, R. N., V. A. Sanborn, R. J. B. Bouwmeester, and M. A. Rider, Sites for Wind Power Installations: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence - Tabulated Data, Rep. No. ERDA/Y-S-06-2438/76/1, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523, 57 pp., December 1976.

Meroney, R. N., Wind in the Perturbed Environment; Its Influence on WECS, Presented at the AWEA Spring Conference, May 11-14, 1977, Boulder, CO.

3.2.10 Measurement of Air Flow in Valleys (5h)

Contract No.: NSF AER 75-00619

School of Meteorology
University of Oklahoma
Norman, OK 73019

Principal Investigator:
Claude E. Duchon

Contract Monitor:
T. W. Horst (509) 942-2861

Objective:

To find empirical relationships of the wind speed and wind direction in the atmospheric boundary layer to the underlying terrain.

Program Status:

The contract, which began in August 1975 and received a 6-month no-cost extension, expired in January 1977. Research has been completed and a draft of the final report is being reviewed.

Progress During the Reporting Period:

Research activities under this contract consisted of selection of a field site, wind measurements, data analysis and documentation of results in a final report. The field measurements of wind speed and direction were made at a height of about 8 m at three locations along a transect through a divide - streambed system in central Oklahoma. The field operations ran from early September 1975 through January 1976. Of the 1272 hours of data collected, 277 hours (22%) were analyzed for the final report.

The data were used to investigate two main topics. The first topic was empirical relationships between wind speed and direction in the boundary layer and the underlying

terrain at the field site. The report states that the air flow near the surface responds to the underlying terrain, on the whole, in a systematic way that is consistent with physical understanding. In the case of airflow parallel to and up the streambed, the speed at mid-slope was typically higher than that at the divide. Apart from this case, the wind speed decreased almost linearly with distance down the slope from the divide, although there is considerable scatter among the individual hourly averages.

The report also states that the annual wind energy potential is highest at the divide and least at the streambed, regardless of wind direction. However, the mid-slope location has only 10% less energy than the divide; the streambed location exhibited a 30% deficit when compared with the divide.

The second topic examined was the development of a method to relate wind measurements collected over a short period at a remote site to routine measurements over a long period at another location. The method uses linear regression techniques to suggest that, in general, short-term simultaneous measurements are sufficient to determine the wind climatology at the remote site, as long as the records reflect exposure to the same synoptic regime and the length of record includes winds from all directions.

Both areas of discussion need more rigorous verification.

Expected Progress During the Next Period:

Review of report for possible publication and/or further research.

Reports and Publications:

Duchon, Claude E., Measurement and Analysis of Wind Flow in Complex Terrain with Application to Siting of WECS, Draft Final Report No. ERDA/NSF-00619/75/1 UC-60, University of Oklahoma, Norman, OK, May 1977.

3.2.11 Vegetation as an Indicator of Wind Velocities (4a)

Contract No.: E(45-1)-2227

Oregon State University
Department of Atmospheric Sciences
Corvallis, Oregon 97331

Principal Investigator:

E. Wendell Hewson (503) 754-4557

Contract Monitor:

R. L. Drake (509) 942-2861

Objective:

To calibrate the type and degree of deformation of vegetation in terms of the mean wind velocity as an indicator of high wind energy. Flagged crowns of conifers in the region of the Columbia Gorge and the depth of salal at the Oregon Coast are being studied and related to wind direction, wind speed, and wind speed duration measurements.

Program Status:

This program was initiated in June 1976 and will continue through February 1978.

Progress During Reporting Period:

Work during the first year has been divided into two geographical study areas: the Columbia Gorge and the Oregon Coast.

Three study sites within the Columbia Gorge have been chosen. At Crown Point, near Lyle in the western portion of the Gorge, historical wind records have been analyzed and show that strong east to northeast winds occur over 60% of the time from November through February. The monthly average wind speed during these cold air outbreaks varies from 25 mph in November to nearly 32 mph in January. The "natural pruning" of the limbs and tops of the exposed trees in the area is extensive. A recording anemometer has been

installed within the site to acquire more detailed wind information to establish a correlation with the nearby historical data.

At Augspurgen Mountain, a 3000 ft ridge located near the center of the Columbia Gorge, a recording anemometer installed since May 1975 shows a mean wind speed of 15.7 mph. Numerous flagged trees are present along the west slope and crest of the ridge. Moderate west winds prevail during the growing season from March through August. An anemometer, camera mounts, and scale poles have been installed within the site to further study the wind flow near the flagged vegetation.

At the Dalles, near the Eastern end of the Columbia Gorge, an anemometer was located on a 25 ft mast in a pasture adjacent to several well-flagged Ponderosa Pine trees in November 1976. Camera mounts and scale poles were also installed in the site. Long-term wind records (1948-1954) from the airport at Dallesport indicate that persistent moderate west winds occur during much of the growing season.

The results of the studies in the Columbia Gorge show that the deformation of trees at Lyle is a "Type 2," i.e., the trunk is vertical, but branches on the windward side of the tree are severed by the effects of winter winds carrying snow or frozen rain. At Lyle the trees are more sparsely distributed and thus are more subject to wind stress. The trunks of many of the trees are leaning away from the wind. The deformation of branches at this site is less pronounced than at the other two sites. The trees at Augspurgen seem to be affected primarily by Type 1 deformation, i.e., the trunk is vertical but the branches are bent drastically to the leeward of the tree by the prevailing winds during their growing period.

