**Annual Report of the
Wind Characteristics Program
Element for the Period
October 1979 Through
September 1980**

September 1981

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

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ANNUAL REPORT OF THE
WIND CHARACTERISTICS PROGRAM
ELEMENT FOR THE PERIOD
OCTOBER 1979 THROUGH SEPTEMBER 1980

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September 1981

Prepared for
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under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

As part of the Federal Wind Energy Program, the Wind Characteristics Program Element (WCPE) conducts research activities to provide relevant wind characteristics information to those involved in:

- energy program planning
- selecting sites for wind turbine installation
- the design and performance evaluation of wind turbines
- the operation of wind turbines.

During this reporting period the Pacific Northwest Laboratory (PNL), which manages the WCPE for the U.S. Department of Energy (DOE), also continued the management responsibility for the data collection at the DOE's candidate sites and the tasks of providing technical assistance to DOE evaluation and site selection panels for new candidate sites and turbine sites.

This annual report briefly describes the technical progress within each segment of the WCPE from October 1979 through September 1980. It includes the progress accomplished directly by the Pacific Northwest Laboratory (PNL) and by subcontractors funded directly by DOE or through PNL. To expedite the management of the activities to produce the required information, the WCPE has been divided into three program areas: Wind Energy Prospecting, Support for Design and Operations, and Site Evaluation. Accomplishments in each of these program areas, summarized below, provide a highlight of WCPE activities in FY 1980.

The Wind Energy Prospecting Program Area is subdivided into two major technical activities. The first is the development and application of resource assessment techniques and the second is the development and testing of site screening methodologies. Major activities during this reporting period included:

- statistical evaluation of the National Climatic Center TD1440 data set and data from the National Fire Weather Data Library for wind resource assessment.
- completion (to draft atlas stage) of regional wind energy assessments for the ten remaining U.S. wind energy regions and publication of atlases for the Northwest and Northeast regions.

- publication of reports on methodologies for assessing the local wind field with instrumentation.
- completion of a literature survey of wind turbine wakes and interactions in clusters.
- revision and publication of a Siting Handbook for Small Wind Turbines.
- revision of the draft of a report on the meteorological aspects of siting large wind turbines.
- transfer of a detailed outline of an audio-visual WECS siting course to SERI for packaging in a modularized presentation.

The Support for Design and Operations Program Area is also divided into two major technical activities. The first is to conduct research to provide descriptions of meteorological characteristics relevant to the design and performance evaluation of wind turbine generators. The second is to conduct research to provide wind characteristics information relevant to operation of wind turbines, especially those which have been integrated into a utility grid. Some of the significant accomplishments for this reporting period included:

- development of a model describing the statistical nature of the field of turbulence over a rotor disk, which yields nine turbulent inputs that drive the turbine excitations.
- preparation a report on fluctuating wind shears based on data obtained from the vertical plane array, and publication of a report on gust statistics.
- hosting a working-group meeting with wind turbine designers for the purpose of discussing wind turbine design processes and relevant atmospheric characteristics.
- completion of a study of the wind environment at a mid-Atlantic coastal site, which emphasized the variability of wind characteristics as a function of wind direction and the discrete gust structure at the site.
- conducting verification studies on previously produced data sets containing wind forecasts produced through conventional techniques.

- providing wind forecasts, corresponding observed data and descriptions of the forecast technique to participants in an International Energy Agency wind-forecasting verification program. Assistance was also provided in the preparation of the final report for the program.
- preliminary development of probabilistic and deterministic wind forecasting equations. Initial testing produced mixed results. At some stations having regular diurnal cycles of wind speed, 21 to 24-hour forecasts were more reliable than 12 to 15-hour forecasts.
- development of a model to compute the power output of a wind turbine using time series wind data and a specified operating strategy.

The PNL support of the DOE candidate sites (Site Evaluation Program Area) involved three major activities: site selection support, site meteorological measurements and analysis, and large machine site evaluation. During this reporting period, the following efforts were conducted:

- A data base for the 14 original candidate sites was established on PNL's computer system, facilitating responses to data requests and publishing data summaries.
- Assistance was provided to DOE in the selection of 20 new candidate sites.
- PNL conducted initial site visits and managed the installation of meteorological towers and equipment at the new candidate sites (about half the new sites were operational by the end of the reporting period).
- Working with NASA/Lewis, Boeing and BPA, PNL provided a role in establishing the location of the three MOD-2 wind turbine clusters and designing a meteorological data acquisition system for the array.
- A 160-foot meteorological tower was installed adjacent to the Kahuku MOD-0A wind turbine. Arrangements were made to have turbine output parameters recorded on the data logger simultaneously with meteorological parameters.

Because of the number and diversity of projects in the WCPE, this report is not designed to provide a wealth of technical detail. More complete descriptions of the research results may be obtained from the referenced published reports or by directly contacting the appropriate principal investigator.

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1.0 INTRODUCTION

The primary objectives of the Federal Wind Energy Program are to accelerate the development of reliable and economically viable wind energy systems and to enable the earliest possible implementation of wind power (U.S. Department of Energy 1978). Information about wind characteristics that directly affect the reliability and economics of wind energy conversion systems (WECS) is one element of this multifaceted federal program. In April 1976, the Pacific Northwest Laboratory (PNL) was assigned the responsibility for management and technical coordination of the Wind Characteristics Program Element (WCPE). This Annual Report of the Program Element outlines the technical progress from October 1979 through September 1980.

The primary objective of the WCPE is to provide, through research and development projects, appropriate information about wind characteristics to those involved in the design and evaluation of WECS, in energy program planning, in selecting sites for WECS installations, and in the day-to-day WECS operations. To more effectively meet these various needs, the WCPE has been divided into the following technical areas:

- Wind Energy Resource Assessment
- Siting Methodologies
- Meteorological Characteristics for Design and Performance Evaluation
- Meteorological Characteristics for WECS Operations
- Site Selection Support
- Site Meteorological Measurements
- Large Machine Site Evaluation.

The Wind Energy Resource Assessment technical area has the primary responsibility of developing and presenting analyses of wind energy potential over large areas. The analyses are to identify smaller areas of favorable wind characteristics and to quantify the wind-energy potential over the entire area. In FY 1980 the emphasis has shifted from the broad national assessment to the more detailed regional assessments.

The purpose of the Siting Methodologies technical area is to devise strategies for selecting specific sites for WECS installation, to develop

tools to implement these strategies, and to supply this methodology to WECS users. To meet its objectives, this area has been divided into two sections:

- Site Screening and Localization Technique Development and Documentation
- Verification of Siting Techniques.

The Meteorological Characteristics for Design and Performance Evaluation technical area, which is also divided into two subareas, is concerned with the direct interaction between meteorological phenomena and a WECS. The design portion characterizes wind and other meteorological phenomena. Performance evaluation recommends meteorological instrumentation, instrumentation deployment, data collection, and analysis techniques for testing WECS. The WCPE does not intend to design WECS nor to evaluate their performance; however, it does provide meteorological support to those involved in such activities.

The Meteorological Characteristics for WECS Operations technical area assesses the specific wind characteristics needs of potential users of wind turbines and attempts to provide availability and reliability information in the areas of wind forecast technology and utility applications. This information is applicable to dispatching, maintenance, unit commitment and reserve requirements.

The Site Selection Support technical area is intended to provide assistance to DOE in the selection process for candidate and turbine sites. This assistance has included doing the technical analyses of the wind energy potential at each proposer's site, advising the DOE site selection committee on wind characteristics, and documenting the results of all the proceedings.

The Site Meteorological Measurements technical area is responsible for collecting and analyzing meteorological data from DOE candidate sites, and publishing monthly summaries of this data. During FY 1980, this technical area also supported the installation of data acquisition systems at the new candidate sites chosen by DOE in January 1980.

The Large Machine Site Evaluation technical area is responsible for the meteorological measurement program at turbine sites. The measurement program at turbine sites is expanded from the program at candidate sites to include turbine output parameters such as wind turbine output, yaw error, and nacelle wind speed and direction.

The technical progress covered in this report includes that accomplished directly by PNL and by subcontractors funded directly by DOE or through PNL. Because of the urgency to provide information pertinent to the goals of the Federal Wind Energy Program, highest priority has been given to those projects that answer specific and immediate needs.

This report is divided into seven major parts corresponding to the seven technical areas of the WCPE. Each section includes an overview of the progress in the technical area as well as the progress in each individual task within that technical area. A summary of the administrative aspects of the program is presented in Appendix A.

Because of the number and diversity of projects in the WCPE, this report is not designed to provide a wealth of technical detail, but rather to provide the reader with sufficient information to lead him to a detailed report (see Appendix B) or to personal contact with those directly involved in the work. In this way, one of the important functions of the WCPE, which is to promote fruitful exchanges of information, may be realized.

