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**Semi-Annual Report of the
Wind Characteristics Program
Element for the Period
April 1976 Through
December 1976**

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

January 1977

**Prepared for the Energy Research
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Battelle

Pacific Northwest Laboratories

BNWL-2220 WIND-2

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by
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BATTELLE
Pacific Northwest Laboratories
Richland, Washington 99352

SUMMARY

The Wind Characteristics Program Element (WCPE) provides wind information, through the Wind Energy Conversion Program (WECP), for those involved in: energy program planning, design and evaluation of performance of wind energy conversion systems (WECS), selection of sites for WECS installation, and WECS operations. Battelle, Pacific Northwest Laboratories (PNL), provides the ERDA Wind Systems Branch (WSB) with technical and management support for the WCPE. A framework has been established to develop and disseminate needed wind information, and a Program Development Plan has been prepared and is continuously being updated to ensure that the needs of the WECP are met. Two invitational workshops have been held to obtain planning input and to encourage and facilitate information exchange.

Currently the technical work within the WCPE is divided among four program areas. These areas are to provide wind characteristics for:

- Design and Performance Evaluation
- Site Selection
- Resource Assessment, and
- Operations.

Work is being undertaken in the first three areas. The Operations area was identified late in the reporting period, and although no work is funded in this area, current work in other program areas is related to it.

Design and Performance Evaluation

The goal of the work performed in the Design and Performance Evaluation area is to provide meteorological input to support these engineering tasks. To be of value, the input must include realistic and worst case estimates and must be presented in readily usable formats.

During the reporting period the following milestones have been accomplished:

- Wind descriptors related to ultimate strength, fatigue, turbine performance, and control system design have been identified. (PNL, 1d)*

* Organization performing work and Program Development Plan Task Number.

- A statistical model of horizontal and vertical wind shear fluctuations has been developed. (PNL, 1c)
- Liaison has been established with NASA Lewis Research Center, Rocky Flats Small WECS Test Center, and Sandia Laboratories.

A single contract was awarded during the reporting period. That contract was to AeroVironment, Inc. for demonstration of an acoustic doppler wind measurement system.

Site Selection

In the Site Selection Program Area, the emphasis is on the development and evaluation of siting tools and the preparation of site selection strategies. The roles of numerical and physical models in siting were examined; both are useful in large turbine siting strategies although each has limitations. The initial steps have been taken to expand the work on non-modeling techniques for site selection.

The following results and conclusions have been reached in the Site Selection Area:

- Siting Handbooks have been identified as the primary end products of the Site Selection Area.
- It has been determined that the WCPE should not develop numerical models, rather it should promote the application of existing models to Wind Energy Conversion.
- Meteorological data sets potentially useful in validation and comparison of models for WECS siting applications have been identified. (PNL, 5j)
- Liaison has been established with NASA Lewis Research Center and its contractor with respect to documentation and evaluation of the meteorological characteristics of the 17 Candidate Wind Turbine Sites.

The following new contracts have been awarded to provide information for use in Site Selection:

- American Wind Energy Association - Survey of Historical and Current Site Selection Techniques for the Placement of Small Wind Energy Conversion Systems

- Oregon State University - Vegetation as an Indicator of High Wind Velocities
- Poseidon Research - The Effect of Atmospheric Density Stratification on Wind-Turbine Siting
- University of Virginia - Coastal Zone Wind Energy
- FWG Associates - Technology Development for Assessment of Small-Scale Terrain Effects on Available Wind Energy.

Resource Assessment

Resource Assessment is directed toward those in planning roles. Its scope includes the description of wind energy available on national, regional and local scales. In addition, it is concerned with determination of the reliability of wind energy and matching available energy with load demands.

During the reporting period the following results have been obtained:

- A synthesis of three existing National Wind Energy Resource Assessments has been prepared. (PNL, 9a)
- Wind data submitted to the Nuclear Regulatory Commission have been summarized for use in wind energy applications. (PNL, 7b)
- The probability of realizing a given average energy from WECS can be increased 10% to 20% by utilizing widely dispersed WECS arrays. (Georgia Institute of Technology, 6a)
- The measurement periods required to estimate annual average wind speed and power to predetermined accuracy and confidence level using only onsite measurements has been determined for two regions of the country. (Northwestern University, 6b)

There were no new contracts awarded in the Resource Assessment area during the reporting period.

Special Studies

The WCPE responded to requests from the WSB to provide assistance in several areas. Among these were the preparation of potential research topics for International Cooperative Studies, assistance in the evaluation of the Candidate Sites for the Demonstration Wind Turbines, and the review of reports from other WECP program elements.

CONTENTS

SUMMARY	i
1. INTRODUCTION	1
2. PROGRESS IN RESEARCH AREAS	4
2.1 PROGRESS DURING REPORTING PERIOD	4
2.2 EXPECTED PROGRESS DURING NEXT REPORTING PERIOD	15
2.3 REPORTS, PUBLICATIONS AND PRESENTATIONS	18
3. PROGRESS IN TECHNICAL TASKS	19
3.1 METEOROLOGICAL STUDIES FOR WIND POWER	20
3.2 ANALYSIS OF WIND SHEAR FLUCTUATION DATA	23
3.3 ASSESSING THE LOCAL WIND FIELD FOR SITING OF WIND POWER SYSTEMS	26
3.4 SURVEY OF HISTORICAL AND CURRENT SITE SELECTION TECHNIQUES FOR THE PLACEMENT OF SMALL WIND ENERGY CONVERSION SYSTEMS	29
3.5 VEGETATION AS AN INDICATOR OF HIGH WIND VELOCITIES	31
3.6 LOCATING AREAS OF HIGH WIND ENERGY POTENTIAL BY REMOTE OBSERVATIONS OF AEOLIAN GEOMORPHOLOGY AND TOPOGRAPHY . . .	34
3.7 WIND POWER STUDIES	36
3.8 DEVELOPMENT OF A WIND ENERGY SITE SELECTION METHODOLOGY . .	40
3.9 TECHNIQUE FOR OPTIMALLY LOCATING WIND ENERGY SYSTEMS BASED ON PREDICTED WIND STATISTICS	45
3.10 THE EFFECT OF ATMOSPHERIC DENSITY STRATIFICATION ON WIND- TURBINE SITING	47
3.11 COASTAL ZONE WIND ENERGY	50
3.12 TECHNOLOGY DEVELOPMENT FOR ASSESSMENT OF SMALL-SCALE TERRAIN EFFECTS ON AVAILABLE WIND ENERGY	54
3.13 SITES FOR WIND POWER INSTALLATIONS: WIND TUNNEL SIMULATION OF THE INFLUENCE OF TWO-DIMENSIONAL RIDGES ON WIND SPEED AND TURBULENCE - TABULATED EXPERIMENTAL DATA	58
3.14 SURVEY OF EXISTING METEOROLOGICAL DATA SETS FOR MODEL VALIDATION	62
3.15 NATIONAL WIND ENERGY STATISTICS FOR LARGE ARRAYS OF WIND TURBINES	64

3.16	STOCHASTIC MODELING OF SITE WIND CHARACTERISTICS	70
3.17	SUMMARY OF NUCLEAR POWER PLANT WIND DATA	74
3.18	SYNTHESIS OF EXISTING NATIONAL WIND ENERGY ASSESSMENTS . .	78
3.19	WIND SPEED AND POWER FREQUENCY DISTRIBUTION	82

SEMI-ANNUAL REPORT
FOR THE
WIND CHARACTERISTICS PROGRAM ELEMENT

1. 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 semi-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 through December 1976. Future reports in this series will cover subsequent six month periods.

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. Conceptually the needs of the users of wind characteristics information can be grouped into four areas:

- Design and Performance Evaluation
- Resource Assessment
- Site Selection
- Operations

The four areas are not independent, rather there is significant overlap. Information developed by tasks that fall within an area of overlap contributes to the needs of more than one user. The four areas and their interactions are schematically shown in Figure 1. In addition, special studies are conducted to satisfy specific needs of the WSB; they are generally short-term, fast response efforts and may fall within any of the four areas. It is not possible to foresee their specific nature.

FIGURE 1. Wind Characteristics Program Element

The wind characteristics information required for WECS design and performance evaluation is primarily directed toward users involved in the design and manufacturing of hardware. This information includes description of: the distribution of hourly average wind speeds, the statistical moments of the wind speed and direction fluctuations, the spatial and temporal variations of the wind including correlations and power spectra, wind shears, and peak gusts. Additional information required in this area includes guidance in deployment of meteorological instrumentation for WECS performance evaluation, and assistance in identifying relationships between wind input and machine output.

Resource Assessment is directed toward those in planning roles. The scope of Resource Assessment includes the descriptions of energy available in the wind on national, regional and local scales. In addition, this area is concerned with the determination of the reliability of wind energy and the matching of available energy with load demands. Within the region of overlap between the areas of Resource Assessment and Design and Performance evaluation falls the task of assessing the wind energy that is extractable.

The area of Site Selection is concerned with the problem of identifying specific locations for installation of WECS. The Site Selection process has two stages. The initial stage is screening a pre-determined area to identify subregions with the best wind energy potentials. Site screening is followed by localization within the subregions. Tools used in the screening and localization processes may range from complex numerical computer models to relatively simple observations of local vegetation. Tasks within the area of Site Selection are designed to develop siting tools and present information on the use of the tools in formats that can be followed by individuals involved in siting. Siting tools have as their objective the identification of the best, or at least, dependably very good sites. The quantitative estimation of the energy availability at a specific site falls within the overlap between Site Selection and Resource Assessment and is assigned to the area of Resource Assessment.

The Operations area is concerned with supplying wind characteristics information for the operational use of WECS within a power grid. Within

this area are the tasks of: developing and evaluating wind forecasting techniques for use in the day-to-day scheduling of generating facilities and determination and development of information for power dispatching.

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 report is divided into two sections. The first section describes progress in research areas as they relate to specific wind characteristics user needs. In the second section the progress in each technical task is described. In both sections the descriptions of progress are divided between progress in the current reporting period and progress expected in the next period (January through June 1977). Throughout the report where specific technical tasks are discussed the task is identified by number and letter. This identification is the task number assigned in the Development Plan for the Wind Characteristics Program Element prepared by PNL and dated November 15, 1976. The title as it appears in this report is the title on the contract.

2. PROGRESS IN RESEARCH AREAS

In the first part of this section the progress since April 1976 in each of the five general research areas described in the Introduction is discussed. In the second part the next semi-annual period is discussed.

2.1 Progress During Reporting Period

At the outset the ERDA Wind Characteristics Program Element consisted of nine contractors working on problems generally related to wind energy conversion and several proposals. Many of the contractors were working under contracts originally let by the National Science Foundation and transferred to ERDA during FY 1975. Upon assuming responsibility for providing technical and management support for the WSB's WCPE, PNL began the process of identifying the needs of the Wind Energy Conversion Program and the relationships between the existing contracts and the WCPE needs.