For the coastal studies, an experimental site has been installed at Yaquina Head about 20 m northwest of a 30 m meteorological tower. The experiment consists of comparing the growth of salal between obstructed and unobstructed wind regimes. Anemometry is located at the test and control sites to relate the growth to wind speed. To monitor the growth during the growing season, growth stakes were placed near each anemometer and three stakes were placed around the site to mark locations from which photographs will be taken during the growing season (April through September). A second similar experiment is conducted in a clump of salal exposed to both northerly and southerly winds. Three branches will be selected from a plant near each anemometer and marked with a plastic flag. New shoots on each branch will be counted and measured. The plants in the unscreened environment are likely to have fewer or shorter shoots than plants screened from the wind.

A Workshop on Biological Wind Prospecting was attended by the investigators in August 1976. The topics discussed were directly related to the goals of this study and were a valuable contribution to this year's research efforts by providing both new ideas and reinforcing the original concept of using vegetation as an indicator of wind speed. In addition, techniques are now being developed to analyze tree rings to determine wind history.

Expected Progress During the Next Period:

At the three sites in the Columbia Gorge, more data will be collected with the newly installed anemometry to obtain better correlation with the historical wind data, and to obtain more accurate descriptions of the wind flow near the deformed vegetation. At Augspurger and Lyle, photographs will be taken monthly during the spring season to correlate tree deformation to wind speed. As more information about the seasonal variation of wind speed at the sites becomes

available, better correlation of the degree of flagging with wind velocity will become possible. This will result in further refinement of classifying the type of deformation observed at the sites, and allow the use of other indices such as the deformation ratios, the eccentricity, the compression ratio of tree rings between windward and leeward sides, the circumference to height ratio, and the Griggs-Putnam Scale on degree of deformation, to be applied to the deformed vegetation in the Columbia Gorge.

As data from the experimental site at Yaquina Head become available after the end of the 1977 growing season, it will be possible to define the effect the average wind speed has on the growth of salal in a coastal environment.

Reports and Publications:

Hewson, E. W., R. W. Baker, and J. Wade, Vegetation as an Indicator of Wind Velocities, Annual Progress Report RLO-2227-T24-1, Oregon State University, Corvallis, OR 97331.

3.2.12 Satellite Observations of Aeolian Features (4b)

Contract No.: EY-76-S-06-2343

University of Wyoming
Department of Geology
Laramie, WY 82071

Principal Investigator:

R. W. Marrs (307) 766-2330

Contract Monitor:

D. S. Renne (509) 942-6717

Objective:

To develop an efficient way to identify high wind energy sites by inferring wind characteristics from aeolian geomorphologic features mapped from LANDSAT imagery. Aeolian features, including dunes, playa lakes, and deflation hollows, in central Wyoming are used as a test area. Larger-scale applicability of the techniques will be determined from satellite imagery for other areas.

Program Status:

This program was initiated in September 1976 and will continue through October 1977.

Progress During Reporting Period:

Work during the reporting period has been divided into three tasks: 1) determining the utility of stabilized aeolian features as indicators of present-day wind characteristics, 2) developing techniques for quantitatively estimating wind characteristics from the aeolian features, and 3) assessing the regional applicability of LANDSAT imagery for locating areas of high wind energy potential.

The purpose of Task 1 is to determine if stabilized aeolian features can be used to estimate wind characteristics as well as active aeolian features. The initial work on this task has involved mapping and sampling active and stabilized

dunes in the central Wyoming area including the Seminoe and Killpecker dunes. A map of the study area is given in Figure 3.12. The dunes and surface lithologies were mapped from 1973 aerial photographs and the maps were field checked in conjunction with a sand-sampling program. Trenches were cut in some dunes to determine primary internal structure, and notes were kept regarding moisture conditions and vegetation at all sample sites. However, the trenching produced little data for comparison because most of the primary, internal structures of the stabilized dunes have been destroyed by roots and burrowing animals. Sand grain samples collected from depths of 20 cm and 100 cm beneath the surface indicate that the major source of sand in the Seminoe dunes is the Battle Springs Arkose which crops out 6 miles to the west of the dune field. No major sedimentological differences have been noted between the samples from the stabilized dunes and the active dunes, which suggests a similar source for both.

The purpose of Task 2 is to quantify the wind energy associated with aeolian features observed from aerial and satellite imagery. Aircraft measurements of the three-dimensional wind field at the Killpecker and Seminoe test areas confirm directions of flow and relative velocities inferred from the satellite images of the dunes. These observations demonstrated the possibility for detecting areas of persistent high winds through interpretation of satellite imagery. More recent work has attempted to find a means for deriving quantitative estimates of wind-energy potential through careful observation of selected characteristics of dune fields and of active dunes. No relationships have been determined. At this time it is concluded that either the size and shape of dunes are entirely wind independent or the winds are essentially uniform throughout the test area. An examination of dune spacing has resulted in the hypothesis that the wind flow is helical, with undulations due to gravity waves. This

FIGURE 3.12. Index Map of Wyoming Showing Locations of Major Test Areas

hypothesis will be tested by further examination of the aircraft data. The aircraft data show that the regional wind patterns are influenced quite strongly by topographic features.