RESOURCE ASSESSMENT (2.1.1)

The principal thrust of this task area for FY 1980 is the completion of twelve wind energy resource atlases for the United States and its territories. Ten contractors have been working on regional wind energy resource assessments. Regional wind energy atlases for the Northwest and Northeast were completed and published. Work on all other regions has progressed to the point where draft maps and narratives to the atlases have been reviewed by PNL. Besides completing the Northwest atlas and continuing work on the Puerto Rico atlas, PNL has coordinated the work of the ten contractors and provided them with statistical summaries of the National Climatic Center, U.S. Forest Service Fire Weather data and with maps and graphics that are to become part of each regional atlas.

Continuing research in techniques for conducting wind resource assessments in the coastal zone was supported. An approach utilizing numerical model results coupled with a climatology of large weather situations was tested against a set of data collected in a field experiment during a dominant weather situation. Another approach, which analyzed the experiences of charter boat captains and commercial fishermen, was also concluded this year.

Coastal Zone Wind Energy (2.1.1.1.1)

Contract No.: B-93492-A-E and DE-AS06-76ET20274

Department of Environmental Sciences
University of Virginia
Clark Hall
Charlottesville, VA 22903

Principal Investigator:

Michael Garstang (804) 977-3733

Contract Monitor:

W. R. Barchet (509) 375-6161 ext. 284

Objective:

To test and verify estimates of wind energy potential obtained for the East and Gulf coastal zones of the United States. Based upon the verification study the objective is to provide a method of wind energy assessment based upon a climatology of storm and inter-storm conditions and using a numerical model to determine the local distribution of the wind.

Program Status:

This program was initiated in March 1979 and reported upon in October 1980. Work on the assessment and method, and the final report, will be completed in mid-FY 1981.

Progress During the Reporting Period:

During the reporting period the potential wind power density fields were calculated from the three-dimensional model for the dominant wind regimes for three East and Gulf coastal areas. Figure 1 shows the results for one test area, the Chesapeake Bay, for an annual average, 100-m layer mean power density. Values are given for each 100 km^2 (10 km north-south x 10 km east-west) determined from meteorological variables predicted by the University of Virginia's mesoscale model. Equally weighted minute-by-minute values were used to compute the daily averages. The following heights above the surface and weightings (in parentheses) were used in the determination of the layer mean: 10 m (0.20), 30 m (0.20), 50 m (0.35) and 100 m (0.25). Centers of relative maximum (X) and minimum (N)

are indicated along with solid isolines drawn at 50 watts per m^2 (W/m^2) intervals. Numbers in the background are the power density values for each grid square. The land-water boundary is depicted in detail for ease of orientation and location. In the computer integrations the character of the surface for each grid square is represented by its percent of land area. Intersections of 75° , 76° and 77° W with 37° , 38° and 39° N are marked.

Table 1 shows a comparison between the model-predicted 100-m layer mean annual average power density and the observed power density. Good results are obtained for the Chesapeake and Apalachee Bay areas. Poor results are obtained on the south Texas coast.

A field program based on the Delmarva Peninsula was carried out to further determine the validity of the method (climatological storm-inter-storm classification and modeling) and to clarify the results obtained above. Aircraft and surface stations provided detailed wind measurements over a 120×30 km region, illustrated in Figure 2. Comparisons were made with days such as those illustrated in Figure 2 and model calculations were illustrated for the same day, as shown in Figure 3. The correlation between model-predicted and measured wind speeds ranged from 0.75 to 0.79. Somewhat lower correlation (0.62) existed when wind direction was included as a parameter.

We conclude that under certain circumstances, i.e., when the large-scale meteorological situation is stationary or changing only very slowly, model predictions of the wind and wind power density are good and probably well within acceptable limits for planning for the use of the resource. When the meteorological situation is changing, model predictions are poor. Changes in the meteorological conditions may be due to rapidly changing large-scale effects or oscillating mesoscale effects. We believe that in the south Texas coast area the latter situation prevails and thus predictions with the current model are unreliable. At many other locations conditions are stable enough to allow accurate prediction. Based upon these results a preliminary procedure to determine the wind power potential of the coastal zone was outlined.

TABLE 1. Coastal Stations Used in the Verification of 100 m Layer Mean Annual Average Power Density

Station Name	Anemometer* Height (m)	Years of Data	Single-Level	Exponent (α)	100 m Layer-Mean Annual Average Power	
			Annual Average Power Density (Wm^{-2})		Density (Wm^{-2}): From Data	From Figs. 5, 9 or 13
CHESAPEAKE BAY AREA						
Dover (AFB), DE	<u>4.6</u>	1957-64	85	0.124**	196	203
Wallops Island						
(X-85), VA	<u>10.0</u>	1967-76	99	0.209**	250	254
Hampton (Langley	<u>29.3</u>	1955-59	160			
AFB), VA	<u>4.0</u>	1960-64	57	0.209	210	223
Virginia Beach	<u>12.8</u>	1955-59	122			
(Oceana NAS), VA	<u>4.0</u>	1960-64	73	0.240	313	274
APALACHEE BAY AREA						
Tampa (McDill AFB),	<u>22.9</u>	1955-57	66			
FL	<u>4.0</u>	1958-64	47	0.061	73	67
Panama City (Tyndall						
AFB), FL	<u>3.0</u>	1958-64	51	0.066	86	88
SOUTH TEXAS COAST AREA						
Corpus Christi (NAS),	<u>19.2</u>	1955-60	259			
TX	<u>6.7</u>	1961-64	160	0.213	455	151
Brownsville (Int.						
Airport), TX	<u>17.1</u>	1955-60	191	0.213**	362	141

*Underlined heights used as basis for computing layer-mean values.

**Exponent not determinable for this station; value of nearest station used. (In the case of Dover, DE, Atlantic City, NJ was used.)

FIGURE 2. Isopleths of Measured Power Density (10^2 W/m^2) at 150 m Above the Surface on January 30, 1980, 0740-0900 Local Time, in the Vicinity of Wallops Flight Center. 'X' specifies area of maximum power density (approximately 1300 W/m^2); 'N' the area of minimum (approximately 150 W/m^2). Land areas are stippled. Open circles are land-based measurement locations. Solid lines are the aircraft box pattern, $120 \times 30 \text{ km}$. Dashed line is the Maryland-Virginia border. The intersections of $75^\circ 00'$, $75^\circ 30'$ and $76^\circ 00' \text{W}$ with $37^\circ 30'$ and $38^\circ 00' \text{N}$ are marked. Winds were from the north-northwest.

FIGURE 3. Isopleths of Predicted Wind Power Density (10^2 W/m^2) Perpendicular to the Wind) at 30 m Above the Surface in the Southern Portion of the Delmarva Peninsula. 'X' specifies area of maximum power density ($4.7 \times 10^2 \text{ W/m}^2$), 'N' specifies area of minimum ($1.7 \times 10^2 \text{ W/m}^2$). Predictions made by the University of Virginia mesoscale model for a wintertime situation at sunrise; large scale (geostrophic) winds from the north-northwest at 10 m/s, sea surface temperature, 8°C . Land areas are stippled, dashed line is Maryland-Virginia border. Superimposed rectangle is the aircraft box pattern.

Expected Progress During the Next Reporting Period:

A detailed intercomparison of model results and observations of the wind field will be completed. Based upon these results the procedures for determining coastal wind power potential will be finalized.

Reports and Publications:

Lindsey, C. G. "Analysis of Coastal Wind Energy Regimes," M.S. Thesis, Department of Environmental Sciences, University of Virginia, Charlottesville, VA.

Gusdorf, J. M. "The Relationship Between Surface and 850 mb Winds as a Function of Synoptic State," M.S. Thesis, Department of Environmental Sciences, University of Virginia, Charlottesville, VA.

Garstang, M., R. Pielke and J. W. Snow. 1980. Coastal Zone Wind Energy, Part I: Potential Wind Power Density Fields Based on 3-D Model Simulations of the Dominant Wind Regimes for Three East and Gulf Coast Areas. PNL-3905 Pacific Northwest Laboratory, Richland, WA.

Garstang, M., R. Pielke and J. W. Snow. 1980. Coastal Zone Wind Energy, Part II: Validation of the Coastal Zone Wind Power Potential: A Summary of the Field Experiment. PNL-3904 Pacific Northwest Laboratory, Richland, WA.

Garstang, M., R. Pielke, J. Gusdorf, C. Lindsey, and J. W. Snow. 1980. Coastal Zone Wind Energy, Part III: A Procedure to Determine the Wind Power Potential of the Coastal Zone. PNL-3903 Pacific Northwest Laboratory, Richland, WA.

Garstang, M., J. W. Snow and G. D. Emmitt. "Wind Shear and Gustiness at the MOD-1 Site," Boone, NC. Accepted for publication in Journal of Energy, March/April 1981.

Wind Power Potential in a Coastal Environment (2.1.1.1.1A)

Contract No.: B-36379

University of Texas
Atmospheric Science Group
Austin, TX 78712

Principal Investigator:

Norman K. Wagner (512) 471-3611

Contract Monitor:

David S. Renné (509) 375-6161 ext. 258

Objective:

To develop a technique for determining the space and time variations of wind speed in data-sparse coastal areas by interviewing appropriate local residents.