In June 1976, PNL and the WSB sponsored an invitational Workshop on Wind Characteristics which was held at the American Meteorological Society in Boston, Massachusetts. The specific objectives of the workshop were: 1) to introduce PNL to program element contractors, 2) to obtain input for use in preparation of a Program Development Plan, and 3) to encourage and facilitate communications between program element contractors and users of wind characteristics information within the Wind Energy Conversion Program. At that time the users of wind characteristics information were identified as engineers involved in the design, manufacture and evaluation of WECS, ultimate users of WECS, and policy makers in the WSB, DSE other governmental agencies.

By the time of workshop, the overall position of the WCPE as a service element had been established, and the program objectives had been identified as follows:

- 1) To provide wind characteristics information to expedite and reduce the cost of development of efficient and durable WECS.
- 2) To develop reliable and inexpensive techniques for identifying suitable wind energy conversion sites.
- 3) To prepare and maintain an up-to-date national assessment of wind energy potential and provide input to mission studies.

The general research areas and program objectives outlined in the Introduction are clearly rooted in the concepts developed by the June Workshop.

A second invitational workshop was held in November at the Battelle Seattle Research Center in Seattle, Washington. This workshop focused on the site selection problem and particularly on the role of modeling in site selection. The role of modeling in site selection was not clearly identified in the Boston Workshop. Participants in the Seattle workshop were generally limited to WCPE modeling contractors and potential model users within the Wind Energy Conversion Program because of the programmatic review aspects of the workshop. The distinctions between Resource Assessment and Site Selection, and the various stages of the siting process were clarified in the November workshop.

The current grouping of technical tasks and understanding of program objectives was developed toward the end of the reporting period. It is anticipated that minor changes in the task groupings and objectives will continue as new problems arise and old problems become better understood, but the overall structure is well established.

2.1.1 Design and Performance Evaluation

At the start of the reporting period the design of WECS was found to be based largely on mean wind speed. Steady-state winds were assumed and in most cases the winds were assumed to be uniform in the vertical. The frequency distribution of mean wind speeds (as represented in velocity duration curves) was also used in design. The existence of temporal and spatial variations were recognized but not treated.

Discussions in the Boston Workshop on WECS hardware focused on the engineering considerations of:

- Ultimate Strength
- Structural Fatigue
- Wind Turbine Performance
- Wind Turbine Control System Design

and the design stages of

- Preliminary Design
- Final Design
- Design Verification
- Wind Turbine/Site Optimization.

The wind environment was partitioned into mean and fluctuating parts. The mean wind was defined as a 10 minute to 1 hour average, and the fluctuations were defined as short-term departures therefrom. Characteristic WECS frequencies were determined to range up to $\sim 5 H_z$ for the blade bending vibrations and $\sim 1 H_z$ for blade rotation rate. These frequencies correspond to wind turbulence frequencies in the atmospheric boundary layer that contain significant energy. It was concluded that wind data and models with a time resolution of $5 H_z$ should be considered in design.

Since the Boston Workshop numerous informal discussions have been held on wind and other meteorological characteristics important in WECS design. Currently the list of wind characteristics considered to be important includes:

- 1) Mean wind speeds and their frequency distribution
- 2) Statistical moments of the wind fluctuations
- 3) Temporal and spatial correlations and spectra of the wind fluctuations
- 4) Mean wind shear and wind shear fluctuations
- 5) Wind direction variability
- 6) Peak wind gusts.

Other meteorological factors of known or potential importance are air temperature, pressure and humidity (density), icing, hail, lightning, and other severe storms.

In many instances existing meteorological information is adequate to permit upgrading of the meteorological input to WECS design. An example of this is the data on wind shear fluctuations summarized in Technical Task 1c.* Wind shear fluctuation data were obtained in a Federal Aviation Administration sponsored research program, but the analysis was not completed. The analysis of the shear fluctuation data has been completed and the results have been described under WCPE sponsorship. With the information thus gained it is possible to estimate the probability of occurrence of a given wind shear along the blades of a WECS. In addition it is possible to estimate the time scale of the wind shear fluctuations.

Active liaison has been established between the WCPE and other program elements to permit transfer of existing wind information to WECS designers and to identify areas where additional research is required to provide needed information. The other programs with which active liaison exists are the NASA Lewis Research Center, Sandia Vertical Axis Wind Turbine, and Hamilton-Standard programs. The results of PNL turbulence

* Technical task identification is keyed to the WCPE Program Development Plan.

research has been provided to Hamilton-Standard and are being used in blade design for the ERDA/NASA MOD 1 Wind Turbine. Liaison with designers of small WECS has been established through the American Wind Energy Association.

As the WECP has developed during the reporting period, the consideration of meteorological input to WECS performance evaluation has become increasingly important. The meteorological aspects currently considered to be significant in WECS performance evaluation are:

- 1) Wind instrumentation and its deployment
- 2) Statistical relationships, including spatial and temporal correlations, between wind input and WECS output, and
- 3) Physical interpretation of the relationships between wind input and WECS output.

Liaison in the area of performance evaluation has been established between the WCPE and the ERDA sponsored program at NASA Lewis Research Center, which is developing large, horizontal-axis systems; Sandia Laboratories, which is developing Darrieus, vertical-axis systems; and ERDA's Rocky Flats Plant, which is establishing a small system test center. In addition, the WCPE has encouraged liaison between the Rocky Flats program and NOAA's Wave Propagation Laboratory (WPL) located in Boulder, Colorado. The remote sensing capabilities of WPL have the potential to make a significant contribution to the Rocky Flats program. In particular, WPL's laser Doppler anemometer may provide definition of WECS wakes that is not possible using conventional meteorological measurement techniques.

2.1.2 Resource Assessment

At the beginning of the reporting period, the area of Resource Assessment was arbitrarily limited to providing a realistic National Assessment of wind energy potential and input to mission studies. As understanding of the role of wind characteristics in the WECP has grown, the area of Resource Assessment includes local and regional assessments as well as the National Assessment. It is no longer limited to evaluation of wind energy potential on the basis of mean wind speeds. Wind energy reliability and the correlation between available wind energy and energy demands are now included.

With the expansion of the Resource Assessment area, technical tasks previously considered part of Site Selection have been found to be more intimately related to Resource Assessment. Specifically, these are: National Wind Energy Statistics for Large Arrays of Wind Turbines (6a), Stochastic Modeling of Site Wind Characteristics (6b), and Summary of Nuclear Power Plant Wind Data (7b). The other task in Resource Assessment undertaken during the reporting period is Synthesis of Existing National Wind Energy Assessments (9a). Other technical tasks still associated with Site Selection that contribute or can potentially contribute to Resource Assessment include: Locating Areas of High Wind Energy Potential by Remote Observations of Aeolian Geomorphology and Topography (4b), Wind Power Studies (5a), Development of a Wind Energy Site Selection Methodology (5b), Technique for Optimally Locating Wind Energy Systems Based on Predicted Wind Statistics (5c), Coastal Zone Wind Energy (5e), and Survey of Existing Meteorological Data Sets for Model Validation (5j).

National Wind Energy potential has been assessed by Sandia Laboratories, Lockheed Corporation and General Electric under ERDA and NSF sponsorship. Although the assessments were based upon a single set of surface wind data, these data were supplemented in the Lockheed and General Electric assessments. In addition, differing assumptions were made in the three assessments. As a result there are small but significant differences in the results. The Synthesis of Existing National Wind Energy Assessments (9a) has evaluated the data sets and assumptions made in the previous assessments and has attempted to resolve the differences. The result is described in the technical task discussion.

The reliability of wind energy can be increased if the energy output of turbines in an array are not positively correlated. Reliability in this sense is synonymous with the probability that a single turbine or an array of wind turbines can produce usable power at any given time. The correlation between mean winds at two locations decreases as the separation increases and becomes essentially zero when the separation becomes several

hundred kilometers. If sufficient reliability can be obtained by increasing array dimensions, it may become possible for a utility to gain capacity credit for wind energy. Two regions of the United States have been examined (6a).

The data acquisition period required to estimate seasonal mean wind speed and power potential with a predetermined confidence level using only onsite measurements is being evaluated (6b). Results for a region of the Midwest and the Montana indicate that long term mean values of wind speed can be estimated within ± 10 percent with a 90 percent confidence level within a relatively short measurement period (less than 1 year). Estimation of mean power with the same confidence requires almost an order of magnitude longer. Estimation of mean power to within ± 5 percent with confidence level of 95 percent on the basis of on-site measurements alone is impractical because of the time required.

2.1.3 Site Selection

Following the Boston Workshop it was evident that neither the historical techniques for siting WECS nor the siting requirements of future WECS users were clearly understood. The Seattle Workshop clarified the goals of and relationships within the Site Selection area. It is the goal of the site selection process to identify the best wind energy conversion sites within a preselected region. It is sufficient if the initial site selection process provides a reasonable assurance that the sites selected are the best available within the region and that the energy potential is adequate. Quantitative estimates of the energy potential at the identified sites are desirable but not essential. Onsite meteorological measurements will probably be required to establish the site wind energy potential before financing can be obtained for WECS installation.

Both the selection of specific locations for WECS installation and the completion of the process, including onsite measurements to confirm the resource in a timely and economical fashion, are important. Climatological wind data will generally not be available for all potential wind energy conversion sites at the start of the site selection process. Therefore, techniques are required that can reliably and economically provide

information for use in the absence of actual onsite data. Specifically, the techniques must: 1) identify and permit ranking of the most favorable wind energy conversion sites; 2) identify regions with unfavorable wind characteristics, such as low speeds, flow separation or high wind variability; and 3) reduce the time required for onsite meteorological measurement programs.

The WCPE must sort out those site selection tools that provide cost effective results and establish their reliability in a variety of siting scenarios. Development of efficient siting strategies requires consideration of information on historic siting practices, insights that numerical and physical modeling can offer, and wind characteristics information available from sources other than numerical and physical modeling. To accomplish this development, seven subareas have been defined within the Site Selection area; six are to obtain the information for incorporation in siting strategies, and the seventh is to compile the information in usable formats. The subareas are:

- 1) identification of historic siting practices (3b),
- 2) modification and application of numerical and physical modeling techniques to WECS siting (5a, 5b, 5c, 5d, 5e, 5f, 5g),
- 3) validation and evaluation of modeling techniques for siting applications (5j),
- 4) development and consolidation of generic information on air flow for use in siting (4a, 4b, 5d, 5e, 5f, 5g),
- 5) development of site screening techniques that are independent of numerical physical models (4b),
- 6) development of site localization techniques that are independent of numerical and physical modeling (4a),
- 7) documentation of current siting strategies (5f, 8a, 8b).

Numerical and physical modeling provide systematic techniques for making maximum use of existing climatological data in the siting process. They can contribute to both the reduction in the number of potential sites under consideration, and the reduction in the number and duration of meteorological measurements required to evaluate specific sites. The most

economical and cost-effective application of models to siting may involve the use of a sequence of specialized models rather than a single comprehensive model.

The site selection process can be conceptually divided into two stages. The first stage is a screening in which a large region is examined and the best subregions are identified and ranked. These subregions may each be relatively large. The second stage is a localization in which exact locations are chosen for WECS construction within the subregions.