The purpose of Task 3 is to determine the applicability of LANDSAT imagery to location of areas of high wind energy potential by examination of aeolian features in other regions of the country. Forty color-composite images of seven test areas outside the state of Wyoming have been examined, and preliminary results show that recognizable aeolian features are present in most of the scenes. These features should be interpretable in terms of wind characteristics.

Expected Progress During the Next Period:

During the remainder of the contract period, radiocarbon dating of bison bone and wood fragments collected from subsurface sand layers will be completed under Task 1. The dates obtained will allow estimation of the approximate rate of sand accretion in the sampled area. These estimates, together with comparisons of new and old aerial photography, will provide a determination of the rate of development and migration of the dunes, so that relationships between stabilized and active dunes can be established.

Under Task 2, the aircraft data analysis will be completed. Local wind patterns will be correlated with terrain features and thermal conditions. Various methods will be used to seek relationships between sand movement and wind speed. Aircraft data will be examined to determine if gravity waves can be related to dune spacing so that wind speed could be inferred from these characteristics. In addition, the hypotheses that the dimensions of alkaline plumes downwind of playa lakes and the spacing between playa lakes are directly related to wind speed will be evaluated. This will be done by a synthesis of the aircraft data, playa lake spacing, observed

gravity wave characteristics, and theoretical models. In addition, the aircraft data will be examined to determine if relationships exist between wind speed and the characteristics of deflation hollows.

Under Task 3, a detailed examination of the 40 scenes of LANDSAT images from 7 areas where aeolian features have been identified will be completed. This information, together with the results of the investigations relating wind speeds to observed aeolian features, will be assembled to produce a wind speed atlas for these regions.

Reports and Publications:

Marrs, R. W., K. E. Kolm, D. R. Gaylord, J. Marwitz, and P. Dawson, Locating Areas of High Wind-Energy Potential by Remote Observation of Aeolian Geomorphology and Topography, Technical Report, March 1976 through February 1977, RLO/2343/77/1, University of Wyoming, Laramie, WY 82071, May 1977.

3.2.13 Technology Development for Assessment of Small-Scale Terrain Effects on Available Wind Energy (5f)

Contract No.: EY-76-C-06-2443

FWG Associates, Inc.
R. R. 3, Box 201-B
Tullahoma, TN 37388

Principal Investigator:

Walter Frost (615) 455-1982

Contract Monitor:

T. W. Horst (509) 942-2861

Objective:

To develop the technology for siting wind energy machines relative to small-scale terrain features (i.e. a mountain, valley, etc.) contained within a region selected for wind energy utilization and to develop techniques for wind energy enhancement based on microscale site modification.

Program Status:

This is a 3-year program: the initial 12-month period began in August 1976.

Progress During Reporting Period:

A primary product of this project will be a Design Manual describing the effects of terrain features located upwind of a wind turbine on the wind field at the turbine site. During the first year the effects of flat and two-dimensional microscale terrain features are being assessed. Step-by-step procedures have been developed for calculating the wind field modifications due to single and multiple surface roughness changes and due to a shelterbelt. These have been incorporated into Manual chapters which are specifically designed to assist in maximizing wind turbine output as a function of turbine locations relative to the terrain features.

A sample chapter of the Manual has been prepared and is currently being reviewed for form and content.

Expected Progress During the Next Period:

Work is in progress on the assessment of the effects of multiple shelterbelts, two-dimensional bluff bodies, two-dimensional linearly sloping contours, and two-dimensional smooth contours. Step-by-step procedures will be developed for siting in relation to these terrain features and they will be similarly incorporated into chapters of the Manual. Further, a separate report will be written to define the experimental requirements for measurement of wind energy at a given site.

During the second year of the study the Design Manual and the measurement requirements will be extended to include three-dimensional smooth and bluff-like terrain irregularities. In addition, techniques will be developed for wind energy enhancement based on micro-scale terrain and site modifications.

Publications:

None.

3.2.14 Siting Handbooks for Small WECS (8a)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

R. L. Drake (509) 942-2861

Objective:

To supply data and techniques that can be used to make preliminary assessments, estimates and decisions concerning the use and proper siting of small WECS; to list the sources of data that may prove useful in the siting process; and to outline the ongoing research projects that will contribute to the siting process.

Program Status:

This is a 4-year program; the initial 12-month period began in June 1976.

Progress During Reporting Period:

The primary product of this program will be a Siting Handbook along with supporting documents. These documents will be used to guide potential users of WECS to site wind turbines in the most efficient manner, while minimizing the hazards that will be encountered by the turbines. During the current reporting period the first draft of an interim siting handbook has been prepared. It is currently being reviewed. The Table of Contents of the handbook are included hereafter.

Expected Progress During the Next Period:

The draft of the interim handbook will be revised and published. The first draft of an annual update of the Siting Handbook will be submitted for review in June 1978.

Reports and Publications:

Drake, R. L., M. M. Orgill, and C. Huang, An Interim Handbook for Siting Small Wind Energy Conversion Systems, BNWL-2220 WIND-7, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 323 pp, in review.

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3.2.15 Siting Handbooks for Large WECS (8b)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

R. L. Drake (509) 942-2861

Objective:

To supply data and techniques that can be used to make preliminary assessments, estimates and decisions concerning the use and proper siting of large WECS and farms of small WECS; to list the sources of data that may prove useful in the siting process; and to outline the ongoing research projects that will contribute to the siting process.