Program Status:

This study, which began in February 1978, was concluded in January 1980.

Progress During Reporting Period:

A pilot project, which involved interviewing charter boat captains and commercial fishermen in a data-sparse coastal region, was initiated in the spring of 1978 and concluded during the reporting period. At the same time, additional wind instruments were installed in the study area, which includes Corpus Christi and Port Aransas, Texas, and in the adjacent bays, inland waters, and the Gulf of Mexico. Interviews were obtained orally, and summarized on an interview form. The interviews were made in three distinct areas: bay, inshore, and offshore. Results of the interviews were consistent with annual data records, showing a wind maximum during late winter and spring, and a minimum during late summer. The interviews indicate the existence of a complicated diurnal pattern inshore and in the bay, but little diurnal variation offshore. Wind speeds tend to increase with distance offshore.

In conclusion, the interview results were remarkably consistent with each other and with measurements. Most people whose profession forces them to

coexist with nature are remarkable observers. The interview process is judged to have excellent potential for use in the early phase of wind energy siting.

Reports and Publications:

Wagner, N. K. and C. E. Meyer. 1979. Coastal Wind Assessment: Interviews and Observations. PNL-3870, Pacific Northwest Laboratory, Richland, WA.

Prototype Regional Wind Energy Resource Assessment - Northwest Region (2.1.1.2.1)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

Dennis L. Elliott (509) 375-6161 ext. 275

Objective:

To develop resource assessment techniques for the entire United States, to apply these techniques to the Northwest region and to provide information on the distribution of the wind resource suitable for planning for the implementation of WECS.

Program Status:

This study, which was initiated in FY 1978, was concluded in FY 1980 with the publications of the Northwest wind atlas.

Progress During Reporting Period:

Publication of the Wind Energy Resource Atlas - Vol. 1: The Northwest Region marked the conclusion of this study. This atlas contains maps showing the geography, land-surface form, and wind data station locations as well as maps of the annual and seasonal distribution of wind power class for each state in the region. Other maps portray the areal distribution and an estimate of the certainty with which the power class could be estimated. Wind characteristics at stations available on the National Climatic Center (NCC) TD1440 data set are presented as a set of graphs for stations in each state. Color maps were produced showing the annual and seasonal wind energy for each state.

Expected Progress During Next Reporting Period:

Publication of the atlas completes the work on this task. However, a report in technique will be published as part of the national synthesis volume in the set of wind atlases.

Reports and Publications:

Elliott, D. L. and W. R. Barchet. 1980. Wind Energy Resource Atlas: Volume 1 - The Northwest Region. PNL-3195 WERA-1. Pacific Northwest Laboratory, Richland, WA.

Coordination of Regional Wind Energy Resource Assessments (2.1.1.2.2)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

W. Richard Barchet (509) 375-6161 ext. 284

Objective:

To ensure that all regional wind energy resource assessments are completed in a timely, cost-effective, compatible and comparable fashion.

Program Status:

This task was initiated in February 1979 and will continue until atlases for all regions have been completed in mid-FY 1981.

Progress During Reporting Period:

All NCC TD1440 data were processed and the resulting statistical summaries output on microfiche for distribution to the regional assessment subcontractors. An analysis of the National Fire Weather Data Library was completed and distributed to the subcontractors. PNL completed the redrafting of land-surface form maps and generating gridded overlays for all base maps needed by the regional contractors.

Technical reviews of contractor analysis of the wind resource were held with each contractor to ensure technique compatibility and uniformity of presentation. These training sessions were followed by detailed technical reviews of draft maps and atlas narratives.

Graphic material for station locations, areal distribution and certainty rating as well as station statistics were prepared for each region as data were received from the contractor.

Several atlases were received for final editing and assembly and one was published.

Expected Progress During Next Reporting Period:

The remaining atlases will be received, assembled and published by mid-FY 81.

Reports and Publications:

Pickering, K. E. et al. 1980. Wind Energy Resource Atlas: Vol. 4 - The Northeast Region. PNL-3195 WERA-4, Pacific Northwest Laboratory, Richland, WA.

Coordination of Regional Wind Energy Resource Assessments (2.1.1.2.2A)

Contract No.: B-50369

Marlatt and Associates
3611 Richmond Drive
Fort Collins, CO 80526

Principal Investigator:

William E. Marlatt (303) 226-4857

Contract Monitor:

W. Richard Barchet (509) 375-6161 ext. 284

Objective:

To process the U.S. Forest Service's National Fire Weather Data Library (NFWDL) for use in wind energy assessments.

Program Status:

The project, which began in 1978, was concluded in 1980 with the receipt of the NFWDL analysis.

Progress During Reporting Period:

The NFWDL was screened for stations at which more than 75% of the wind data exceeded 4.5 m/s. Statistics on the mean wind speed and wind energy flux were generated and summarized in a standard format for each station; see Table 1. Means and standard deviations were given for each season and the year. A separate data tape giving the frequency of occurrence of wind speed was also generated. More than 1000 stations were analyzed.

Reports and Publications:

None.

TABLE 1. A Typical Page of Output Showing Wind Statistics for Given Fire Weather

	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	44301	
	W I N T E R			S P R I N G			S U M M E R			F A L L			ANNUAL	MEAN	ANNUAL	STD DEV	TOTAL	
YEAR	SPEED	POWER	OBS	SPEED	POWER	OBS	SPEED	POWER	OBS	SPEED	POWER	OBS	SPEED	POWER	SPEED	POWER	OBS	
	M/S	W/M**2		M/S	W/M**2		M/S	W/M**2		M/S	W/M**2		M/S	W/M**2	M/S	W/M**2		
1961	1.12	6.24	25	3.29	25.14	86	3.71	34.53	32	2.98	18.55	60	3.16	25.12	1.18	19.92	263	
1962	2.35	15.79	23	3.31	25.44	72	3.63	30.19	92	1.75	6.15	51	3.00	22.21	1.16	17.89	238	
1963	2.36	12.23	55	3.01	19.41	87	3.78	45.20	92	2.15	11.30	74	2.92	23.89	1.34	32.84	308	
1964	2.23	15.46	53	2.74	16.90	78	3.89	378.16	91	2.18	10.78	62	2.83	131.05	2.40	1830.25	284	
1965	2.14	10.46	36	2.33	20.34	65	3.71	34.94	92	2.51	18.18	71	2.95	23.50	1.32	22.61	264	
1966	2.40	32.52	47	3.23	23.95	78	3.60	31.69	92	2.55	16.39	74	3.04	25.86	1.25	62.05	291	
1967	2.40	14.09	87	2.60	14.05	88	2.80	15.63	92	1.93	8.37	92	2.43	13.01	1.06	14.36	359	
1968	1.97	8.51	91	3.15	22.78	81	3.40	26.42	92	2.31	13.08	89	2.70	17.60	1.18	16.61	353	
1969	2.23	11.31	84	3.05	20.88	91	3.16	23.28	92	2.04	10.22	80	2.65	16.74	1.12	13.44	347	
1970	2.26	10.79	74	3.18	26.94	91	3.73	36.51	92	3.78	372.84	55	3.25	86.89	2.12	981.14	312	
1972	0.00	0.00	0	2.15	14.27	59	2.70	14.72	90	2.32	13.48	19	2.46	14.42	1.12	20.36	168	
1973	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	1.37	4.12	41	1.37	4.12	1.03	5.58	41	
1974	0.00	0.00	0	2.43	14.98	44	2.25	68.82	89	1.51	6.40	55	2.07	37.96	1.80	331.54	188	
1975	0.00	0.00	0	2.05	9.34	39	2.32	12.79	79	1.67	7.07	63	2.03	10.06	1.19	13.05	181	
1976	1.13	3.71	16	2.37	13.98	59	2.39	14.04	90	1.41	4.53	63	2.03	10.67	1.27	14.11	228	
1977	3.00	35.03	30	2.43	14.79	83	2.71	19.67	77	1.16	4.77	69	2.24	15.92	1.49	31.44	259	
TYP VAR	1.57	2092.		1.12	325.		2.07	770660.		2.27	289726.							
I-A VAR	.13	60.		.15	24.		.33	7873.		.38	6734.							
S E A S O N A L S U M M A R Y				S P E E D			P O W E R											
				SEASON	VGAR	SIG-V	OBS	PBAP	SIG-P									
				WINTER	2.21	1.30	621	14.12	46.39									
				SPRING	2.85	1.13	1101	19.57	18.67									
				SUMMER	3.21	1.55	1344	53.02	882.35									
				FALL	2.10	1.63	1018	29.99	544.48									
				ANNUAL	2.68	1.51	4084	32.35	575.12									
THE ENTIRE RECORD CONSISTS OF 4084 VALID AND 0 INVALID READINGS																		

Regional Wind Energy Resource Assessments (2.1.1.2.3-.13)

Contract No.: B-87926 Vol.2 - North Central

Western Scientific Services, Inc.
1716 Heath Parkway
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Fort Collins, CO 80524

Principal Investigator:

Daniel L. Freeman (303) 482-3364

Contract No.: B-87922 Vol. 3 - Great Lakes

Environmental Research & Technology, Inc.
696 Virginia Road
Concord, MA 01742

Principal Investigator:

Arthur Bass (617) 861-6400

Contract No.: B-23452 Vol. 4 - Northeast

GEOMET Technologies, Inc.
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Rockville, MD 20850

Principal Investigator:

Kenneth E. Pickering (301) 424-9133

Contract No.: B-87924 Vol. 5 - East Central

NUS Corporation
4 Research Place
Rockville, MD 20850

Principal Investigators:

Ronald R. Stoner/Roger W. Brode (301) 948-7010

Contract No.: B-87925 Vol. 6 - Southeast

GEOMET Technologies, Inc.
1801 Research Boulevard
Rockville, MD 20850

Principal Investigator:

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Contract No.: B-87923 Vol. 7 - South Central

Institute for Storm Research
4104 Mt. Vernon
Houston, TX 77006

Principal Investigator:

Leon Graves (713) 529-4891

Contract No.: B-87921 Vol. 8 - Southern Rocky Mountain

Western Scientific Services, Inc.
1716 Heath Parkway
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Principal Investigator:

Steven R. Anderson (303) 482-3364

Contract No.: B-87920 Vol. 9 - Southwest

Global Weather Consultants, Inc.
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Palo Alto, CA 94306

Principal Investigator:

Richard L. Simon (415) 493-7289

Contract No.: B-87917 Vol. 10 - Alaska

Arctic Environmental Information
and Data Center
University of Alaska
707 A Street
Anchorage, AK 99501

Principal Investigator:

James L. Wise (907) 497-7607

Contract No.: B-87918 Vol. 11 - Hawaii and the Pacific Islands

Department of Meteorology
University of Hawaii
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Principal Investigator:

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Vol. 12 - Puerto Rico and U.S. Virgin Islands

Pacific Northwest Laboratory
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Principal Investigator:

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Contract Monitors:

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Objective:

To provide a detailed assessment of the wind energy resource available in the regions of the country, shown in Figure 1, using all available summarized and unsummarized wind data. Sources of data include the National Climatic Center, state and local air pollution control agencies, power companies, the U.S. Forest Service, and universities and research groups. Data will also be obtained through the use of meteorological, topographical, and biological indicators. The final product of each investigation will be a regional wind power atlas.

Program Status:

The bulk of contractor work for the Northeast, East Central and Southwest regions has been completed. Work is continuing on the remaining regions. It is anticipated that all work will be completed early in FY 1981. The status of each regional atlas is:

<u>Volume</u>	<u>Region</u>	<u>Status</u>
1	Northwest	Published
2	North Central	Draft reviewed
3	Great Lakes	Draft reviewed
4	Northeast	Published
5	East Central	Camera-ready received
6	Southeast	Draft received
7	South Central	Draft received
8	Southern Rocky Mountain	Draft received
9	Southwest	Draft reviewed
10	Alaska	Draft received
11	Hawaii and Pacific Islands	Draft reviewed
12	Puerto Rico and Virgin Islands	Draft received

FIGURE 1. Regional Divisions Used in Wind Resource Assessments

Progress During Reporting Period:

All subcontractors have acquired the bulk of their source data and are well into the analysis of the wind resource. Draft maps and narratives have been received from all contractors. Review comments by PNL have been returned on all but two of the available drafts.

Figures 2 through 13 show the annual wind power for each region of the United States. Some of these maps are the final version completed in FY 1981 of the draft maps available in FY 1980. Each atlas contains additional maps showing the geography, land-surface form and station locations on a state-by-state basis. Detailed descriptions of the wind characteristics at selected sites are portrayed in graphs of interannual, monthly and diurnal mean wind speed, and of wind speed and direction frequency.

Expected Progress During Next Reporting Period:

Final versions of all atlases will be sent to PNL early in FY 1981 with contracts being closed as the atlases are published.

Reports and Publications:

Pickering, K. E. et al. 1980. Wind Energy Resource Atlas: Volume 4 - The Northeast Region. PNL-3195 WERA-4, Pacific Northwest Laboratory, Richland, WA 99352, 228 pp. (GPO Stock No. 061-000-00486-6)

FIGURE 2. Annual Average Wind Power in the Northwest Region

FIGURE 3. Annual Average Wind Power in the North Central Region

FIGURE 4. Annual Average Wind Power in the Great Lakes Region

FIGURE 5. Annual Average Wind Power in the Northeast Region

FIGURE 6. Annual Average Wind Power in the East Central Region

FIGURE 7. Annual Average Wind Power in the Southeast Region

FIGURE 8. Annual Average Wind Power in the South Central Region

FIGURE 9. Annual Average Wind Power in the Southern Rocky Mountain Region

FIGURE 10. Annual Average Wind Power in the Southwest Region

FIGURE 11. Annual Average Wind Power in Alaska

FIGURE 12. Annual Average Wind Power in the Hawaiian Islands

FIGURE 13. Annual Average Wind Power in Puerto Rico and the U. S. Virgin Islands

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SITING METHODOLOGIES (2.1.2)

Selecting the specific locations best suited for siting wind turbines on the basis of wind characteristics information is the primary objective of this task area. Activities fall into two main areas: technique development and documentation, and technique verification.

Two studies using instrumentation to assess the local windfield and identify potential sites were completed. Work on the use of biological indicators of wind energy potential was extended to new species. The use of various ground-based remote-sensing systems was evaluated and a study on the satellite and high altitude remote sensing was initiated. The adjustment of short-term or incomplete data to the long-term climatology was pursued using a model to synthesize the annual and diurnal patterns. Six anemometer systems were tested in wind tunnel in a study of inexpensive wind instruments.

Major efforts were directed at revising the Small WECS Siting Handbook and a report on the meteorological aspects of siting large wind turbines. Materials for a siting course were prepared for the Solar Energy Research Institute (SERI) to package into a modular audio-visual presentation.

Technique verification focused on numerical modeling activities within Annex II of the International Energy Agency (IEA) agreement on research and development of WECS. Verification of numerical models to simulate the near-surface windfield, performed by SAI and the University of Virginia, were involved in PNL's portion of the IEA. Primitive-equation models as well as mass-consistent interpolative models were verified against data sets from Hawaii, Nevada and Sweden.

Vegetation as an Indicator of High Wind Velocities (2.1.2.1.1)

Contract No.: DE-AT06-76ET20316

Oregon State University
Corvallis, OR 97331

Principal Investigators:

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J. E. Wade (503) 754-4557

C. L. Rosenfeld (503) 754-3141

Contract Monitor:

Thomas R. Hiester (509) 375-6161 ext. 243

Objective:

To demonstrate the feasibility, costs and the utility of satellite imagery and remote observation of ecological, geomorphological and cultural indicators of wind energy potential to wind energy prospecting.

Program Status:

Remote sensing research began in June of 1979 under DOE contract EY-76-506-2227 (later changed to DE-AT06-76ET20316), "Vegetation as an Indicator of High Wind Velocity." Work on remote sensing will continue through October 1981 on B-92627-A-H, "Remote Observations of Wind Indicators." An interim report "Remote Sensing for Wind Power Potential - A Prospector's Handbook" was submitted in July of 1980. A final report is due in October of 1981.

Progress During Report Period:

A handbook has been produced that describes the use of remote sensing in wind power prospecting. A wide variety of remotely sensed evidence was described in terms of the scale at which the evidence can be identified, and the appropriate remote sensors for distinguishing such evidence. Information from small-scale imagery (i.e., satellite imagery) is most often qualitative and may be transitory (such as whitecaps) and, thus, requires examination of a number of images taken over time to verify the

persistence of the feature. On the other hand, small-scale imagery allows rapid screening of large areas and enables the wind prospector to quickly select the most promising locations for more detailed subregional investigations.

Medium-scale imagery (U-2 and high-level aerial photographs) provides better resolution of evidence observed in small-scale imagery. At this scale it is most cost effective to use existing imagery. Criteria relating to land use, accessibility, land area and proximity to transmission lines can also be effectively evaluated from medium-scale imagery. A variety of image enhancement techniques described in the handbook include density slicing of shade variations, edge enhancement and digital processing.

Large-scale imagery (low-level aerial photographs and ground-level observation) provides the most quantitative evidence of the strength of the wind. Wind-deformed trees can be identified from the air over a large area using only a few hours in a locally chartered aircraft. A computer mapping technique has been documented that permits quantitative evaluation of the local wind field based on evidence from wind-deformed trees.

Expected Progress During Next Reporting Period:

The techniques for using remote sensing will be tested during FY 1981 in a series of case studies conducted in three different areas of the United States. Wind power potential will be estimated from remotely sensed evidence and the estimate will be verified where existing wind data are available.

Reports and Publications:

Wade, J. E., P. A. Maule, C. L. Rosenfeld, and S. G. Woolley. 1980. Remote Sensing for Wind Power Potential: A Prospector's Handbook. DOE/ET/20316-80/3, Oregon State University, Corvallis, OR. Available from NTIS.