Numerical and physical models, themselves, may be used as tools for site screening. Their sophistication requires that the actual model user be highly trained. It is therefore probable that model use in this context would be limited to specialists who will exercise the models and interpret the results for the ultimate user. Numerical and physical models can also contribute to siting by providing generic information on airflow. The generic information so developed can subsequently be interpreted and included in handbooks for use by individuals with varying levels of expertise. Handbooks could provide the information needed for site screening in many cases and would provide information for localization in most cases. The documentation of WCPE siting information and strategies (5f, 8a, 8b) will be in handbook form.

Modeling provides useful tools for site selection, but as with all tools there are limitations. Numerical models used in a site screening mode will generally not be capable of identifying small scale features such as localized areas of high turbulence and flow separation. These features are most likely to be identified by the application of the results of smaller scale generic modeling. Physical modeling is limited, in a screening mode, to somewhat smaller areas than the large numerical models by the need to maintain dimensional similarity. If the lateral dimensions of an area being examined are too large, resolution of features of the boundary layer flow is lost. Physical modeling will permit identification of both areas of increased turbulence and flow separation in many cases.

Potential modeling tools documented in the existing literature range in complexity from relatively simple wind field-interpolation models to

primitive equation models, which require extensive computer memory and long run times. Prior to use in a systematic siting strategy, the ability of a model to produce usable results should be evaluated, and intermodel comparisons should be made to determine cost-effectiveness. PNL started compilation of a list of meteorological data sets for model evaluation in FY 1976 (5j). This compilation is nearing completion and detailed planning of the evaluation tests is to begin in the second quarter of FY 1977.

Numerical and physical modeling are both relatively expensive. A cost-effective siting strategy requires that these tools be used in a "case study" approach to screening. That is, the number of model runs required should be relatively small. Objective techniques for identifying cases to be modeled and for synthesizing the results of the individual cases into a consistent climatological statement are under development (5a, 5b, 5c), but they have not been validated.

The use of remote sensing from satellites to identify high wind energy areas is being examined (4b). There are indications that aeolian geomorphological features that appear on satellite photographs can be used in site screening.

In site selection, a point will be reached where the further application of screening techniques will not be cost effective. At that point generic localization techniques will be required. The literature contains much generic information on flows over and around obstacles, in boundary layers, etc. In addition, the WCPE is currently funding 3 modeling programs (5d, 5g and 5e) that are to produce generic results. The specific flow features being examined are, in order: flow of stratified air over terrain and identification of criteria for separation; the effects of terrain shape on the speed up of air flow; and the effects of land-sea temperature difference and latitude on wind near the Atlantic Coast. In addition, a non-modeling program (4a) examining vegetation deformation as an indicator of high wind energy may produce generic results for use in localization. Research in these programs has not progressed to the point where definitive results have been achieved.

The generic information on airflow pertinent to WECS siting is being compiled and presented in useful format to be of value in site screening and localization (5f). The result of this program will be a siting handbook. Continued compilation of generic flow information is essential if up-to-date, cost-effective siting strategies are to be achieved and maintained.

In the area of Site Selection, the WCPE is actively involved with the NASA Lewis Research Center. PNL is providing meteorological assistance to Lewis in connection with their measurement programs at the 17 candidate sites for Wind Turbine Field Tests.

2.1.4 Operations

The identification of the area of wind characteristics for operational use of WECS as a separate area did not occur until late in the reporting period, although many of the required tasks were recognized as early as the Boston Workshop. None of the current technical tasks are assigned to this area. However, current tasks in the areas of Design and Performance Evaluation, Resource Assessment, and Site Selection are developing information that will be useful in Operations. Specifically, the work on array reliability (6a) and stochastic modeling of site wind characteristics (6b) is related to large scale (long time) predictability of the wind. Work on wind characteristics for design of turbine blade control and tracking strategies is related to small scale (short time) predictability. In addition, the National Weather Service and the Federal Aviation Administration are currently involved in research on short range forecasting techniques.

2.1.5 WSB Special Studies

During the reporting period 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. Completed descriptions of the three studies were prepared and submitted to WSB in October 1976.

2.2 Expected Progress During Next Reporting Period

In the next reporting period the WCPE will continue to emphasize the transfer of wind characteristics information to WECS designers and those involved in performance evaluation. The interactions with the NASA Lewis, Rocky Flats, Sandia and Hamilton-Standard programs will be continued and expanded as appropriate.

The WCPE efforts related to performance evaluation will be expanded to better support the Rocky Flats, Sandia and NASA Lewis programs. Small scale experiments will be run to determine the optimum placement of meteorological instruments for performance evaluation. These experiments will also provide data that can be used to develop and evaluate mathematical and statistical techniques for comparing wind input with turbine output.

A set of experiments will be conducted to study the spatial and temporal characteristics of wind passing through a vertical plane. The experiment will provide data on the winds experienced by a simulated horizontal axis WECS blade as the turbine rotates.

Both experimental programs will be conducted using existing equipment. If successful, these experimental programs may be repeated on a larger scale during subsequent reporting periods. The larger scale experiments would require additional equipment.

On a somewhat lower priority basis, the WCPE will continue to evaluate wind characteristics descriptors related to design and performance evaluations. Existing information will be compiled on those descriptors that are determined to be significant. If serious deficiencies in existing meteorological information are identified, remedial research will be initiated.

2.2.2 Resource Assessment

Early in the next reporting period there will be a mini-workshop dealing with Resource Assessment. The invitational workshop will review current programs and is expected to result in a better definition of the Resource Assessment area. Topics to be discussed include: National, Regional and

local assessments, wind characteristics of interest in Resource Assessments, the current state of Resource Assessments, and the identification of the next task in Resource Assessment.

A request-for-proposals has been issued to obtain information on techniques that are currently available for predicting wind characteristics at specific sites. It is anticipated that several prediction techniques will be proposed. Successful bidders will be asked to use their technique to estimate the wind characteristics at several of the Candidate Sites for Wind Turbine Field Tests. The estimated characteristics will ultimately be compared with the observed characteristics at the site in order to evaluate the accuracy of each technique. Contracts should be awarded and work begun on this project during the next reporting period.

Final reports will be issued on the Synthesis of Existing National Wind Energy Assessments (9a) and the Summary of Nuclear Power Plant Wind Data (7b).

The work on National Wind Energy Statistics for Large Arrays of Wind Turbines (6a) will continue. The new regions to be evaluated are the Pacific Northwest and the Great Lakes. The program will examine diurnal variations more extensively and will evaluate correlations between wind power and heating and cooling loads. Results of the work on Stochastic Modeling of Site Wind Characteristics (6b) will be extended by examination of data from more diverse geographical areas.

Priority topics from additional work in Resource Assessment include: 1) the preparation of detailed regional assessments for promising high wind energy areas, 2) refinement of wind energy resource estimates to account for extractability of the energy, 3) evaluation of wind energy storage requirements and potential, 4) wind energy, and 5) refinement of the accuracy of Resource Assessments.

2.2.3 Site Selection

The emphasis of the work in Site Selection will shift, during the next reporting period, from model development and modification toward model validation and transfer of siting technology. There will be increased emphasis on the development of non-modeling techniques for use in the site selection process.

Two current tasks in the Site Selection area will be completed in the next reporting period. These are: Survey of Historical and Current Site Selection Techniques for the Placement of Small Wind Energy Conversion Systems (3b), and Survey of Existing Meteorological Data Sets for Model Validation (5j). These studies will be replaced by: 1) a study to design numerical model validation tests (new Task); 2) the preparation of Interim Site Selection Handbooks (8a, 8b); and 3) a number of studies to evaluate non-modeling techniques for possible use in site screening and localization (4c). The initial steps in preparation of a request-for-proposal for evaluation of non-modeling techniques have been taken. It is expected that work in this area can be started prior to the end of the next reporting period. Further expansion of the Site Selection area is not warranted at this time.

Support for the NASA Lewis Research Center siting work is expected to increase during the next period. Anticipated interactions include visits to several of the Candidate Sites and assistance in the area of data processing and analysis.

2.2.4 Operations

Progress in this area during the next reporting period is expected to occur only as a result of overlaps with other areas. Initial work directly in the area of operations is not scheduled until FY 1978.

2.2.5 WSB Special Studies

PNL and the WCPE will continue to respond to WSB requests with its best efforts.

2.3 Reports, Publications and Presentations

The following reports and publications have been prepared by PNL in support of the technical tasks of the WCPE. They do not fall within specific tasks and are, therefore, listed here.

Proceedings of the Wind Characteristics Workshop, Boston, MA, June 2-4, 1976. BNWL-2220-WIND-1, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 125 p., to be published.

"Pacific Northwest Laboratory Quarterly Technical Report for the Period 1 July to 30 September, 1976,"* submitted to the Wind Systems Branch, ERDA Division of Solar Energy, October 28, 1976.

Development Plan for the Wind Characteristics Program Element,* submitted to the Wind Systems Branch, ERDA Division of Solar Energy, November 15, 1976.

The Role of Modeling in Siting* (mini Program Development Plan) submitted to the Wind Systems Branch, ERDA Division of Solar Energy, December 15, 1976.

Elderkin, C.E., Ramsdell, J.V., and Tennyson, G.P., "Workshop Summary - Wind Characteristics Workshop, 2-4 June 1976, Boston, MA," Bul. Amer. Meteor. Soc., 58, p. 45, January 1977.

During the present reporting period the following presentations have been made in support of the Wind Energy Conversion Program and the Wind Characteristics Program Element:

Ramsdell, J.V., "The Wind Characteristics Program Element/Workshop Organization" Wind Characteristics Workshop, Boston, MA, 2-4 June 1976.

Ramsdell, J.V., "The Wind Characteristics Program Element," American Wind Energy Association Meeting, Madison, WI, 15-17 July 1976.

* Limited distribution, contains program review material.

Ramsdell, J.V., Chairman Siting and Weather Instrumentation Workshop, Annual Meeting of the American Wind Energy Association, Warren, VT, 21-24 October 1976.

Ramsdell, J.V., "Overview of the Battelle Laboratory Research into Characteristics of the Wind," Annual Meeting of the American Wind Energy Association, Warren, VT, 21-24 October 1976.

3. PROGRESS IN TECHNICAL TASKS

This section of the Semi-Annual Report of the Wind Characteristics Program Element describes the progress in the major technical tasks. Each task is identified by contract title and task number from the Development Plan for the Wind Characteristics Program Element dated November 15, 1976. 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 do not imply or guarantee funding beyond the current contract.

3.1 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) 942-2861

Objective:

To provide meteorological support for the Vertical Axis Wind
Turbine Program

Program Status:

This is a continuing program, started in 1973. During the course of time the program has contributed to a number of areas including resource assessment and wind information for WECS design and performance evaluation.