Program Status:

This is a 4-year program; the initial 12-month period began in June 1976.

Progress During Reporting Period:

The primary product of this program will be a Siting Handbook along with supporting documents. These documents will be used to guide potential users of WECS to site wind turbines in the most efficient manner, while minimizing the hazards that will be encountered by the turbines. During the current reporting period a draft of the first interim siting handbook has been prepared. The Table of Contents of this handbook are included hereafter.

Expected Progress During the Next Period:

The interim handbook will be revised and published. The first draft of an annual update of the Siting Handbook will be submitted for review in June 1978.

Reports and Publications:

Orgill, M. M., C. Huang, and R. L. Drake, An Interim Handbook for Siting Large Wind Energy Conversion Systems, BNWL-2220 WIND-8, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 447 pp, in review.

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3.3 PRESITING EVALUATION

It will be remembered that the Presiting Evaluation Program Area is concerned with providing wind information for national and regional energy policy planning and for preliminary planning for specific applications. It relies, in general, on available data, and it is intended to give an overview of wind energy potential rather than to identify sharply defined, small-scale regions of high potential.

Three studies conducted prior to the formation of the WCPE prepared National Wind Energy Assessments which gave pictures of the national distribution of wind energy and estimates of its magnitude. The pictures were not entirely consistent. Section 3.3.1 describes the progress in preparing a synthesis of the three National Assessments.

A conclusion reached in the Synthesis of National Assessments was that refinement of the National Assessments could be best accomplished through regional wind energy evaluations. Section 3.3.2 discusses the preparation for a prototype regional evaluation to establish criteria for following regional evaluations. Sections 3.2.3 and 3.3.4 describe progress in studies of wind energy in Alaska and Hawaii, respectively. These studies will contribute to regional evaluations in their areas.

The three National Assessments and the synthesis deal almost exclusively with annual and seasonal averages of available wind energy. The regional evaluations will increase the scope of the available information to include estimates of extractable power based on current WECS designs and of other wind characteristics of interest in planning. This expansion will be based in part on the results of other studies in the Presiting Evaluation Program Area that are examining specific aspects of wind energy.

Wind energy potential described in the National Assessments is based on averaged data from individual locations. Time and spatial variations in the energy potential are therefore lost. Section 3.3.5 describes the progress in a study of large arrays of WECS which is examining the effect of these variations on average power output and the reliability of the wind as a power source. Section 3.3.6 describes the progress in a complementary study which is attempting to develop statistical models for wind characteristics at specific sites.

Tasks discussed in Sections 3.3.7 and 3.3.8 also provide supplementary information for use in the regional evaluations. The work described in Section 3.3.7 is exploring the errors introduced into wind power estimates by various observational and summarization techniques commonly used with wind data. The work discussed in Section 3.3.8 is concerned with errors introduced in wind statistics due to changes in instrument position. It is also concerned with long-term (year-to-year) variations in the wind energy potential at a given site.

The final two tasks discussed have as their goals the expansion of the number of existing data set available for use in wind energy studies. Section 3.3.9 discusses the progress in preparation of an index to the summarized wind data available from the National Climatic Center, and Section 3.3.10 describes the summarization of wind data collected at nuclear power plant sites throughout the United States.

3.3.1 Synthesis of National Wind Assessments (9a)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator

Dennis L. Elliott (509) 942-5040

Objective:

To perform a synthesis of existing national wind energy assessments to develop an improved, consistent assessment of the geographical distribution of the available wind power over the United States.

Program Status:

The synthesis of existing national wind energy assessments is complete and a report covering the work has been published.

Progress During Reporting Period:

Three previous national wind energy assessments were reviewed and discrepancies were found, among them the estimated magnitude and geographical distribution of wind power. Information used in the three assessments, supplemented by data from selected additional sources, has been used to prepare a synthesized national assessment.

The refined analysis of the mean annual wind power at 50 m above exposed areas over the contiguous United States is shown in Figure 3.13. Exposed areas refer to locations which are unobstructed, such as hilltop locations in regions of gently rolling terrain, and capes and open shoreline sites along coastal regions. The estimates are considered to be lower limits for exposed sites. Isolated areas may have 50% to 100% greater wind power than the analysis shows. The estimates must not be construed as representative of all sites within an area. Specifically, the estimates are not representative where topographical features block or channel airflow.

FIGURE 3.13. Mean Annual Wind Power (W/m^2) Estimated at 50 m Above Exposed Areas. Over Mountainous Regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges.

In mountainous regions, the estimates are the lower limits expected for typical, well-exposed sites along mountain summits, ridges, and gaps. Over some isolated mountains and ridges, the wind speeds are enhanced considerably, and the wind power may be a factor of 2 or 3 greater than the values indicated. The slope and orientation of a ridge to the prevailing winds greatly affect the wind power. Thus, relatively low isolated ridges, gaps, and saddles may have greater wind power than higher mountain summits. All mountainous regions, with the exception of some areas in the Southwest, are estimated to have considerable wind power potential (at least 300 W/m^2).