Wade, J. E. and E. W. Hewson. 1980. A Guide to Biological Wind Prospecting. DOE/ET/20316-80/2, Oregon State University, Corvallis, OR. Available from NTIS.

Assessing the Local Wind Field With Instrumentation (2.1.2.1.2)

Contract No.: B-92864

Aerovironment, Inc.
145 Vista Avenue
Pasadena, CA 91107

Principal Investigator:

Thomas G. Zambrano (213) 449-4392

Contract Monitor:

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Objective:

To demonstrate and evaluate, in a field test, a large wind turbine siting concept based on a wind measurement system and methodology for assessing wind characteristics over an area the probable size of wind turbine clusters or arrays.

Program Status:

The program began in December 1978 with most of the field work done in 1979. A final report in FY 1980 concluded the project.

Progress During Reporting Period:

This project concerns the development and testing of a technique for the initial screening and evaluation of potential sites for (WECS). The methodology was developed through a realistic siting exercise. The siting exercise involved measurements of winds near the surface and winds aloft using a relatively new instrument system, the Tethered Aerodynamic Lifting Anemometer (TALA) kite, notation of ecological factors such as vegetation flagging, soil erosion and site exposure, and verification of an area best suited for wind energy development by establishing and maintaining a wind-monitoring network. The siting exercise was carried out in an approximately 100-square-mile region of the Tehachapi Mountains of southern California. The results showed that a comprehensive site survey involving field measurements, ecological survey, and wind monitoring is an effective tool for the preliminary evaluation of WECS sites.

The first step involved preliminary screening of the site using available data and a tour of the area. Of the 100 square miles in the study region, only a 20-square-mile area containing major ridgelines (see Figure 1) was considered suitable for WECS investigation. The preliminary site investigation showed that in this remaining 20 square miles there would most probably be one orographic feature per square mile which would provide some area suitable for WECS siting.

The second step involved investigating 16 sites in a detailed field assessment survey. The survey was conducted during a 1-week period when winds were from the dominant northwest direction. The goal of the survey was to use various wind energy assessment techniques to judge the merits and disadvantages of wind monitoring at each respective site. Each site was evaluated in terms of its ecological features, short-term anemometry results, and serviceability, and ranked with respect to the other 15 in order of merit. The three sets of rankings were combined into a matrix to obtain, from best to worst, the most suitable sites for installing wind-monitoring stations.

Many of the techniques used in this second step were novel to wind energy assessment. The TALA kites proved to be a versatile field instrument and continually indicated a more uniform vertical profile of wind speed than would be obtained from a $1/7$ power law. The vegetation survey involved the development of a deformation index for California oak, which will be refined when annual wind speed statistics for the data are obtained. Portable, modular 10-m wind-monitoring stations specifically designed for study application were shown to be satisfactory low-cost field instruments.

In the third step, 9 of the original 16 sites were equipped with 10-m wind-monitoring stations. Wind speed and wind direction were continuously recorded during a 6-month period. Two stations out of nine had wind-direction monitoring capabilities. However, for future surveys it is recommended that wind direction data be taken at all wind-monitoring locations. Presently, an additional 6 months of wind-monitoring is being performed with support from the California Energy Commission.

FIGURE 1. Prominent Ridgelines of Tehachapi Study Region

The recorded 6-month data, results from the field assessment survey, and continued TALA measurements were used to make wind-field analyses, power-availability estimates, and comparisons of wind energy assessment techniques.

The wind-field analysis identified four basic wind-flow patterns in the study region--summer northwest, winter northwest, summer southeast, and Santa Ana flow--and their respective diurnal patterns, frequency, and wind speed distribution. In general, it was seen that during the summer and early fall northwest flow can be enhanced by a channeled northwest flow up the axis of the San Joaquin Valley (see Figure 2). The study region is located at the terminus of the valley and is recipient of the up-valley flow. At other times during summer and early fall, an inversion layer caps the San Joaquin Valley and inhibits the flow of air over the study region. During late evening, the high ridges of the study area were exposed to upper-level flows (see Figure 3). Periods of high winds on these ridges corresponded to strong upper-level winds associated with weather fronts and active upper-level atmospheric circulation. These winds tend to be the strongest during the winter and spring seasons when the atmospheric circulation is most active.

The wind-speed distributions for each of the nine wind-monitoring sites were determined and the wind-energy flux obtained on a seasonal (summer and fall) and annual (estimated) basis. There is a ridgeline running approximately 7 miles in an area referred to as La Liebre, where the annual estimated wind-energy flux exceeds 400 W/m^2 , corresponding to a constant steady energy wind of about 9 m/s (20 mph) at the 50-m level, with some areas showing a seasonal wind-energy flux in excess of 500 W/m^2 (a steady energy wind of 22 mph). The energy wind is defined as the continuous wind which would have the same energy as the actual wind distribution. Most other regions that were investigated showed an estimated seasonal wind energy flux rarely exceeding 200 W/m^2 (a steady energy wind of 15 mph) at the 50-m level (see Figure 4).

Wind-energy distributions were applied to a hypothetical large WECS, of which the Boeing design for the MOD-2 (a 100-m rotor diameter, propeller-type unit rated at 2500 kW) is a typical example. In the most promising

FIGURE 2. Comparison of Mean Hourly Averages Taken in Tehachapi Mountains With Long-Term Mean Hourly Averages From Sandberg and Bakersfield Stations

FIGURE 3. Diurnal Cycle of Wind Speed for Selected Sites (Data from Table 2)

- Area I $>400 \text{ watts/m}^2$ (good wind energy potential) *
- Area II $>200 \text{ watts/m}^2$ (fair wind energy potential) *
- Area III $>100 \text{ watts/m}^2$ (poor wind energy potential) *

* based on calculation of annual wind-energy density flux through a vertical plane at 50-m AGL

FIGURE 4. Areas Suitable for Wind Turbine Development

regions of the study area such a single unit would produce 5.7×10^6 kWh per year, corresponding to an annual average power of 0.65 MW. Based upon simplified single-line design with a two-rotor-diameter spacing between hubs and an assumed 90% land availability, an array of 56 units located in the most promising ridgelines could produce 320×10^6 kWh per year, corresponding to an average power of 36.4 MW. Array modifications and optimum turbine sizing and selection were not considered in the initial survey.

Comparisons of recorded 6-month data to the results of the field assessment survey showed that the wind-energy assessment techniques used were able to identify sites which were most immediate and reliable for WECS development, and also those with marginal development potential. Data analysis showed a need to refine initial relationships concerning the mechanics of tree deformation.

The insights gained during the course of this program are the basis of our conclusion that, with improvement of the vegetation indices and further field experience with the TALA systems, this methodology for assessing local wind fields constitutes a reliable cost-effective technique for WECS siting in complex terrain.

Reports and Publications:

Zambrano, T. G. 1980. Assessing the Local Wind Field With Instrumentation. PNL-3622, Pacific Northwest Laboratory, Richland, WA 99352.

Assessing the Local Wind Field With Instrumentation (2.1.2.1.3)

Contract No.: B-23453

New Mexico State University
Physical Sciences Laboratory, Box 3
Las Cruces, NM 88003

Principal Investigator:

Kenneth M. Barnett (505) 646-1846

Objective:

To conduct field investigations and conduct analyses that will help electric utility and "wind farm" engineers and meteorologists who wish to use anemometer systems for evaluating the wind energy potential of mountainous sites.

Program Status:

The project was completed in September 1980 and a final report was sent to PNL in September 1980.

Progress During Reporting Period:

The concept of directly measuring wind speed and direction at several spots on a mountain to obtain data for deciding on a large WECS location was assessed. The methodology was evaluated by operating a specific type of wind-measuring system for 6 months, June through December 1979.

Six anemometer systems were installed on top of Sierra Grande, a nearly symmetrical mountain in New Mexico about halfway between Raton and Clayton. Two systems were on the peak, one at 10 m above the surface and the other at 20 m, and four other systems (at 10 m) were located roughly north, east, south, and west from the peak on secondary ridge lines to measure certain horizontal variations of the wind. These four were within 110 to 230 m of the peak to encompass a radius of 1 to 2.5 diameters of a large WECS--a minimum area to be dedicated to a single large WECS.

The study showed the methodology of instrumenting an isolated peak and leaving the equipment unattended for a month at a time is feasible. The wind-measuring equipment, after recommended improvements, proved to be an

effective way to obtain wind data for proposed WECS sites, except for the uncertainties of extrapolating wind conditions to a hub height in mountainous areas.

During this 6-month investigation the peak of the mountain did not provide the greatest wind energy. A slightly greater maximum, about 11% more, was east of the peak. The wind speed change with height from the 10 to 20-m levels on the central tower varied considerably and appeared to be a function of speed magnitude, direction, and time of day. The maximum mean wind speed for 6 months (June 6 to December 5) was 18.8 mph at 10 m with a mean power density of 542 W/m^2 . The estimated annual values are 19.7 mph and 680 W/m^2 , respectively. The estimated energy output of a MOD-2, if installed at the peak, for 6 months (June 6 to December 5) was calculated to be 4.5 million kWh. This assumed that the wind increased above 20 m by the 1/7 power law.