Progress During Reporting Period:

A parametric response study has been made of energy storage requirements as a function of system capacity, cycling efficiency and reliability. The study shows that interannual variations of available wind power are more significant in determining energy storage requirements than are seasonal or diurnal variations. For two representative small systems, the study indicates that 10 to 20 KWHr of storage capacity per square meter of swept area minimizes the cost of electricity. The cost of electricity can also be reduced by increasing the height of the surface.

The changes of wind speed distributions with height at selected weather stations have been examined. Frequently wind data for a given site represent the combination of

observations taken at two or more locations with different heights above ground. A technique for correcting the wind speed distributions in these cases has been tested using the data for 9 National Weather Service stations. The correction of the wind speed distributions for changes in height is a function of wind speed. In most cases the correction approaches the $1/7$ power of the ratio of the anemometer heights as the wind speed increases.

Expected Progress During Next Period:

Wind speed time series, which have been normalized to a single height over flat terrain, will be used to generate estimated distributions at 10m, 20m, and 50m heights, at each of the 15 selected locations. Each of these derived distributions will be used to calculate wind power extraction potentials for parameterized turbine characteristics of rated, cut-in, and cut-off speeds. They will also be used to explore storage capacity, cycling efficiency, and reliability. The storage calculations will also be modified to show the effectiveness of systems designed to be augmented by commercial power.

Hourly records from several additional locations will be obtained and analyzed by computer routines developed for the first 15 stations. Higher frequency recordings, obtained by Sandia at the VAWT laboratory, at the Solar Thermal facility, on Sandia Crest, and the Waste Isolation Pilot Plant in southeast New Mexico, will be subjected to similar analysis. Results will be compared to those obtained from nearby long term weather station records of both surface and upper air observations.

A preliminary evaluation will be made of the noise propagated from a 5m diameter VAWT under various operating conditions of wind speed and power output.

Reports and Publications:

During this reporting period J. W. Reed's Wind Power Climatology of the United States, SAND 74-0348, was printed for the third time. Other reports and publications include:

Reed, J.W., "Anemometry Data Processing" in Proceedings of the Vertical-Axis Wind Turbine Technology Workshop, Albuquerque, NM, SAND 76-5586, pp. II-270-290, 1976.

3.2 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, is nearly complete. The analysis of the wind shear fluctuation data collected downwind of large surface roughness elements in a Federal Aviation Administration sponsored program is complete. Results of the analysis have been presented at the Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites, sponsored by the American Meteorological Society, November 16-19, 1976, in Melbourne, FL.

Progress During Reporting Period:

Examination of the distributions of the fluctuations of vertical and horizontal shear of the longitudinal component of the wind indicates that they are described by a Pearson Type IV probability distribution. The statistical parameters that define the distribution are functions of the mean wind speed, height above ground and separation distances. Empirical models have been developed for these parameters. Using the empirical models and the Type IV distribution, it is possible to estimate the frequency with which a wind energy conversion system will experience various shears.

Examination of the time series of the wind shear data indicates that the integral time scales of the wind fluctuations are related to mean wind speed and separation distances. The time scales for the fluctuations of wind shear are approximately proportional to the $2/3$ power of the ratio of the separation distance to the mean wind speed. Typically the time scales are of the order of 2 sec for ratios near 1 and 5 sec for ratios near 5. The relationships are shown in Figure 1 where the Coriolis Parameter, f , has been used to non-dimensionalize the variables. In this figure τ is the integral time scale of the shear fluctuation, ΔZ and Δy are vertical and lateral separations, and $\bar{U}$ is the mean wind speed at the mean height.

Expected Progress in the Next Period:

In the next reporting period, the paper presented at the American Meteorological Society meeting in Melbourne, FL, will be revised and expanded and the results submitted to the Journal of Meteorology for publication. This publication will conclude the project.

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. Nov. 16-19, 1976; Melbourne, FL, American Meteorological Society, Boston, MA, p. 22-27.

FIGURE 1. Non-dimensional Time Scales for Wind Shear Fluctuations as a Function of Separation Distance and Wind Speed (Upper, Vertical Separation; Lower, Lateral Separation)

3.3 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:

Paul B. MacCready, Jr. (213) 449-4392

Contract Monitor:

R. K. Hadlock (509) 942-5040

Objective:

To tailor the Doppler acoustic radar technique for wind measurement for wind energy conversion applications. Tasks include the construction of the dual array radar system, operation vs. a tall meteorological tower system, and deployment of the system at a site specifically involved with the Wind Energy Program.

Current Status:

The duration of the present contract is 12 months. The effective date of the contract was June 1976 with research underway during July 1976. Work has proceeded to the point that a comparison measurement program has been completed at White Sands with the completed Doppler system.

Progress During Reporting Period:

The full dual array radar system was assembled and tested at White Sands Missile Range (WSMR), NM, between November 30 and December 16, 1976. The radar was installed adjacent to a 500 ft (152 m) instrumented tower at Launch Complex 36 (LC 36). Center of Array 1 was located approximately 300 ft east of the tower. The center of Array 2 was placed 50 ft south of the center of Array 1.

Initial system setup required approximately 120 man-hours. Tape recording commenced at 16:59, December 3. System checkout was complete by 12:05, December 5. Three axis data (u, v, and w) were taken from both arrays until 10:50, December 8, 1976. At this time Array 2 was modified to produce single axis data because of the highly reflective nature of the tower. Operation continued in this manner until 15:08, December 13.

The tower at LC 36 is operated under contract to the U.S. Navy in support of ballistic missile and other rocket test firings. The Atmospheric Sciences Laboratory (ASL) has an agreement with the Navy under which ASL acquires data from the tower in support of its own programs. Acquisition of data from the tower requires the presence of ASL, as well as contractor personnel. ASL acquires data on a lowest priority, noninterference basis. For these and other reasons the tower was available only intermittently.

A wind set composed of a cup anemometer and wind vane was mounted at each of the following heights: 8, 23, 38, 53, 69, 91, 122 and 152 m. When operational, the tower produces two or three instantaneous samples per minute of u and v at the eight heights above ground level. Data was output to ASCII magnetic tape. The volume of data, as well as the format of the tower output, complicate the task of drawing conclusions based on the inspection of the raw tape dumps. The major activity over the next weeks will be the reduction and analysis of this data.

It is possible, however, to state the following at this time:

1. The radar is fully operational and reliable. Only two component failures (transmit antenna voice coils) occurred during the test. These were replaced with the system on line.

2. The radar produced 187.25 hours of apparently valid data, 51.75 hours with both arrays taking three axis data and 135.5 hours with three axis data from Array 1 and single axis data from Array 2. The radar was on line approximately 95% of the available 195 hours. All operating periods are rounded to the nearest quarter hour.
3. The tower produced 26 hours of apparently valid data. The tower was on line approximately 13% of the available time. All operating periods are rounded to the nearest quarter hour.
4. The radar and tower produced apparently valid data simultaneously for a total of 23.75 hours.
5. Acoustic reflections from the tower produced significant errors in the radar data. The magnitude of these errors is not known at this time.

Expected Progress in the Next Period:

It is expected that progress during the next reporting period will include: 1) the completion of the comparison between the acoustic radar and tower wind measurements, 2) assessment of the nature and extent of the interference and errors caused by acoustic signal reflections by structures, and 3) demonstration of the acoustic radar system at a site of interest to the Wind Energy Conversion Program.

Reports and Publications:

To date there have been no reports or publications under this contract. However, the following presentations are related to the instrument system being evaluated:

Davey, R. F., "A Coherent Acoustic Doppler Radar for Real Time Wind Measurements," presented at 17th Conference on Radar Meteorology, Seattle, WA, October 1976.

3.4 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
1919 14th St. #401
Boulder, CO 80302

Principal Investigator:

Jack Park (213) 367-8291

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.

Current Status:

This program was funded in September 1976 and is to be completed in March 1977. The program is on schedule.

Progress During the Reporting Period:

Following preliminary work, questionnaires were distributed to individuals throughout the United States with past and current experience with small wind energy conversion systems in November. These questionnaires were followed by interviews. The results of the questionnaires and interviews have been compiled on a regional basis.

Expected Progress in the Next Period:

The regional compilations are to be combined into a final report. That report is scheduled to be complete in draft

form for review at the end of January. Publication of the final report should occur in March 1977.

Reports and Publications:

None.

3.5 Vegetation as an Indicator of High Wind Velocities (4a)

Contract No.: EY-76-S-06-2227

Oregon State University
Corvallis, OR 97331

Principal Investigator:

E. W. Hewson (503) 754-4557

Contract Monitor:

R. L. Drake (509) 946-2961

Objective:

To calibrate, in terms of wind velocity and persistence of wind, wind deformed vegetation of various types. The purpose is to permit the identification of potential wind power sites in the initial stages of assessing the wind power potential in complex terrain without elaborate wind measurement programs.

Current Status:

This project was initiated in June 1976. The current contract will run through May of 1977, however, the project is planned for two years.

Progress During Reporting Period:

During the first six months of this project activity has occurred on several tasks and at several field locations. The nature of this research is such that no task has been completed at this time; however, several significant activities have occurred. They are as follows:

1. Required recording anemometer and wind vane equipment have been purchased for the studies in the Columbia Gorge;

2. A report was written for the Workshop on Biological Wind Prospecting, see Publications;
3. A small feasibility study was initiated to consider the possibility of using the Corps of Engineers' aerial photographs to locate wind deformed vegetation; it may be possible to identify flagged trees on the photographs taken from as high as 800 meters above the ground;
4. An Aerovane anemometer has been mounted on Augspurger Mountain, WA; this site has many flagged trees in the area and is also one of the 17 candidate sites for the installation of the large ERDA wind turbine;
5. An anemometer and recorder have been installed along the Columbia River at Lyle, WA, as well as, on a ranch near Crown Point, OR; both of these sites exhibit deformed vegetation due to wind effects;
6. An installation has been set up on Yaquina Head on the Oregon Coast near Newport, OR; this site will be used to study the effects of wind on vegetation that is unprotected and on vegetation that is protected from the wind by a screen-type barrier. It is expected that the protected vegetation will have a different growth pattern than the vegetation exposed to the full impact of the wind.

Expected Progress During the Next Period:

During the next six month period, significant results should be obtained in this project. The reason for this optimism is at least threefold: one, several sites are already instrumented and meteorological data and photographs of vegetation are being obtained; two, more potential study sites are being identified and instrumentation will be installed as money permits; three, the next six months will contain a significant part of the growing season for the vegetation and during this period high winds are known to be present.

Some of the results that are anticipated are as follows:

1. The eccentric tree ring structure of specimens from Lyle, Crown Point, and Augspurgen Mountain will be studied and an attempt will be made to correlate the degree of eccentricity with wind speed and persistence.
2. The shapes and axis-tilts of trees in all instrumented areas will be correlated with wind speed and persistence.
3. On Yaquina Head, the relationship between the growth of vegetation without protection and with protection versus wind speed and persistence will be determined.
4. Since instrumented sites exist at the eastern and western end of the Columbia Gorge, as well as the center, and since there is a site on the Oregon Coast, an attempt will be made to separate the effects on vegetation due to winter storms, persistent winter winds, persistent winds during the growing season, salt effects, severe winds during summer time storms, and other biological factors.