Seasonal patterns of wind power are similar to the annual patterns. Over the eastern one-third of the nation, maximum wind power occurs during the winter and early spring. Spring maxima occur over the Great Plains, the North-Central states, the Texas coast, and offshore areas of central and southern California, and maximum occur over all mountainous regions. In some mountainous areas in the lower Southwest the spring wind power is about as large as the winter maximum.

Expected Progress During the Next Period:

This task is completed. Further refinement of estimates of wind power magnitude and distribution will be undertaken in the Regional Presiting Evaluation.

Reports and Publications:

Elliott, D. L., Synthesis of National Wind Energy Assessments, BNWL-2220 WIND-5, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, July 1977.

3.3.2 Prototype Regional Wind Energy Evaluation*

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

Dennis Elliott (509) 942-5040

Objective:

To determine the criteria for regional evaluations of wind characteristics for planning and siting purposes and to test the criteria in a prototype regional evaluation.

Program Status:

The project was initiated in April 1977 and will continue through March 1978.

Progress During Reporting Period.

The initial phase of this task was the division of the United States into geographic regions, considering topography, climatology, Federal Power Commission (FPC) Reliability Council Regions, and state governments. The suggested geographic regions within the contiguous states are shown in Figure 3.14. It is recommended that Alaska be treated as a region itself due to its enormous size and the extent and diverse climatic regimes. Hawaii is also recommended as a separate region because of its separation.

It is desirable to consider each state in its entirety, rather than dealing with various fraction of states, because meteorological data and summaries are usually given by state.

The Northwest region has been selected for a prototype evaluation. This region was selected because of its diverse climatology and topography. A region with diverse characteristics (i.e., coasts, mountains, plains) is needed for the prototype evaluation establishing the criteria for all other regions of the country.

*This program was added following re-evaluation of the Presiting Evaluation/Resource Assessment area in January 1977.

FIGURE 3.14. Suggested Geographic Divisions for Regional Wind Energy Evaluations

Work is in progress to determine the methodologies for conducting the prototype evaluation. An essential part of the evaluation is gaining an understanding of mechanisms which cause high wind speeds in some areas but not in other areas.

In addition to standard data (including those used for the national assessments), the availability of nonstandard data from the National Climatic Center has been reviewed. These data are being acquired for selected areas.

The prototype evaluation will primarily be based on available standard and nonstandard data, and methodologies developed for estimating areas of high wind power potential. Additional data available from various other sources will be used for verification purposes.

Expected Progress During the Next Period:

A prototype evaluation will be performed utilizing additional nonstandard available data and appropriate methodologies for the analyses. The output will document the criteria and methodologies for conducting region evaluations which provide:

1. favorable areas for application of siting strategies
2. wind characteristics in the region
3. estimates of extractable power
4. estimates of power from arrays.

Documents will be produced describing the wind power potential of the Northwest region and guidelines for other regional evaluations.

Reports and Publications:

None to date.

3.3.3 Alaskan Wind Power Study*

Contract No.: E(45-1)-2229 #12

University of Alaska
Geophysical Institute
Fairbanks, AK 99701

Principal Investigator:

Tunis Wentink, Jr. (907)479-7607

Contract Monitor:

Dennis Elliott (509) 942-5040

Objective:

To determine, by analysis and experiment, the potential of Alaskan wind power and its possible applications. Major emphasis is on an assessment of the wind resource throughout Alaska for presiting evaluation.

Program Status:

This program was initiated in May 1976 and will continue through August 1977. A second year continuation of this contract has been proposed for August 1977 through July 1978, with preliminary emphasis on an evaluation of wind characteristics for presiting analyses.

Progress During Reporting Period:

The following results were achieved during the reporting period.

1. Wind data from 28 Alaskan sites were analyzed and the velocity duration curves evaluated. The Weibull Function and an empirical function by Wentink were found to be applicable for the description of most Alaskan wind regimes.

*This program was transferred to the Wind Characteristics Program Element in February 1977.

2. The vertical wind speed gradients were measured and analyzed at two locations.
3. Wind power predictions were made for selected areas.
4. A 6 kW WECS was operated at Ugashik, destroyed by the wind, and a replacement obtained.
5. Applications of WECS, user needs, user power statistics, and economics of WECS (especially of payback through oil conservation) were studied.

Expected Progress During the Next Period:

A report on the first phase through August 1977 will be completed. During the second phase, the following tasks will be undertaken:

1. Wind analyses will be continued at additional Alaskan sites. The results of these analyses will be presented in a format appropriate for assessment of the wind resource in the region and for presiting evaluation efforts.
2. Power predictions will be made for horizontal axis WECS, one or two state-of-the-art vertical axis WECS and selected ERDA/NASA machines for all sites.
3. Wind measurements will continue at two locations to examine the vertical variation of the wind with height.
4. A handbook for small machine siting in Alaska will be prepared.

Reports and Publications:

Wentink, T., Jr., "Surface Wind Characteristics of Some Aleutian Islands," in Proceedings of First Workshop on Wind Energy Conversion Systems, Washington, DC, (June 11-13, 1973), NSF/RA/W-73-006, December 1973.

Wentink, T., Jr., Wind Power Potential of Alaska, Part I: Surface Wind Data from Specific Coastal Sites, Geophysical Institute Scientific Report UAG R-225, University of Alaska, August 1974, available through NTIS as PB 238-507.

Wentink, T., Jr., "Wind Power for Alaska, in The Northern Engineer, 5, 8 (Winter 1974).