Based on the study, several recommendations to proposed users of this methodology or equipment can be made. Wind measurements approximately every 2 minutes with direction to the nearest 5 to 10° are needed at hub height, for a year, to calculate an accurate estimate of the annual energy output to be expected from a large WECS in mountainous areas. The instrumentation should have a reader that will put data from the cassette tape directly into any standard computer; the anemometers need to be stronger; the wind vanes need to be stronger and with a much slower response time. Exact synchronization of two or more observations on one tower is mandatory so that calculations of instantaneous wind velocity changes with height are accurate. Time synchronization of all observations is needed.

Reports and Publications:

Barnett, K. M. and R. D. Reynolds. 1980. Assuming the Local Wind Field at Sierra Grande Mountain in New Mexico With Instrumentation. PNL-3623, Pacific Northwest Laboratory, Richland, WA.

Climatological Adjustment of Short-Term Wind Statistics (2.1.2.1.4)

Pacific Northwest Laboratory
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Richland, WA 99352

Principal Investigator:

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Objective:

To develop techniques for improving estimates of climatological wind statistics derived from short-term measurements.

Program Status:

This project began in FY 1979, continued through FY 1980 and will conclude in FY 1981 with the publication of a report on the simulation model.

Progress During Reporting Period:

A wind speed simulation model has been developed in which the speed is treated as a locally stationary stochastic process superimposed upon a mean wind that includes systematic seasonal and diurnal variations, and the magnitude of the random fluctuations is also allowed to undergo both seasonal and diurnal variation. Initial computer programs have been developed to derive model parameters from data and to test the simulation technique. If the simulation model provides reasonably realistic wind speed time series, it will be a useful tool for evaluation of techniques for adjusting short-term climatological statistics to be more representative of long-term conditions.

Expected Progress During Next Reporting Period:

The computer programs will be refined, and the model will be tested. A report will be prepared describing the model. The computer programs will be documented.

Reports and Publications:

None.

Wind Turbine Wake Flow (2.1.2.1.5)

Contract No.: DE-AC06-79ET23160

Flow Industries, Inc.
21414 68th Avenue
Kent, WA 98031

Principal Investigator:

James V. Riley (206) 872-8500

Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To define the critical technical issues related to the problem of wake effects in wind turbine clusters and to determine the current state of knowledge of wake characteristics and how to model them. A final objective was to recommend further research necessary to solve the problems in this field.

Program Status:

This project was completed in FY 1980.

Progress During Reporting Period:

The objectives were achieved through an extensive literature review, of both directly and indirectly related work, and through discussions with key individuals involved in the field.

The issues critical to treating wake effects can be categorized into two groups: first, how a wake(s) affects the performance and structure of a downwind machine; and second, the characteristics of the wake of single units and of multiple units in arrays. The wake(s) of an upwind unit(s) can affect the performance of downwind units through i) intercepting ambient wind energy and thus decreasing the energy flux to the downwind unit, ii) generating gradients in the mean wind, iii) generating turbulence, and iv) producing discrete flow structures such as tip vortices. The structure of the downwind unit can be affected by i) induced wind

shear, ii) fluctuating loads due to wake turbulence, and iii) specific flow structures such as tip vortices. The wake characteristics needed are thus the mean wind speed, wake turbulence characteristics and specific flow structures as a function of the distance downwind of a machine. These should be known as functions of ambient wind conditions and characteristics of the particular turbine under consideration. In addition, when wind turbines are placed in arrays, these wake characteristics are needed as a function of the configuration of the array.

Several theoretical models have been developed to treat the effects of wind turbine wakes. The model most developed, and possessing the most potential for future applications, is that of Lissaman (1979). It calculates the reduction in velocity in the wake of a wind turbine by using a semiempirical model based upon the analogy of wind turbine wakes to jet-type flows (see Figure 1). It then uses linear superposition of these velocity defects from upstream turbines to calculate the kinetic energy flux intercepted by a downstream turbine in order to determine the reduction in power caused by the wake environment. It can be used for arbitrary array configurations and accounts for most major influences (see Figure 2). However, this model needs validation because of many simplifying assumptions made in developing the model.

A second theoretical approach has been direct numerical calculations using the governing primitive equations of motion. Although less assumptions are needed here than with Lissaman's model, this approach is more difficult to use, and cannot easily be extended from single units to arrays. Theoretical techniques have been borrowed from aeronautics for a third approach, which computes the behavior of the shed vortices in the near field behind the turbine. While probably applicable in the near field (less than about 3 diameters), these techniques do not apply to the mid-to-far field. Other methods have been developed to treat arrays using boundary layer similarity theory. However, because of the extensive assumptions made in developing these models, only very qualitative results can be obtained from them.

FIGURE 1. General Wake Geometry (Walker and Lissaman, 1978)

FIGURE 2. Staggered, Three Row Array of 10 Wind Turbines

Another approach to modeling wind turbine wakes is physical, or laboratory, modeling. Approximately scaled models of horizontal- and vertical-axis turbines have been used. Although this approach has much potential, confidence levels in the technique need to be established since all the similarity requirements cannot be met. In particular, due to the small size of the models (roughly 20 to 30 cm diameter), the Reynolds number is not duplicated. Some experiments have been carried out with larger models (roughly 2 m) in aeronautics wind tunnels, where scaling effects appear to be much less significant. However, these tests are limited to structural and near-wake studies, and are incapable of treating the mid-to-far wake.

Greatly simplified (e.g., porous disc) models have also been used in wind tunnel studies (see Figure 3). Because of the small size (about 7 cm) and simplicity of the models, they can be used in array studies. However, in addition to the scaling problems mentioned above, these models also suffer because no power is extracted from the flow. They are obviously poor models in the near field, realistic operating curves cannot generally be matched, and their effect on the ambient wind is probably erroneous.

The knowledge of wind turbine wake effects has been advanced using the mathematical and physical models as well as by carrying out field experiments. However, little reliable quantitative information has been obtained, because of difficulties inherent in carrying out field programs and the uncertainties of the mathematical and physical models. There is, though, a considerable amount of qualitative information now available. For example, estimates have been made of the dependence of power output in arrays on array spacing; ambient and wake turbulence have been found to profoundly influence wake recovery rates; and the relative effects of varying such parameters as the tip speed has been determined. But it is clear that much more needs to be known.

With regard to wake turbulence effects on performance of downwind machines, some estimates of wake turbulence intensities and frequencies have been made from the laboratory studies. It appears that in the range of 5 to

FIGURE 3. Mean Velocity Profiles in the Horizontal Direction (Bultjes 1979a)

10 diameters downwind of a turbine, wake turbulence can be comparable with or greater than the ambient turbulence. The frequencies of the wake turbulence appear to be much higher than in the ambient turbulence.

Although a little work has been done to estimate the effects of ambient turbulence on turbine performance (using both mathematical and physical modeling), the results are ambiguous and cannot be extended to determine the effects of wake turbulence. No work has directly addressed wake turbulence effects.

No work has been done to estimate the effects of wake turbulence on structures. However, computer programs have recently been developed that can probably address this problem.

Recommendations resulting from this study fall into three categories: mathematical modeling, physical modeling, and field studies. The main thrust of the mathematical modeling effort should revolve around Lissaman's model, because of its potential usefulness. Work should be initiated to exercise the model (e.g., to determine the relative importance of various factors and the sensitivity of the power output to them), improve the model, and validate the modeling (using both laboratory and field data). Theoretical work should also be initiated to address the questions of wake turbulence effects on performance and turbine structures.

Work should also be initiated in physical modeling. First, a list of past experimental work, both published and unpublished, including a general description of each experiment, should be catalogued. Secondly, studies using approximately scaled models should be started. These studies should have the dual purpose of obtaining a better understanding of wake effects (by examining, e.g., the effects of turbulence on performance, the structure of the flow in wakes, and wake interactions) and validating mathematical models. Although the laboratory models have not been completely validated themselves, laboratory experiments should still be useful in gaining better understanding of and more confidence in the mathematical models.

With regard to field studies, all existing and planned experiments should be catalogued. Secondly, studies should be initiated using smaller scale

(5 m to 20 m diameter) turbines, under as ideal conditions as possible. This work should address both isolated units and units in small (5 or less) clusters. Finally, planning should begin on instrumenting the Boeing MOD-2 wind turbines that are to be installed near Goldendale, Washington. This should involve design of instrumentation and procedures, and possibly influencing the decision on the array configuration, for both performance and structural studies.

Reports and Publications:

Riley, J. J. et al. 1980. A Review of Wind Turbine Wake Effects.

DOE/ET/23160-80/1, Flow Industries, Inc., Kent, WA. Available from NTIS.

A Review of Remote Sensor Potential for Wind Energy Studies (2.1.2.1.7)

Contract No.: DE-AI06-79ET23151

NOAA-Wave Propagation Laboratory
Environmental Research Laboratories
Boulder, CO 80302

Principal Investigator:

William H. Hooke (303) 497-6378

Contract Monitor:

Thomas R. Hiester (509) 375-6161 ext. 243

Objective:

To assess the potential of remote sensors for wind energy studies.