Reports and Publications:

To date, there have been no formal reports or papers published under this contract. However, two reports on related research are listed below:

Hewson, E.W., Baker, R.W., and Brownlow, R., Fourth Progress Report on Research on Wind Power Potential in Selected Areas of Oregon, Rep. No. PUD76-4, Dept. of Atm. Sci., Oregon State University, Corvallis, OR 97331, 43 pp, June 1976.

Hewson, E.W., Proc. of a Workshop on Biological Wind Prospecting, held at Douglas Lake, Michigan on August 16 to 20, 1976, 92 pp.

3.6 Locating Areas of High Wind Energy Potential by Remote Observations of Aeolian Geomorphology and Topography (4b)

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

University of Wyoming
Department of Geology
P. O. Box 3006
Laramie, WY 82071

Principal Investigator:

Ronald W. Marrs (307) 766-2330

Contract Monitor:

David S. Renne (509) 946-2984

Objective:

To develop satellite imagery as a tool for rapid assessment of wind energy potential by identifying quantitative relationships between wind characteristics and aeolian morphologic features.

Program Status:

The current program is the continuation of work initially funded by the National Science Foundation in 1975. Completion of the work is scheduled for July 1978.

Progress During Reporting Period:

Tasks worked on during the reporting period include:

1) assessment of regional applicability of LANDSAT imagery as a tool for locating areas of high wind energy potential; study of parameters which would allow quantitative estimation of wind characteristics; 3) collection of data on the utility of stabilized dunes as indicators of present-day wind characteristics. Work has not been completed on any of these tasks.

NCAR aircraft data collected in support of this program in January and February 1976 were received and are being analyzed. Preliminary synthesis of the data tends to confirm several important wind/land form relationships. Further data collection flights were conducted in November and December 1976.

A summary report on the initial NSF/ERDA contract was completed and is currently being reviewed.

Expected Progress During the Next Period:

Results achieved should include determination of the extent to which surface wind energy can be quantified from remote sensing of active dune features. During this time, field sampling of active dune characteristics should be completed and rate of dune movement analyzed. By combining this information with a synthesis of surface wind data, it should be possible to quantify the wind speed over the Wyoming dunes and specify the accuracy of the result.

A regional analysis of active dune features will be completed using LANDSAT imagery, and aeolian features will be used to make a regional assessment of wind power.

Results and Publications:

Kolm, K., Marrs, R., Marwitz, J., and Fletcher, J.,
Evaluation of Wind-Energy Sites from Aeolian Geomorpho-
logic Features Mapped from LANDSAT Imagery, First Re-
sults, Departments of Geology and Atmospheric Sciences,
University of Wyoming, NSF Grant AER 75-00598.

3.7 Wind Power Studies (5a)

Contract No.: UCRL-50034-76

Lawrence Livermore Laboratory
University of California
Livermore, CA 94550

Principal Investigator:

D. M. Hardy (FTS) 457-1100

PNL Contact:

R. L. Drake (509) 946-2961

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).

Current Status:

This program started at the beginning of FY 76 and is to continue into FY 78, and possibly into FY 79. 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:

During this period a field measurement program was initiated on the Island of Oahu, Hawaii, to supplement existing wind velocity measurements with data obtained specifically for wind-energy purposes, to provide current wind velocity data

during favorable wind conditions, and to focus measurements on locations important in the numerical analysis of wind-energy potential. The actual field measurements were initiated during August and September 1976 at locations where high wind velocities were expected and at sites important in numerical studies of the regional wind field. Instrument systems to record wind speed and direction were installed at Laie, Kahuku, Waialua and Mokuleia.

The northern portion of Oahu was selected for study, with highest priority given to the Kahuku Point and Kaena Point areas. Selection was based upon the expected occurrence of velocity maxima and the absence of regularly reported velocity measurements.

Northeast winds predominate during trade wind conditions on Oahu. Under such conditions, the wind first encounters the steep Koolau, or windward, mountain range. After flowing over and around the windward range, the wind crosses a valley and then encounters the Waianae or leeward range. Four measurement points were chosen in part to document the air flow as it approached these two mountain barriers, flowed around them, and crossed the valley between them. Few measurements along the north shore of the island existed prior to the present study.

The Laie measurement point is near sea level and is well exposed to the prevailing offshore trade winds. The Kahuku measurement point is in the hills of the windward range and is also well exposed to offshore winds. The Waialua measurement point is in the valley between the windward and leeward ranges. The Mokuleia measurement point is located on the ridge of the leeward range.

Laser scintillation anemometers (LSA) which measure path-averaged wind speed were used in the Kahuku Point and Kaena

Point areas. The LSA measurements confirmed that intensified wind speeds occur over distances of a kilometer or more in length.

Analog wind data are being acquired from numerous cooperating agencies which conduct wind velocity measurements in southern Oahu. These data will be digitized and analyzed, and will supplement the data obtained by Lawrence Livermore Laboratory at the four locations in northern Oahu.

Additional numerical model calculations are planned after these data have been reduced, evaluated, and organized for model use.

Expected Results During the Next Period:

Work will proceed on the following tasks:

1. Applications of the principal component analysis methods to climatological data;
2. Collection and digitization of data from agencies on Oahu, Hawaii;
3. Limited maintenance of existing wind measurement stations on Oahu;
4. Processing of data collected in the summer of 1976;
5. Data - banding of data from all sources for Oahu;
6. Model adaptations for annual assessments;
7. Model calculations;
8. Reporting of work and conclusions.

Reports and Publications:

The following reports were published 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.

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.

The following reports were published prior to the current 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.

3.8 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:

B. E. Freeman* (714) 459-0211

Contract Monitor:

R. L. Drake (509) 946-2961

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.

Current Status:

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

Progress During Reporting Period:

Tasks performed during the last six months represent a continuation of the development of techniques for the calculation of the meteorological and climatological characteristics of potential wind energy sites. Emphasis during the reporting period has been placed first on making the methodology of

* R. M. Traci (714) 459-0211 has replaced B. E. Freeman as Principal Investigator.

site selection more specific, and, second, on increasing the accuracy and efficiency of tools developed earlier to calculate the local meteorological effects of a given synoptic pattern. In both areas the basic work is now complete.

The site selection methodology consists of (1) obtaining climatological data, (2) analyzing the data into a compact representation of the principal weather patterns for use as initial conditions in calculations, (3) performing calculations that account for local effects, and (4) combining the calculated results into a wind energy climatology for candidate wind energy sites.

Various methods for analyzing the climatological data obtained from NWS stations in the vicinity of wind energy sites were studied. A promising technique known as Empirical Orthogonal Eigenfunction (EOE) analysis has been investigated and appears to be applicable to the input data requirements of the objective analysis codes as well as the primitive equation models. With this method the principal weather patterns for the region are identified, thereby greatly reducing the number of calculations required to construct a local climatology.

During the reporting period the efficiency and accuracy of SIGMET family of computer codes have been substantially improved, and a method for determining an optimum choice of code parameters and initial data has been developed. Techniques developed in the course of this work constitute advances in the art of mesoscale meteorological simulation.

The multidimensional SIGMET codes have been successfully reformulated to increase their calculation speed by up to an order of magnitude. This has been accomplished by the semi-implicitization technique in which gravity waves, traveling with phase speeds up to 300 m/s, can be calculated without the necessity of limiting the time interval with an explicit

stability criterion. This decomposition of the solution contributes substantially to numerical efficiency. Test calculations indicate that the anticipated gains in calculational efficiency are realized without numerical difficulty.

In the last two months of the reporting period a new one-dimensional (vertical) version of the SIGMET computer code was written. This code serves the function of testing the physical processes contributing to the evolution of the boundary layer and the mathematical implementation of them. With this code, the factors incorporated in the multidimensional SIGMET codes can be checked out with much smaller computing expense, and the parameters required for the meso-scale calculations can be determined in advance. This code is expected to be very useful in future applications, where it will be used to determine initial conditions and assess sensitivity to input data.

Work was performed on simple meteorological computer codes, as well as on the more complex codes, SIGMET, because the simple codes are less expensive to run and may be entirely adequate in many cases. Two versions of an Objective Analysis (OA) type of simulation have been adapted and applied to the siting task. These are MODMAT, a modified version of Lawrence Livermore Laboratory's MATHEW code, and WEST, a conceptually similar formulation developed at SAI. Comparisons were made between these two codes and both were applied to the calculation of winds in the Rush Valley near the Dugway Proving Ground in northwestern Utah. Results were similar, with the WEST code showing greater flexibility in accounting for the observed data. A second type of simple wind simulation, based on the shallow fluid approximation, has also been analyzed. It has been concluded that the shallow fluid approximation suffers from serious deficiencies, but that it might nevertheless be useful if properly calibrated.

As summarized above, work to date has concentrated on developing and improving certain elements which make up the siting methodology. These elements include the primitive equation mesoscale simulation models, objective analysis windfield models and collection and reduction procedures for stratifying climatological data. Significant advances have been achieved in each of these areas. Thus, these elements are ready for prototype testing and application to site selection methodology.

Expected Progress During the Next Period:

Many of the elements developed to date are ready for prototype testing and application to site selection methodology. Thus, in the next period prototype applications will be made.

Work will also continue on defining the manner in which the SIGMET simulations can be efficiently combined to complement the inexpensive OA simulations. The use of SIGMET simulations in this manner will be investigated in coming months by comparing SIGMET and OA model calculations of certain model problems.

Another aspect of the method which will receive considerable attention in the short term is the use of the EOE method to stratify climatological data. The efficiency of the method will be evaluated by comparing windfields calculated using the EOE-analyzed data with those calculated using the full time-dependent input data.

Further work on implementation of the SIGMET implicitization scheme is planned since this promises to significantly enhance the computational efficiency of SIGMET calculations. The 1-D version of SIGMET, developed in recent months, will continue to be used to study the sensitivity of the boundary layer to parameters such as the surface roughness, soil thermal conductivity, albedo, and cloud cover. It will also

continue to be used as a test bed for updating physical models being developed for the 2-D and 3-D SIGMET codes and to improve initialization procedures.

Reports and Publications:

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

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

Freeman, B.E., Development of a Wind Energy Site Selection Methodology, RL0/2440-76/4, Sci. Appl. Inc., La Jolla, CA 92038, December 1976.

3.9 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) 549-8311, Ext. 2657

Contract Monitor:

L. L. Wendell (509) 942-2861

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 typically not available.

Current Status:

The present contract began on September 20, 1976, and is to continue until September 20, 1977. The work started during the previous year with NSF funding. Final comparisons of predicted data and validation data are planned for a follow-on year.

Progress During Reporting Period:

The major accomplishment during this reporting period was to prepare the primitive equation model to run the remainder of the case studies required for the statistical prediction routine and to actually complete about 40% of these cases. Preparations have been in progress to start the computation of parameters for the statistical model. Some independent tests of the statistical model were suggested.