Wentink, T., Jr., "Summary of Alaskan Wind Power and Its Possible Applications," in Proceedings of Second Workshop on Wind Energy Conversion Systems, Washington, DC (June 9-11, 1975), NSF-RA-N-75-050 (Mitre Corp. MTR-6970), December 1975.

Wentink, T., Jr., Alaskan Wind Power and Its Possible Applications, extensive Final Report to the National Science Foundation, NSF/RANN/SE/AER74-00239A01/FR/74/4, February 29, 1976, available through NTIS as PB 253-339.

Wentink, T., Jr., Wind Power Potential of Alaska, Part II: Wind Duration Curve Fits and Output Power Estimates for Typical Windmills, Geophysical Institute Scientific Report UAG R-240, University of Alaska, July 1976. ERDA Report RL0/2229-T12-76/1; available through NTIS.

Wentink, T., Jr., Alaskan Wind Power Study, Annual Report (draft), Geophysical Institute, University of Alaska, February 1977, ERDA report RL0/2220-T12-2.

3.3.4 Assessment of the Potential of Wind and Solar Energy in Hawaii*

Contract No.: NSF Grant AER76-05596

University of Hawaii
Honolulu, Hawaii

Principal Investigator:

John W. Shupe (808) 948-7727

Contract Monitor:

Dennis Elliott (509) 942-5040

Objective:

To evaluate the wind and solar energy potential of the Hawaiian Islands. The wind analyses will be based on wind surveys for Hawaii, Maui, and Oahu and modeling techniques.

Program Status:

The responsibility for technical monitoring the University of Hawaii contract was transferred from NSF to ERDA and assigned to Battelle, Pacific Northwest Laboratories, in February 1977. The program continues through December 1977.

Progress During Reporting Period:

Wind surveys have been made for the islands of Hawaii, Maui, and Oahu to identify areas where winds favor electric power generation. Mobile sampling programs have been carried out in selected areas without historical data to make a tentative evaluation of wind power potential and identify sites for permanent wind monitoring. Diurnal variations of the station winds and synoptic weather regimes during the monitoring periods were evaluated. All three islands indicate areas of strong persistent winds and high wind power potential.

Expected Progress During the Next Period:

More detailed analyses of the wind power potential will be made for Hawaii. The surveys will incorporate field

*The current work is funded by NSF.

measurements, standard historical data and data from other sources, numerical simulations of air flow, and evaluations of the wind characteristics. Application studies will be made for several areas.

Reports and Publications:

Daniels, A., B. Palmer, T. Tarlpon, and T. Schroeder, 1976: A Survey of Wind on the Island of Maui for Potential Wind Power Generation, Part 1, Mobile Sampling Program, August 7-26, 1976, Dept. of Meteorology, University of Hawaii, UHMET 76-6.

Schroeder, T., T. Tarlpon, and A. Daniels, 1976: A Survey of Wind on the Island of Hawaii for Potential Wind Power Generation, Part 1, Mobile Sampling Program, September 3-12, 1976, Dept. of Meteorology, University of Hawaii, UHMET 76-7.

Ramage, C., A. Daniels, T. Schroeder, and N. Thompson, 1977: Oahu Wind Power Survey, First Report, Dept. of Meteorology, University of Hawaii, UHMET 77-1.

3.3.5 Wind Energy Statistics for Large Arrays of Wind Turbines (6a)

Contract No.: EY-76-S-06-2439

Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, GA 30332

Principal Investigator:

C. G. Justus (404) 894-3014

Contract Monitor:

J. C. Doran (509) 942-2861

Objectives:

To examine the power production characteristics of simulated large-scale arrays of wind turbines in various geographic regions of the United States, and to develop and verify a simplified array simulation model.

Program Status:

The current contract, May 1977, continues work begun in May 1976.

Progress During Reporting Period:

Simulated arrays of 0.5 MW, Mod 1 1.5 MW and Mod 2 2.0 MW wind turbines in the Great Lakes and Pacific Coast regions were studied, supplementing earlier reports on the New England and Central United States areas. Basic wind statistics, time and spatial correlations, mean wind power output, wind power frequency and run duration of wind speed and array power were analyzed and tabulated. A simplified array simulation model was shown to represent the observed results reasonably well. A study of wind speed and degree days failed to show any relationship between the two quantities.

A simplified model was also developed for use in incorporating density variations, wind shear, gusts and directional changes in power estimates from wind turbines.

Expected Progress During the Next Period:

The array analysis will continue with emphasis on large, multiregion arrays; refinement and verification of the simplified array simulations not requiring time series analysis, and time series array analysis of storage with explicit simulation of storage charge and discharge cycling. Additional analytical and experimental studies will examine the influence of such factors as gusts and wind shear on power performance of individual wind turbines, and farms and regional arrays of turbines.

Reports and Publications:

Justus, C. G. and W. R. Hargraves, Wind Energy Statistics for Large Arrays of Wind Turbines (Great Lakes and Pacific Coast Regions), RLO/2439-77/2, Annual Progress Report, May 1977.

Justus, C. G., W. R. Hargraves, Amir Mikhail and Denise Graber, "Methods for Estimating Wind Speed Frequency Distributions," submitted to Journal of Applied Meteorology.