Program Status:

The project was initiated in September 1979; a final report was submitted in the summer of 1980.

Progress During Reporting Period:

The final report evaluates a number of remote-sensing systems, such as radars, lidars, and acoustic echo sounders, which are potential alternatives to the cup and propeller anemometers routinely used in wind energy siting. The high costs and demanding operational requirements of these sensors currently preclude their use in the early stages of a multi-phase wind energy siting strategy such as that articulated by Hiester and Pennell in the Large WECS Handbook (see Task 2.1.2.1.9). Instead, these systems can be used most effectively in the lattermost stages of the siting process--what Hiester and Pennell refer to as the "site development phase," necessary only for the siting of large WECS or WECS clusters. Even for this particular application only four techniques appear to be operational now; that is, if used properly, these techniques should provide the data sets currently considered adequate for wind energy siting purposes. They are, in rough order of increasing expense and operating demands:

- optical transverse wind sensors
- acoustic Doppler sounders
- time-of-flight and continuous wave (CW) Doppler lidar
- frequency-modulated, continuous wave (FM-CW) Doppler radar.

Not all these instruments are presently commercially available. While the first two are, the latter two are not. Nor can such instruments necessarily be operated as simply, as reliably, or as economically as their in situ counterparts. For the most part, remote sensors are more expensive and demanding in their operating requirements than the most rudimentary in situ capability for the siting phase (which for this discussion can be taken to be a single tall tower with three anemometers, mounted respectively at the bottom of the rotor disk, at hub height, and at the top of the rotor disk). Neither will the data sets obtained by these instruments necessarily be entirely free of shortcomings. In some cases, it is possible that the data may be biased as a result of variations in system performance with meteorological conditions. However, it appears that these shortcomings could be tolerated in siting studies.

Despite these caveats, the use of remote-sensing systems in wind-energy applications may be viable in the next 5 years, if not now. Some of the instruments can operate virtually unattended for extended periods. The cost of their operation, while sometimes high, often falls within the rather large dollar limits determined by cost-benefit analyses to be available for site survey, particularly for the larger WECS systems and WECS clusters. In addition, remote-sensing systems may prove quite useful, perhaps essential, in advancement of WECS technology generally. As user requirements on wind-energy data sets become more stringent, as inflation increases the cost of conventional siting methods, and as improved technology reduces the cost of remote-sensing alternatives, these should continue to look increasingly attractive.

The report summarizes these findings. It describes briefly the principles underlying the operation of remote-sensing systems and discusses their advantages and limitations for wind energy applications. The emphasis

is on siting but some material on design work is included. Future data needs for wind energy siting and design are projected and compared with the capabilities of the new instruments. Some lines of research and development that could be fruitfully pursued in order to increase the effectiveness of remote-sensing systems in wind energy applications are indicated.

The views of several members of the remote-sensing community representing both the public and the private sectors were solicited to aid in preparation of the report; their responses are presented, essentially unedited, in an appendix. A final appendix contains an extensive bibliography of published literature in remote sensing.

While the report provides no pat formulas for decision making, it does supply information that DOE, PNL, and potential users will need to make intelligent, informed choices in their allocation of research dollars and in their selection of meteorological instrumentation for wind energy siting and design.

Reports and Publications:

Hooke, W. H. 1981. A Review of Remote Sensor Potential for Wind Energy Studies. DOE/ET/23151-80/1, NOAA-Wave Propagation Laboratory, Boulder, CO. Available from NTIS.

Large WECS Handbook (2.1.2.1.9)

Pacific Northwest Laboratory
P.O. Box 999
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Principal Investigators:

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William T. Pennell (509) 375-6161 ext. 200

Objective:

To provide siting strategies, critical evaluation of available siting techniques and other meteorological information that can be used to site single units or clusters of large WECS.

Program Status:

Revision of The Meteorological Aspects of Siting Large Wind Turbines is nearly complete. This report is scheduled for publication early in FY 1981.

Progress During Reporting Period:

The first draft of the report was sent out for extensive peer and sponsor review. Review comments were incorporated into a new draft containing these chapters:

- Strategies for Wind Turbine Siting
- Numerical Modeling
- Physical Modeling
- Topographic Indicators of Wind Power Potential
- Biological Indicators of Wind Power Potential
- Geomorphological Indicators of Wind Power Potential
- Social and Cultural Indicators of Wind Power Potential
- Wind Turbine Wakes and Cluster Design
- Measurement and Instrumentation.

This draft has also been reviewed and final revisions are in progress.

Expected Progress During Next Reporting Period:

Revisions will be completed early in the fiscal year and publication of the report, The Meteorological Aspects of Siting Large Wind Turbines, will follow.

Reports and Publications:

None in FY 1980.

Update Small WECS Handbook (2.1.2.1.9A)

Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352

Principal Investigator:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To revise A Siting Handbook for Small Wind Energy Conversion Systems in order to provide the general public with effective and inexpensive siting methods.

Program Status:

Publication of A Siting Handbook for Small Wind Energy Conversion Systems in March 1980 completed this task.

Progress During Reporting Period:

Incorporation of review comments on the first edition resulted in the reorganization and updating of the material. A new chapter on wind measurements and an appendix on sources of wind instruments are major additions to the text. Virtually all the narrative and graphics have been revised for improved clarity and readability.

Reports and Publications:

Wegley, H. L., J. V. Ramsdell, M. M. Orgill, and R. L. Drake. 1980.
A Siting Handbook for Small Wind Energy Conversion Systems. PNL-2521
Rev. 1, Pacific Northwest Laboratory, Richland, WA.

Siting Short Course for Small WECS (2.1.2.1.10)

Pacific Northwest Laboratory
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Richland, WA 99352

Principal Investigator:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To develop a short course on the meteorological aspects of small WECS siting for agricultural extension agents and WECS dealers.

Program Status:

Work began in October 1978, and preliminary versions of the course were presented in April and May 1979. Packaging of the course into a concise audio/visual presentations has been the FY 1980 focus. A completed version is expected in FY 1981.

Progress During Reporting Period:

Comments on preliminary versions of the course resulted in the reorganization of the course into small modules, each addressing a particular aspect of siting small wind machines. PNL completed detailed outlines of the narrative for these modules. SERI was to assist PNL in generating a production version of the course. SERI employed a professional writer to draft a narrative and workbook and a photographer to obtain the accompanying visual material. PNL reviewed a draft of the narrative and workbook and returned these with extensive comments to SERI. As of the end of the fiscal year SERI was still working on the narrative.

Expected Progress During Next Reporting Period:

PNL will review SERI material and help SERI complete the short course in FY 1981.

Reports and Publications:

None in FY 1980.

Evaluation of Inexpensive Meteorological Instruments (2.1.2.1.11)

Pacific Northwest Laboratory
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Principal Investigator:

J. V. Ramsdell (509) 375-6161 ext. 344

Objective:

To identify, test and evaluate inexpensive meteorological instrumentation for potential use in siting small wind energy conversion systems (SWECS).

Program Status:

This project began in FY 1979. In FY 1980 the initial results of wind tunnel tests were completed. Publication of the results of these tests in FY 1981 will conclude the project.

Progress During Reporting Period:

Six anemometer systems were tested in a wind tunnel to determine system response and linearity. Table 1 shows the linear fit to the calibration points for the various anemometers. The slope is the ratio of anemometer reading (output) to wind tunnel speed. Systems were evaluated in terms of the completeness of instructions, ease of operation and readout interpretation. Long-duration field testing of the units for reliability studies was not done.

Expected Progress During Next Reporting Period:

A report documenting the wind tunnel tests will be completed and published to conclude this phase of the project.

Reports and Publications:

None in FY 1980.

TABLE 1. Wind Tunnel Testing of Wind Instruments

<u>Instrument</u>	<u>Intercept (mph)</u>	<u>Slope</u>
Natural Power A30-101 Wind Speed Compiler	0.4	0.97
Weathermeasure W224 Recording Wind System	-2.3	0.91
Trade Wind II Anemometer	-1.8 LOW	1.09
	-2.2 HIGH	1.03
Wind Power Systems Windometer	-1.0	0.94
Weathermeasure W163	-0.2	1.10
Weathermeasure W164	-0.1	1.03

Technology Development for Assessment of Small-Scale Terrain Effects on
Available Wind Energy (2.1.2.1.12)

Contract No.: DE-AC06-76ET20242

FWG Associates
RR3 Box 331
Tullahoma, TN 37388

Principal Investigator:

Walter Frost (615) 455-1982

Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To analytically and experimentally analyze kite anemometer performance.

Program Status:

The program began in 1976 and is in the last phase of the study of kite performance. A final report in FY 1981 will conclude the project.

Progress During Reporting Period:

Analysis of a kite anemometer immersed in a wind field has been performed. The dynamic equations for analyzing tether configuration and a point-mass approach for analyzing the kite motion have been developed. The analysis has been carried out for both steady-state and unsteady-state conditions.