Expected Progress During the Next Period:

The case studies of simulated winds generated by the primitive equation model should be completed, as well as the computation of the parameters for the statistical model. The predictions of the wind statistics at five locations where RAPS wind data is available should also be completed. The data from these stations should be acquired during the next reporting period and the editing of the data should be well under way in preparation for comparison with the predicted wind data.

Reports and Publications:

No publications or reports have been released under the current contract. However, a form of the primitive equation model used in the prediction of wind statistics is described in the following article.

Vukovich, F.M., Dunn, J.W., IV, and Crissman, B.W.,
"A Theoretical Study of the St. Louis Heat Island:
The Wind and Temperature Distribution," J. Appl. Meteor.
15, 417-440, May 1976.

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

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

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

Principal Investigator:

S. C. Crow (508) 826-5543

Contract Monitor:

R. L. Drake (509) 946-2961

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. The model used is a linearized, mass-conserving system that employs the use of Fast-Fourier transforms. Areas with adverse pressure gradients, which are expected to be poor wind turbine sites, will also be identified.

Current Status:

The current program is a one year effort that was initiated in September 1976.

Progress During Reporting Period:

During the first quarter of this contract, work was initiated and/or completed on three tasks: atmospheric modeling, two-dimensional computations, and theory of airflow over three-dimensional mountains. The task on atmospheric modeling is complete. This task consisted of the following subtasks:

1. A review of the literature on mountain airflows;
2. The development of a two-layer model of the atmosphere that incorporates a change in lapse rate and a possible temperature inversion layer;
3. The derivation of Fourier integral expressions for the wind speed at ground level on a two-dimensional mountain and for the streamlines above the mountain.

The task on two-dimensional modeling is not completed; however, it is ahead of schedule. Work completed to date is as follows:

1. Development of a code to plot and compute wind speeds over an isolated two-dimensional mountain for a one-layer atmospheric model;
2. Development of a code for a two-layer model;
3. The analysis of resonant lee waves in the presence of a strong inversion layer.

Finally, the task dealing with three-dimensional mountains has been initiated. The first efforts have been concerned with the Fourier-integral representation for ground level wind speed and for streamlines around the mountain.

Expected Progress During the Next Period:

During the next six month period the following tasks or sub-tasks will be completed:

1. Two-Dimensional Computations will be completed. Included in this work will be an evaluation of the sensitivity of the results to the assumption of a uniform wind velocity profile which has been questioned. Modification of the assumption will be made if necessary and feasible.

2. Theory of Airflow Over Three-Dimensional Mountains will be completed. The results of this work will be a Fourier integral representation for the airflow. This representation will be put into a form for efficient computation.
3. Code for Three-Dimensional Mountain Airflows will be completed. This task consists of developing a computer code for the computation of Fourier integrals derived in the previous task.
4. Computation of Wind Fields will be initiated. This task is concerned with the generation of a set of wind-field plots for typical topographical and meteorological conditions.

The expected output of the program is a set of contour maps of wind speed for selected combinations of wind regimes, atmospheric densities and mountain shapes.

Reports and Publications:

None.

3.11 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) 946-2961

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.

Current Status:

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

Progress During Reporting Period:

Work during the first quarter (September 15 to December 15, 1976) has been subdivided into two categories: the climatological basis, and modeling. The purpose of the climatological basis task is:

1. to determine definable space and time subdivisions for the coastal zone under consideration; and
2. to specify, for the defined spatial and temporal subdivisions, the variables and/or parameters required by the model.

The initial work on the climatological basis has dealt with the coastal region from the Mexican border to New England. The following coastal regions appear as definable climatological entities:

Region I	Gulf of Mexico:	Yucatan to Tampa Bay
Region II	Florida Peninsula:	Tampa Bay to Cape Kennedy
Region III	South East Coast:	Cape Kennedy to Cape Hatteras
Region IV	Central East Coast:	Cape Hatteras to Cape Cod
Region V	North East Coast:	Cape Cod to Canadian Border

Corresponding to these regions are critical time zones. The differences between one time zone and another time zone are based on atmospheric circulation patterns and the temperature regimes of the land and water. For all regions, except Region I, the time zones are given by:

Spring:	May 6 - June 20
Summer:	June 20 - August 10
Fall:	August 10 - November 6
Early Winter:	November 6 - January 1
Mid-Winter:	January 1 - April 1
Late Winter:	April 1 - May 6

Work is in progress in the following areas: defining the time zones for Region I, and collecting and tabulating the data for the meteorological quantities that will be needed in the modeling activities.

In the modeling activities, the existing three-dimensional model (see Publications) has been evaluated in terms of the coastal wind energy problem. Work is in progress to determine whether a two-dimensional model, which will be far more efficient than the 3-D model, will do the job. The 2-D model is now ready for testing.

Expected Progress During the Next Period:

During the next six month period, the work on the Climatological Task will consist of the following:

1. Definition of the time zones for Region I;
2. Verification of the subdivisions both in space and time;
3. Specification of the meteorological variables required for input to the numerical model; these are
 - a) mean surface velocity fields
 - b) mean surface temperatures, land and ocean
 - c) mean temperature profiles to maximum of 100 mb
 - d) mean velocity fields to maximum of 100 mb
 - e) mean roughness values, land and ocean;
4. Specification of the configuration and topography of the given regions.

In the Modeling Task, the testing of the 2-D model will commence as soon as the statistics from the climatological study become available. Once the first climatological data are available the steps will be to test the model, obtain model predictions of the coastal wind regime, test these against observed wind statistics for a suitable (from model assumptions) coast line, and introduce coast line orientation and coastal topography.

After the testing procedures are completed, the model (either the 2-D or 3-D) will be used to generate the promised output for the different regions and critical time zones.

The final output of the research will include a matrix of results giving the wind energy potential of coastal sites as a function of climatic, oceanographic, and topographic parameters and variables.

Reports and Publications:

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

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

Pielke, R.A., and Mahrer, Y., 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.

3.12 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 contained within a region (i.e., a mountain, valley, etc.) selected for wind energy utilization and to develop techniques for wind energy enhancement based on microscale site modification.

Current Status:

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

Progress During Reporting Period:

The primary product of this task will be a Design Manual describing wind characteristics and their relationships to terrain features as they apply to wind turbines. The Design Manual will have four major sections. These are: General Wind Characteristics, Engineering Philosophy, Portfolio of Terrain Features and Design Criteria Relative to Winds Over Terrain. An outline of the contents of the Design Manual is attached.

An assessment has been made of the effects of surface roughness changes and shelterbelts located upwind of a wind turbine on the wind field at the turbine site. Step-by-step procedures have been developed for calculating the wind field modification due to surface roughness changes and these have been incorporated into a draft manual specifically designed to assist in maximizing wind turbine output as a function of turbine location relative to the terrain features.

Expected Progress During Next Period:

Step-by-step procedures will be developed for shelterbelts and work will begin on assessing the wind field modifications due to hills which can be represented as streamlined objects or two-dimensional bluff objects.

Reports and Publications:

Frost, W., "Comments Pertaining to Wind Turbine Generator Design," in Proceedings of the Wind Characteristics Workshop, BNWL-2220-WIND-1, Battelle, Pacific Northwest Laboratory, Richland, WA 99352, 125 p., to be published.

Initial Outline of the Design Manual

1. General Wind Characteristics

1.1 Introduction

1.2 Atmospheric Boundary Layers

1.2.1 Mathematical Models

1.2.2 Power Law in Logarithmic Law

1.2.3 Turning Layer

1.2.4 Tunderstorms

1.2.5 Major Fronts

1.2.6 Mountain Flows

1.2.7 Sea Breezes

1.3 Design Winds

1.3.1 Reference Winds for General Geographical Areas

1.3.2 Statistics of Reference Winds

1.3.3 Design Wind

2. Engineering Philosophy

2.1 Criteria Concerning Site Selection Relative to Terrain Features

2.2 Criteria Concerning the Influence of Wind Direction

2.3 Criteria Concerning the Influence of Unusual Wind Conditions Like Storms

2.4 Criteria for the Relationship Between Rotor Diameter and Hub Height at Given Locations

2.5 Criteria for the Relationship Between Rotor Profile and Wind Condition

2.6 Criteria for the Relationship Between the Number of Blades of the Rotor and the Typical Wind Condition at the Selected Location

2.7 Criteria for the Relationship Between Energy Input Optimum and Structural Design

3. Portfolio of Terrain Features

3.1 Flat Terrain with Surface Roughness Changes

3.1.1 One Surface Roughness Change

3.1.2 Two and More Roughness Changes

3.1.3 Shelter Belts

3.1.4 Cavities (roads through woods, power lines)

- 3.2 Irregular Terrain
 - 3.2.1 Irregular Terrain with Sharp Contours
 - 3.2.2 Irregular Terrain with Round Contours
- 4. Site Selection Criteria Relative to Winds Over Terrain Features
 - 4.1 Flat Terrain
 - 4.1.1 One Surface Roughness Change
 - 4.1.2 Two and More Roughness Changes
 - 4.1.3 Shelter Belts
 - 4.1.4 Cavities
 - 4.2 Irregular Terrain
 - 4.2.1 Sharp Contours
 - 4.2.2 Round Contours

3.13 Sites for Wind Power Installations: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence - Tabulated Experimental Data (5g)

Contract No.: EY-76-S-06-2438
Colorado State University
Fort Collins, CO 80523

Principal Investigator:

R. N. Meroney (303) 491-8572

Contract Monitor:

R. L. Drake (509) 946-2961

Objective:

To investigate the local flow fields over simple geometric shapes, such as, two dimensional triangular and sinusoidal hills, ridges with canyons and notches, converging valleys and ridges, and three-dimensional conical hills using a wind tunnel.

Current Status:

The program is in the second year of a proposed three year study. The current contract was initiated in June 1976; proposed completion date for the project is May 1978.

Progress During Reporting Period:

During the first year of this project, the measurements of wind speed, static pressure variation, and turbulence intensity were completed over two-dimensional triangular and sinusoidal shaped hills. The hill aspect ratios studied ranged from $1/2$ to $1/6$ with some data available at $1/20$. Hence, during this reporting period, the above data was analyzed and then organized in tabular and graphical forms. Also, during this period, models of canyons, notches, other ridge shapes, and three-dimensional conical hills were constructed for future wind tunnel tests.

Since the reduction of data was the major analytical activity during the reporting period, it will be described in detail in the following paragraphs.

A set of computer programs has been developed in order to represent the data in a way that usage becomes relatively easy. Contour lines can be generated for the pressures, velocities and turbulence in the flow field over the two-dimensional hill models. Also, the stream line pattern can be visualized. In the process of the generation of contour lines a number of steps are built in order to get rid of inconsistencies in the data. A flow chart of the procedure was given in the first annual report (see Publications).

Some of the features of the data reduction procedure are given below:

1. The measurements obtained from a vertical traverse are smoothed and interpolated using cubic spline functions.
2. A microfilm plot is generated of each vertical profile to see if the data points look consistent with their neighboring points.
3. Subsequent vertical profiles are checked for consistency. If there is an indication of an erroneous data point then that particular point can easily be ignored.
4. Any portion of the data set can be retrieved separately.