3.3.6 Stochastic Modeling of Site Wind Characteristics (6b)

Contract No.: EY-76-S-06-2342

Northwestern University
The Technological Institute
Department of Civil Engineering
Evanston, IL 60201

Principal Investigator:

R. B. Corotis (409) 942-3453

Contract Monitor:

J. C. Doran (509) 942-2861

Objectives:

To utilize probability methods of wind data analysis to develop survey guidelines for use in siting wind energy conversion systems.

Program Status:

This contract was begun in October 1976 and is scheduled for completion at the end of September 1977.

Progress During Reporting Period:

Data from a number of additional sites were analyzed with the statistical programs developed earlier, and results were compared to those originally obtained for sites in the mid-west and Montana. Duration of data collection required for specified accuracy and confidence limits for mean velocity and power were determined. A run duration model incorporating a combined power law and exponential fit and dependent upon a single parameter was developed. This parameter is essentially determined by the mean wind alone, with only minor site dependence. Auto and cross-correlations were derived.

A draft report summarizing these findings was completed. The report provides a step-by-step procedure for applying the various statistical methods developed. Two examples are included for illustrative purposes.

Expected Progress During the Next Period:

More complete site survey guidelines will be developed, and the various analysis options will be presented. The reliability of the various approaches will be defined and assessed. In addition, continued development of the run duration model will be carried out and additional sites will be examined.

Reports and Publications:

Corotis, R. B., Stochastic Modeling of Site Wind Characteristics, RLO-2342-77/2, Annual Progress Report, July 1977.

Corotis, R. B., A. B. Sigl, and J. Klein, "Probability Models of Wind Velocity Magnitude and Persistence," submitted to Journal of the International Solar Energy Society.

Corotis, R. B., A. Sigl, and M. Cohen, "Variance Analysis of Wind Characteristics for Energy Conversion," submitted to Journal of Applied Meteorology.

3.3.7 Accuracy of Wind Power Estimates (1c)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

J. C. Doran (509) 942-2861

Objective:

To critically examine various factors which may influence estimates of extractable wind power, specifically: sampling and averaging periods, formulae for extrapolating velocity distributions to heights at which data are not available, and the use of some analytical representations of velocity probability density functions.

Program Status:

The data analysis is nearing completion and a draft of a final report is being prepared. This report shows the range of errors which may be encountered in estimating power output from various wind energy conversion systems when certain assumptions and approximations are used to supplement empirically determined wind velocity distributions.

Progress During Reporting Period:

Wind records collected every 2 min at the Hanford site were reduced and analyzed in an examination of the effects of sampling and averaging effects on power estimates. These data were also used in a preliminary examination of extrapolation formulae for adjustment of wind speed distribution parameters, and the representation of wind velocity distributions by the Rayleigh and Weibull functions. The summarized nuclear power plant data of Verholek (Section 3.3.7) were used as an expanded data base for further evaluation of these two factors. Limitations of the Rayleigh distribution in particular were noted, and difficulties associated with the extrapolation scheme prepared by Justus were identified.

Expected Progress During the Next Period:

The data analysis will be completed and a final report issued.

Reports and Publications:

None to date.

3.3.8 Meteorological Studies for Wind Power (1b)

Contract No.: S189-76-32

Sandia Laboratories
Albuquerque, NM 87115

Principal Investigator:

J. W. Reed (505) 264-3042

PNL Contact:

L. L. Wendell (509) 942-6677

Objective:

To provide meteorological support for the Vertical Axis Wind Turbine Program.

Program Status:

This program started in 1973. During this time the program has contributed to a number of areas including a National wind energy resource assessment and wind information for WECS design and performance.

Progress During Reporting Period:

Ten year records of wind data have been obtained from the National Climatic Center, Ashville, North Carolina, to produce detailed wind power evaluations at 14 selected locations within the continental United States and 1 location in the Marshall Islands. Each station was selected to be representative at a major wind climate regime. Procedures were established to adjust all the wind speed records to a 10 m exposure height, accounting for movement of the anemometers during the period of record. The adjusted 10-year time series of hourly wind speeds have thus been generated for the 15 selected stations for 4 heights, including the final anemometer height near the runway, 10 m, 20 m, and 50 m above the ground.

The above data were used to study effects, on available wind power, of turbine speed limits and performance curves. Wind power distribution function curves were computed and plotted

for each station. Superimposed on these curves were curves representing the relative wind power distribution due various rated speeds of a turbine. The results indicated that specific cut-in and cut-off speed selections were much less important to net power recovery than the rated speed selection. An increased rated speed seemed to reduce losses from power overlooked at higher speeds, but increases losses at lower speeds, depending on the performance curve shape for a specific turbine. This method can be used to design for optimization of the machine output, according to the wind climatology.

The other type of analysis to which the long-term data have been subjected is production reliability and the potential for improvement with energy storage systems.

A preliminary exercise with Dodge City wind data was performed to estimate storage level requirements for a stand-alone system that served a constant demand derived to match exactly the 10-year average supply. A plot of the hourly running accumulation of excess or deficient showed an inter-annual variability somewhat larger than the annual variability. During the 10-year data period the difference in the maximum cumulative excess and minimum cumulative deficient was 1600 kWh for 1 m². This represents 61% of an average annual output and was judged to far exceed any practical storage system capability. It was noted, however, that storage capabilities for filtering diurnal (24 hours) and some synoptic scale variations (up to 4 days) can appreciably improve system reliability.