Other features have been added for the generation of smoothed velocity profiles. The magnitude of the velocity changes drastically close to the surface and in the wake-main flow interface. Those regions require special attention during the measurements as well as during the reduction procedure.

The consistency between successive velocity profiles may be improved by incorporating the assumption that at a height of 10 times the hill height above the hill the stream-line stays horizontal. This assumption is partially justified

by the fact that the variation in velocities generated at that height agrees to a high degree with measurements attained from a horizontal traverse.

An extensive set of data, listed in tabular form, has been published. The tables include the evaluated static pressure, mean velocity, and longitudinal turbulence intensity data. In addition, the tables contain information about the hill configuration, roughness, stratification, and reference approach velocity.

Expected Progress During the Next Period:

During the next six months work will be conducted on the following tasks:

1. The analysis of the data collected on the triangular and sinusoidal ridges will be completed;
2. Wind tunnel testing of the canyons, notches and alternate ridge shapes will be initiated; and the data will be analyzed;
3. Wind tunnel testing and data analysis of the three-dimensional conical hills will be initiated; and
4. Preparation for model validation will begin.

The knowledge gained through these laboratory measurements will provide input for siting handbooks. In addition, the use of the wind tunnel for determining the optimum location of wind turbines in an actual situation will be validated by comparing wind tunnel results with pertinent sets of field data for the actual terrain feature in question.

Reports and Publications:

Reports and publications during the reporting period are given below:

Meroney, R.N., Sanborn, V.A., Bouwmeester, R.J.B., and Rider, M.A., 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., Sanborn, V.A., Bouwmeester, R.J.B., and Rider, M.A., "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., Sanborn, V.A., Bouwmeester, R.J.B., and Rider, M.A., 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-76-S-06-2438/76/1, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523, 57 pp., December 1976.

3.14 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.

Current Status:

This program was initiated in June 1976 and is nearly complete. A draft report has been written and is being prepared for review.

Progress During Reporting Period:

Approximately 130 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. 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 scopes of the field programs in which the various data sets were collected were diverse as was the terrain. The data sets were originally used to study monsoon-sea breeze effects, lake breezes, island effects, valley-slope winds, severe downslope winds, airflow and turbulence in complex mountainous terrain, flow in urban areas, and meso-scale severe weather. A majority of these studies involved

multiple wind measurement sites, but some with a single site have been included because of the nature of the study and the terrain.

Expected Progress During Next Period:

A draft report is expected to be released for review in February 1977 and the Final Report should be published in late March or early April.

Reports and Publications:

Orgill, M.M., Survey of Wind Measurement Field Programs, BNWL-2220-WIND-3, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 64 p., to be published.

3.15 National 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

Objective:

To evaluate and analyze various wind statistics and simulated wind energy production statistics of wind turbines in various regions of the U.S.

Current Status:

The present contract began in May 1976 and continues until May 1977. It is a continuation of research begun under a grant from the National Science Foundation.

Progress During Reporting Period:

Work on National Science Foundation Grant No. AER75-00547 was completed and a final report prepared. The performance characteristics were simulated for large dispersed arrays of 500 kW - 1500 kW wind turbines producing power and feeding it directly into the utility distribution grid in the New England - Middle Atlantic and the Central U.S. regions. These studies show that, in New England, arrays of 500 kW generators could produce (on an annual average basis) from 190 to 240 kW per generator, with Central U.S. average output being about 200 kW per 500 kW per generator, annual average. Output from arrays of 1500 kW generators (similar in design to the new ERDA Mod 1 unit) would produce

240 to 340 kW per generator in New England and about 325 kW in the Central U.S. Best output was estimated from a 1125 kW design which had larger blades and lower cut-in and rated speed than the 1500 kW unit. The 1125 kW machine would average about 460 kW on an annual basis in the Central U.S.

Despite comparable wind regimes in coastal New England and in the Central U.S., wind power is potentially closer to being cost-effective as a fuel saver in New England. This is because of the heavy reliance on expensive fuels in New England as compared with the Central U.S. area. Details of cost-effectiveness as a fuel saver will depend on the reliability with which wind can displace the expensive peak load fuels. Dispersal of the wind turbines into large arrays enhances this reliability. Power levels of 200 kW per 1500 kW generator were found to have reliability (without storage) as high as 60% in New England and over 75% in the Central U.S. Power output reliability of 200 kW per generator for the 1125 kW wind turbines ranged seasonally from 77% to 93% in the Central U.S.

By array power return time analysis, it is estimated that 24 to 48 hours of storage would increase the power reliability of 200 kW per 1500 kW generator to about 95% in New England, and to better than 95% in the Central U.S. For the 1125 kW unit in the Central U.S., 24 hours storage would increase the reliability of 200 kW per generator to about 99%.

Table 12 of the final report is presented here as an example of the results reported. It lists the storage time in hours (T) required to achieve a reliability R (%) of having an average available power of 10, 100 and 200 kW per generator. In the preparation of this table it has been assumed that the storage is fully charged at the beginning of each "drain" period.

Time autocorrelation and spatial cross correlations versus site separation were determined. Applications to simplified analysis of array dynamics have been made. Figure 14 of the final report included here shows an increased reliability that is typical of going from an individual site to an array configuration. Significant improvements are observed for average power outputs of 100 and 200 kW per generator. No storage facilities are assumed.

Similar studies are being pursued for the Great Lakes and Pacific Coast regions of the United States.

Other work during the reporting period was related to wind speed distributions. Wind data from 140 sites across the United States have been developed to derive wind speed probability density functions and cumulative frequency distributions for various heights and annual mean wind speeds. Representative values have been derived for the parameters C and k of the Weibull distribution that is assumed to describe the mean wind speed. Wind turbine capacity and energy recovery factors have been examined.

Expected Progress During the Next Period:

The Great Lakes and Pacific Northwest regions will be continued. Diurnal variations will be studied more extensively, and wind power and degree day correlations will be examined. The simplified array analysis will be extended to produce more accurate estimates.

In addition, simulated time wind fields will be studied for their effects on WECS power outputs; vertical shear will also be incorporated.

Reports and Publications:

Justus, C.G., and Mikhail, A., "Height Variation of Wind Speed and Wind Distribution Statistics," Geophys. Res. Letters, 13, 261-264, May 1976.

Justus, C.G., Hargraves, W.R., and Yalcin, A.,
"Nationwide Assessment of Potential Output from Wind
Powered Generators," J. Appl. Meteor., 15, 673-678,
July 1976.

Justus, C.G., "Wind Energy Statistics for Large Arrays
of Wind Turbines (New England and Central U.S. Regions),"
in Proceedings of International Solar Energy Society
Conference, Winnipeg, Manitoba, August 15-20, 1976.

Justus, C.G., Wind Energy Statistics for Large Arrays
of Wind Turbines (New England and Central U.S. Regions),
ERDA/NSF-00547/76/1, August 1976, 116 p.

Justus, C.G., Reference Wind Speed Distributions and
Height Profiles for Wind Turbine Design and Performance
Evaluation Applications, ORO/5108-76/4, August 1976,
94 p.

Justus, C.G., "Wind Energy Statistics for Large Arrays
of Wind Turbines (New England and Central U.S. Regions)"
submitted to Solar Energy.

TABLE 12

Reliability of Power Levels of 10, 100, and 200 KW per Generator, With and Without Storage. 7 Site Coastal Array or Individual Site. T is Storage Time in Hours. R is Reliability in Percent. T = 0 Indicates No Storage.

	JAN						APR						JUL						OCT					
	GE			KAMAN			GE			KAMAN			GE			KAMAN			GE			KAMAN		
	500	T	R	500	T	R	500	T	R	500	T	R	500	T	R	500	T	R	500	T	R	500	T	R
10 KW/GEN.	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %	hrs. %
IND.	0 78	0 60	0 73	0 57	0 80	0 60	0 66	0 53	0 73	0 55	0 72	0 44	0 63	0 38	0 74	0 51	0 67	0 46	0 74	0 51	0 67	0 46	0 74	0 51
ARRAY	0 98	0 91	0 94	0 57	0 99	0 93	0 83	0 74	0 96	0 89	0 99	0 87	0 92	0 80	0 97	0 87	0 91	0 81	0 97	0 87	0 91	0 81	0 97	0 87
100 KW/GEN.	0 64	0 54	0 57	0 51	0 66	0 53	0 66	0 48	0 54	0 48	0 54	0 36	0 38	0 31	0 59	0 44	0 46	0 40	0 59	0 44	0 46	0 40	0 59	0 44
IND.	0 83	0 75	0 66	0 66	0 83	0 74	0 66	0 66	0 66	0 66	0 70	0 56	0 35	0 42	0 75	0 63	0 55	0 54	0 75	0 63	0 55	0 54	0 75	0 63
ARRAY	20 90	22 90	31 90	32 90	13 90	17 90	27 90	21 90	27 90	21 90	15 90	22 90	26 90	28 90	19 90	28 90	34 90	39 90	27 95	42 95	48 95	66 95	49 99	82 99
IND.	27 95	28 95	36 95	36 95	15 95	19 95	35 95	27 95	35 95	27 95	17 95	26 95	32 95	35 95	27 95	42 95	48 95	66 95	27 95	42 95	48 95	66 95	49 99	82 99
ARRAY	47 99	44 99	46 99	46 99	20 99	23 99	45 99	40 99	45 99	40 99	22 99	36 99	57 99	58 99	49 99	82 99	79 99	87 99	49 99	82 99	79 99	87 99	49 99	82 99
200 KW/GEN.	0 56	0 49	0 43	0 45	0 59	0 48	0 65	0 62	0 38	0 41	0 44	0 31	0 21	0 22	0 51	0 40	0 30	0 32	0 51	0 40	0 30	0 32	0 51	0 40
IND.	0 65	0 62	0 42	0 50	0 65	0 62	0 43	0 51	0 43	0 51	0 44	0 37	0 17	0 23	0 53	0 49	0 30	0 38	0 53	0 49	0 30	0 38	0 53	0 49
ARRAY	29 90	28 90	53 90	45 90	20 90	25 90	40 90	38 90	40 90	38 90	29 90	33 90	79 90	54 90	39 90	38 90	68 90	56 90	39 90	38 90	68 90	56 90	39 90	38 90
IND.	39 95	38 95	68 95	59 95	25 95	33 95	53 95	52 95	53 95	52 95	37 95	49 95	104 95	71 95	53 95	48 95	103 95	77 95	53 95	48 95	103 95	77 95	53 95	48 95
ARRAY	66 99	64 99	88 99	83 99	37 99	43 99	79 99	79 99	79 99	79 99	60 99	110 99	124 99	124 99	80 99	74 99	162 99	128 99	80 99	74 99	162 99	128 99	80 99	74 99

FIGURE 14 - Power Output Frequency Distribution for GE 500 kW Wind Turbines, 7 Site Coastal Array in January. (See Appendix B for Discussion of Interpretation)

3.16 Stochastic Modeling of Site Wind Characteristics (6b)

Contract No.: EY-76-S-06-2342
Northwestern University
Department of Civil Engineering
Evanston, IL 60201

Principal Investigator:
R. B. Corotis (312) 492-3453

Contract Monitor:
J. C. Doran (509) 942-2861

Objective:

This program is intended to provide information and techniques for improving the capability of identifying and selecting sites for wind energy conversion systems, and for estimating the energy conversion systems, and for estimating the energy to be obtained. Probabilistic models are to be formulated for various wind characteristics of interest.