Expected Progress During the Next Period:

During the reporting period, nomograms for selecting turbine operating parameters will be completed for the 15 stations selected. Preliminary trade-off evaluations will be made for wind energy storage requirements.

During the next year of this effort, procedures will be established and documented for selection of turbine operating parameters for select wind climate regimes.

Reports and Publications:

Reed, J. W., Energy Storage Needs for Wind Power Systems, presented at the AAAS Annual Meeting, Denver, CO, February 20-25, 1977.

Reed, J. W., New Details on Wind Power Climatology, presented at the American Wind Energy Association Meeting, Boulder, CO, May 13, 1977.

3.3.9 Index of Wind Summaries Available from the National Climatic Center*

Memorandum Purchase Order No.: RL-76-9540

National Climatic Center
Federal Building
Asheville, NC 28801

Principal Investigator:

Michael J. Changery FTS (704) 672-0216

Contract Monitor:

D. L. Elliott (509) 942-5040

Objective:

To prepare an index of all summarized wind data on file at the National Climatic Center.

Program Status:

The program is complete except for printing of the Index. An index has been prepared that identifies the locations for which summarized wind data are available, specifies the period of record, and indicates the data summary format. The index is divided into two parts. The first part is a geographical listing of summaries. Observation locations are arranged alphabetically by and within states. The second part is arranged by summary format. For each format type the available data are listed by state, location, and period of record.

Progress During Reporting Period:

The index of summarized wind data was compiled and a draft of the index was submitted for review. Following review the final Index was prepared for printing.

Expected Progress During the Next Period:

The Index should be printed in August 1977.

*This project was funded in FY-1976 and was not included in the FY-1977 PDP.

Reports and Publications:

Index - Summarized Wind Data. National Climatic Center,
National Oceanic and Atmospheric Administration, Asheville, NC,
177 pp, to be published.

3.3.10 Summary of Nuclear Power Plant Wind Data (7b)

Battelle, Pacific Northwest Laboratory
Richland, WA 99352

Principal Investigator:

M. Gary Verholek (509) 942-0712

Objective:

To compile and disseminate summaries of wind data collected at the nuclear power plant sites across the United States.

Program Status:

The final report is now in print. The report contains site specific summaries of data relevant to the WCPE. Included are descriptions of each nuclear power plant site's topography and wind measurement system, joint-frequency tables of speed and direction, velocity duration curves, and available wind power.

Progress During Reporting Period:

The information summaries were completed. A simple site description and data summary are presented in the following pages.

Expected Progress During the Next Period:

None, program complete.

Reports and Publications:

Verholek, M. G., Summary of Wind Data from Nuclear Power Plant Site, BNWL-2220 WIND-4, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 340 pp.

JOINT FREQUENCY DISTRIBUTION

MONTAGUE

SITE NW - MA

SPEED (m/s)

LOCATION

	CALM 0.4	1.5	3.3	5.5	8.2	10.8	15.0	20.0	>20.0		9.92
N		3.42	2.13	0.10							
NNE		5.21	1.56	0.19							
NE		4.24	1.31	0.32	0.05						
ENE		2.29	0.91	0.10	0.01	0.01					
E		1.28	0.29	0.04							
ESE		0.79	0.46	0.02							
SE		0.91	0.30	0.07							
SSE		1.55	0.59	0.14							
S		3.35	3.39	0.59	0.01						
SSW		3.79	4.63	1.12	0.06	0.01					
SW		3.42	2.29	0.35	0.05						
WSW		2.81	1.72	0.19							
W		2.77	2.62	1.32	0.12						
WNW		2.54	3.45	1.35	0.37	0.04					
NW		2.15	2.34	0.30	0.21	0.01					
NNW		2.07	1.41	0.27	0.02						
TOT	19.53	42.59	29.41	7.47	0.92	0.07	0				
SUM		62.12	91.53	99.00	99.93	100.0					99.99

VELOCITY-DURATION CURVE

MONTAGUE
42.58°N/72.53°W

Site Location:

The Montague site is located in the Northwestern Massachusetts township of Montague, Franklin County, 2 km SSE of Turner Falls and 3 km E of the Connecticut River.

Topography:

The terrain in the immediate vicinity of the site [plant grade elevation - 105 m (MSL)] is relatively flat for 2 to 3 km radial, except for a nearby ridge to the NW at about 150 m (MSL). At greater distances from the site (out to 8 km), the terrain is gently rolling with peaks to 180 m (MSL) from the S through NE. In other directions, the terrain is even more rugged with peaks between 275 m and 400 m (MSL).

Onsite Wind Measurements:

The onsite meteorological measurements program was initiated on September 1, 1975. A 152-m tower, at an elevation of 95 m (MSL) is instrumented with Climatronics Model F460 wind systems at 10-m, 46-m, 99-m and 151-m heights.

NRC Docket No. 50-496

3.4 PLANNING AND OPERATIONS

The Planning and Operations Program Area, while recognized as necessary, has not been formally organized. As a result, no tasks have been assigned to the area. However, in planning for the future development of this area, it has become obvious that much of the work discussed in Section 3.3.5 will be directly applicable to Planning and Operations. Similarly, the siting methodologies and generic wind information developed in the Site Selection Area will prove useful in Planning and Operations.

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