Current Status:

This program was initiated on January 15, 1975, and is currently funded through September 1977. Initial research was under the auspices of the National Science Foundation.

Progress During Reporting Period:

The first phase of this program has been completed by the publication of a final report in which a number of computer programs are documented. The principal program is designed to process data (hourly wind velocities) to produce a summary of some of the more important wind characteristics at a site, including mean, standard deviations, and skewness. An analysis was made of the results obtained from seven locations, and from this, criteria were obtained for establishing the minimum duration of sampling required for

determining mean wind values to a specified accuracy with a specified degree of confidence. An example of the results contained in the report is given in the accompanying table (Table 2.9). This table indicates that much less data is required to estimate the mean wind speed with a given accuracy and confidence level than is required to estimate wind power with the same accuracy and confidence. For example, to estimate the summer wind speed to within 10% with 95% confidence requires 2.7 independent months of data collection. To estimate summer wind power to the same accuracy and confidence would require 29.2 months of independent data. It was shown that not all data are independent of each other, and the number of real months required for a given number of independent months was determined.

Run duration statistics for wind speeds above and below two reference values were also evaluated; a stochastic model of persistence was developed based on these results. The probability of runs above or below a fixed level was shown to be reasonably well described by a two parameter model; these parameters were, in turn, simply related to the average wind velocity at a site, regardless of season or area (although based on a limited number of locations). Run duration was examined for dependence on length of preceding runs, but no significant effects were found.

Autocorrelations and cross correlations of wind have been examined. The variations of these correlation functions with time were determined, as were the spatial variations of the maxima in the cross correlations. Diurnal fluctuations were noted in the temporal behavior of both auto and cross correlations.

Comparisons of Rayleigh and Weibull distribution fits to observed hourly wind velocity histograms were made, with reasonable fits obtained for each. The implication is that

knowledge of the mean wind alone is sufficient to describe the velocity probability density function adequately.

Expected Progress During the Next Period:

The results from programs already developed will be extended by inclusion of the additional data sources from more diverse geographical areas. Directional persistence of the wind will also be examined, in a manner similar to that used to analyze run duration statistics. Shorter time scale data, if available, will make these studies particularly valuable. The dynamic behavior of small scale arrays may also be studied if suitable data is obtained. Finally, additional probability models will be examined that may permit simple analyses of limited sample data to be used to provide information on wind characteristics which normally require extensive data records.

Reports and Publications:

Corotis, R.B., "Stochastic Modeling of Site Wind Characteristics," ERDA/NSF-00357/76/1, November 1976, 298 pp.

TABLE 2.9 Confidence Level Ranges for Velocity and Power by Location and Season.

VARIABLE	LOCATION	SEASON	90% CONFIDENCE LEVEL						95% CONFIDENCE LEVEL					
			± 5%		± 10%		± 20%		+ 5%		+ 10%		+ 20%	
			HRS	MTHS	HRS	MTHS	HRS	MTHS	HRS	MTHS	HRS	MTHS	HRS	MTHS
WIND VELOCITY	MIDWEST	WINTER	317	10.8	79.2	2.7	19.8	0.7	453	15.5	113	3.9	28.3	1.0
		SPRING	340	8.5	85.1	2.1	21.3	0.5	487	12.1	122	3.0	30.5	0.8
		SUMMER	358	9.8	89.7	2.5	22.4	0.6	517	14.2	128	3.5	32.0	0.9
		FALL	343	16.2	85.8	4.0	21.5	1.0	490	23.1	123	5.8	30.8	1.5
	MONTANA	WINTER	352	17.1	87.8	4.3	22.0	1.1	502	24.4	125	6.1	31.3	1.5
		SPRING	344	12.1	85.8	3.0	21.5	0.8	490	17.2	123	4.3	30.8	1.1
		SUMMER	375	7.6	93.7	1.9	23.4	0.5	538	10.9	134	2.7	33.5	0.7
		FALL	308	15.2	77.2	3.8	19.3	1.0	441	21.8	110	5.4	27.5	1.4
WIND POWER	MIDWEST	WINTER	4041	141	1010	35.2	253	8.8	5772	201	1443	50.2	361	12.6
		SPRING	2361	58	590	14.4	148	3.6	3372	82	843	20.6	211	5.2
		SUMMER	7057	125	1764	31.1	441	7.8	10080	178	2520	44.5	630	11.1
		FALL	3927	123	982	30.7	245	7.6	5609	175	1402	43.8	350	10.9
	MONTANA	WINTER	2363	85	591	21.3	148	5.3	3375	122	844	30.4	211	7.6
		SPRING	3636	126	909	31.5	227	7.9	5193	180	1298	45.0	324	11.2
		SUMMER	6091	82	1523	20.5	381	5.1	8699	117	2175	29.2	544	7.3
		FALL	2269	95	567	23.6	142	5.9	3240	135	810	33.8	202	8.4

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

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

Gary Verholek (509) 942-0712

Objective:

To collect and disseminate wind data from nuclear power plant sites that has been submitted to the Nuclear Regulatory Commission (NRC).

Current Status:

The project was initiated in early September and is now 95% complete. A draft report is being produced which provides descriptions of the nuclear power plant site's topography, wind measurement systems, joint-frequency tables of wind speed and direction for all reported levels at each site, velocity-duration curves, and available power.

Progress During Reporting Period

From early September through mid-November, information was collected from extensive microfiche files of nuclear power plant Environmental Reports, Preliminary Safety Analysis Reports and Final Safety Analysis Reports. Wind data were also collected therein and reduced to annual joint-frequency tables (Fig. 1). Because of the variety of cumbersome formats in which the data were reported, data reduction is still being performed for six of the 107 sites. From the wind speed frequency distributions, velocity-duration curves have been constructed and the available power calculated.

A description of each site has been written. A sample site description and data summary are given in Figures 1 and 2.

Expected Progress in the Next Period:

With 95% of all work complete, the remaining work is reproduction and publication of the final report. Graphics should be complete by mid-February, and typing by early February. Following review, duplication, binding and distribution should be completed in March.

Reports and Publication:

Verholek, M.G., Summary of Wind Data from Nuclear Power Plant Sites, BNWL-2220-WIND-4, Battelle, Pacific Northwest Laboratories, Richland, WA 99352, 340 p., to be published.

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).

On-Site Wind Measurements:

The on-site meteorological measurements program was initiated on September 1, 1975. A 152-m tower, at an elevation of 95m (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

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	0.80	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

3.18 Synthesis of Existing National Wind Energy Assessments (9a)

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

Dennis L. Elliott (509) 946-2982

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.

Current Status:

This research started in August 1976. A draft report is being prepared and should be submitted for review in February 1977.

Progress During Reporting Period:

Previous national wind energy assessments have been reviewed with respect to techniques, assumptions, data sets/summaries, and interpolation schemes used. The overall representativeness of the resource maps produced have been evaluated. Discrepancies exist among previous assessments with regard to geographical variations and the estimated values of wind power.

Information from the existing national wind energy assessments and various other sources has been used to form a synthesized national assessment. As part of the synthesis, additional research was performed to further improve the national assessment. This included a detailed examination of inherent problems with respect to representativeness and reliability of surface and rawinsonde wind data; vertical extrapolation of wind power estimates; estimation of wind

power in mountainous and off shore areas and areas of sparse data, and interpretation and analysis of wind power estimates.

Wind power estimates given are lower limits for typical, well exposed sites, and must not be construed as representative of all sites within an area. Specifically, the estimates are not representative where topographic features block or channel airflow. The refined analysis of the mean annual wind power at 50 m above the average high terrain over the contiguous United States is shown in Figure 1. "Average High Terrain," is defined as higher terrain features suitable for wind turbine siting in areas of gently rolling to hilly terrain. In mountainous regions, the estimates are for typical, well-exposed sites. The relationship between mountain summit wind power and free air wind power at summit height is highly variable. Lower isolated ridges, and gaps or saddles, may have greater wind power than higher mountain summits.

In nonmountainous regions, the mean annual wind power is high ($>400 \text{ watts/m}^2$) over the central and southern Great Plains; offshore in exposed coastal areas of the Northeast and Northwest; and in parts of Wyoming, Montana, and the south Texas coast. Over most of the Southeast, wind power is quite low (100 watts/m^2). All mountainous regions, except possibly for some areas of the Southwest, are expected to have sites with considerable wind power.

Seasonal patterns of wind power are similar to the annual patterns. The season of maximum wind power has typically 30% to 60% greater wind power than the annual average. Over the eastern one-third of the nation, maximum wind power occurs during the winter and early spring. A spring maximum occurs over the Great Plains, the North-Central states, the Texas coast, most nonmountainous regions in the West (e.g., the basins and broad valleys), and offshore areas of central

FIGURE 1. Mean Annual Wind Power (watts/m²) Estimated at 50 m Above the Average High Terrain (Shaded areas are mountainous regions. M designates the estimated wind power for a mountain summit.)

and southern California. Winter maximums occur over all mountainous regions, except for mountains in New Mexico and Arizona where the spring wind power appears about equally as large.

The "large scale" regions of high and low wind power are similar to those identified in previous assessments. However, many significant modifications in data interpretation, wind power estimates, and geographical distributions have been made in the synthesis. This analysis is the best that can be achieved utilizing the existing wind data summaries. In the future, emphasis should be placed on separate regional analyses using data from all available sources.

Expected Progress During the Next Period:

The final report is being prepared and should be ready for publication in March or April 1977. All basic work on the synthesis of national wind energy assessments is completed. The publication of the final report will mark the completion of this work.

Reports and Publications:

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

3.19 Wind Speed and Power Frequency Distribution

Battelle, Pacific Northwest Laboratories
Richland, WA 99352

Principal Investigator:

J. C. Doran (509) 942-2861

Objective:

The intent of this investigation is to examine possible effects that various sampling and averaging periods may have on measured velocity probability density curves and estimated power production by a WECS.

Current Status:

This program was begun in October 1976 and should be completed by early February 1977.

Progress During Reporting Period:

Computer programs designed to calculate velocity probability density curves for various sampling and averaging times were developed. The programs also determine extractable average power for a hypothetical WECS, as well as Weibull parameters, for each of the curves computed. Additional programs were created to extract and pack relevant data from the source tapes containing the raw data. Testing of all programs was carried out successfully.

Expected Progress During the Next Period:

Two seasons' data taken at Hanford will be analyzed, covering the autumn of 1975 and spring of 1976. Comparison will be made of probability density curves and hypothetical power production, and conclusions made about any implications of averaging shorter scale velocity fluctuations.

Reports and Publications:

None.

DISTRIBUTION

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