The steady-state analysis indicates that the kite anemometer can be employed at sites of varying terrain surface roughness without specific calibration for that site because the tether tension force is much larger than the aerodynamic forces acting on the tether. Model results simulating unsteady conditions shows that the transient response of tether tension closely follows the wind (Figure 1).

Expected Progress During Next Reporting Period:

A report will be published in FY 1981 that will describe an analytical model of the kite anemometer. The model will: 1) allow evaluation of different kite configurations and tether systems, 2) provide insight into data acquisition, processing and interpretation, and 3) give an understanding of the physical mechanism of the system. The report will delineate

FIGURE 1. Analytical Model Result of the Response of Kite Tether Tension to Simulated Wind Speed

the proper use of kites in WECS system siting, and ultimately, when verified by experiment, provide design criteria for development of future kite anemometer systems. Both equilibrium and dynamic analysis will be described.

Reports and Publications:

Shieh, C. F. and W. Frost. 1980. "Tether Analysis for a Kite Anemometer." Wind Engineering. 4(2).

Coordinate and Interpret Model Verification (2.1.2.2.1)

Pacific Northwest Laboratory
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Richland, WA 99352

Principal Investigator:

Thomas R. Hiester (509) 375-6161 ext. 243

Objective:

To evaluate the use of several near-surface air flow models in siting wind turbines.

Program Status:

This task was initiated in FY 1979 and was completed in FY 1980.

Progress During Reporting Period:

An evaluation of several numerical models of near-surface wind flow was prepared as Chapter 3 to The Meteorological Aspect of Siting Large Wind Turbines (Hiester and Pennell 1981). The ability of both kinematic and primitive-equation models to model the wind field was discussed. The following conclusions and recommendations were given:

The primary problem with all numerical models is a lack of verification. There have not been enough experiments in which model simulations have been compared with good field measurements. This will remain the case for a long time, since there are not very many good data sets for experiments of this type. The expense of gathering good verification data is large, and the task of gathering enough data to allow the flow over a complex piece of topography to be deduced unequivocally from the data alone is impossible. The only alternative is good judgment. The person analyzing model results should accept or reject them on the basis of how well he feels the model simulates the important physical processes controlling the flow.

Three-dimensional primitive-equation models should be capable of simulating the wind patterns produced either when a large-scale flow interacts with the sea-breeze circulation or from changes in surface roughness. Less is known of the ability of primitive-equation models to handle rugged topography and the effects of surface-temperature variations in sloping terrain (which can cause drainage winds, etc.). The usefulness of primitive-equation models is in locating areas where local circulations, in addition to topographic profile, enhance wind power potential. The existence of these enhanced regions would have to be verified by onsite measurements. Simple kinematic models should be used only in situations where the primary effects of topography are in blocking or channeling the flow or in situations where the input data set is dense enough to define the general flow conditions over the area.

Since conclusions based on modeling (and particularly primitive-equation modeling) are based on a small number of simulations, caution is advised. When applying the models, studies should be conducted to determine how sensitive the location of important wind features might be to relatively small changes in the initial or boundary conditions. Results of such studies could indicate the likelihood of actually finding the enhanced areas. One should also be cautious in attaching too much significance to the magnitude of wind speeds predicted by a model. The patterns predicted by the model are probably more accurate than their magnitudes. Finally, a user should not take model predictions of the boundary layer wind profile or the behavior of the diurnal cycle too seriously. The methods used in existing models to simulate these characteristics of flow over terrain are simply too crude to warrant this level of confidence.

Reports and Publications:

Hiester, T. R. and W. T. Pennell. 1981. Chapter 3 of The Meteorological Aspects of Siting Large Wind Turbines. PNL-2522, Pacific Northwest Laboratory, Richland, WA.

Numerical Model Verification (2.1.2.2.2)

Contact No.: DE-AC06-77ET20280

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

Principal Investigator:

Richard M. Traci (714) 454-0642

Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To expand the verification of wind fields generated by numerical models by assessing their quantitative accuracy in complex terrain represented by the Nevada Test Site.

Program Status:

This project, which began in 1975, has been completed.

Progress During Reporting Period:

FY 1980 work focused on the second part of a two-part verification program for a mathematical-model-based WECS siting methodology. The first part of the program involved windfield simulations and wind data comparisons for the island of Oahu, Hawaii. In the present program, the model verification is expanded by assessing the quantitative accuracy of the models relative to observed data for a midcontinental region of complex topography and meteorology: the Nevada Test Site (NTS), Nevada (Figure 1). In particular, the ability of the detailed-physics SIGMET model to describe dynamic atmospheric and boundary layer effects on the windfield in a mesoscale region with complex terrain and the ability of the simplified-physics NOABL model to predict windfields utilizing a small amount of available data were investigated. Results of SIGMET, NOABL and LINMET simulations for two typical flow events at the NTS are compared and contrasted with available wind data. LINMET is a linear theory model, which was added to the model comparison study, to provide comparative

FIGURE 1. Nevada Test Site Terrain Perspectives From Four Viewing Angles (1.5 km Resolution)

results from a state-of-the-art modeling approach intermediate between SIGMET and NOABL. In addition, 112 NOABL simulations of actual "wind events" in the NTS data network historical record were performed and a detailed statistical analysis of the results relative to the data is presented.

Comparative results of the "typical" event simulations indicated the relative benefits of each modeling approach. Each model predicted the observed lack of a significant site-to-site variation in winds for one event as well as the greater variability for the other event. In each case, the NOABL model tended to overpredict the low wind sites and underpredict the high wind sites (Figure 2); SIGMET tended to underpredict the site wind (by ~ 1 m/s) due to its representation of boundary layer effects (Figure 3); and LINMET tended to overpredict site winds (by ~ 3 m/s due to the absence of boundary layer effects in that model (Figure 4). Both SIGMET and LINMET predicted a significant "slope wind" effect in one case, which is confirmed in the observed data. Although SIGMET, in one case, predicted nonphysical atmospheric wave activity (which requires additional study) the simulations were quite reasonable in terms of phenomena demonstrated; this highlights the level of detail provided in its description of atmospheric flows.

The detailed statistical assessment of the accuracy of the NOABL model included model simulations and field data comparisons for a 28-event matrix of NTS wind events. The results indicate that, on average, the model can predict windspeeds to within 1.5 m/s (based on mean deviation) and wind direction to within $\sim 20^\circ$. Most important for the wind energy siting applications of interest is the qualitative and quantitative accuracy of the station-to-station and region-to-region variation in ensemble mean windspeed and wind energy potential predicted by the model. This indicates that the use of the model in the siting methodology in the manner originally planned will result in a description of the regional windfield that highlights high wind potential regions and distinguishes them from those with low potential.

FIGURE 2. Near-Surface (~ 10 m AGL) Windfield Vectors and Speed Contours (m/sec):
 NOABL Simulation of NTS on 2/20/71 at 0400 LST (Simulation I: Stations 8,
 9, 10, 11, 12, 19 and Yucca Flat Upper-Air Data Used in Initialization)

FIGURE 3. Near-Surface (~ 20 m AGL) Windfield Vectors and Speed Contours (m/sec):
SIGMET Simulation of NTS on 2/20/71 at 0400 LST (1 hr Simulation)

FIGURE 4. Near-Surface Windfield Vectors and Speed Contours (m/s)
for LINMET Simulation of NTS on 2/20/21 at 0400 LST

Expected Progress During Next Reporting Period:

This phase of model verification work is completed.

• Reports and Publications:

Traci, R. M., D. C. Wyatt, P. C. Patniak and G. T. Phillips. 1980. Wind Energy Siting Methodology Windfield Model Verification Program II: Nevada Test Site Data Set. DOE/ET/20280-80/2, Science Applications, Inc., La Jolla, CA. Available from NTIS.

International Model Verification-PNL (2.1.2.2.3)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To evaluate the role of numerical models in wind turbine siting by comparing the results of various windfield models with observations of wind patterns over various types of terrain. This task is part of an international program on windfield model verification undertaken through Annex II of the Implementing Agreement for a Programme of Research and Development on Wind Energy Conversion Systems, established by the IEA.

Program Status:

The program is in progress and will continue through FY 1981.

Progress During Reporting Period:

Plans for the verification exercise were completed at a meeting of the participants in October 1979. At that meeting three sets of wind data were chosen for comparison with the numerical models. The data sets represent wind conditions over the island of Oahu in Hawaii, the Nevada Nuclear Test Site and the island of Gotland in Sweden. These data sets cover a wide range of terrain and meteorological complexity.

Four numerical models were also chosen for the study:

- a simple, mass-consistent, wind interpolation code (the NOABL code developed by Science Applications, Inc., USA)
- a one-level, primitive equation model (SAM, developed by the Atmospheric Environment Service of Canada)
- a multi-level, time-dependent, hydrostatic model (the University of Virginia mesoscale model)
- a multi-level, time-dependent, nonhydrostatic model (the Tapp and White model of the UK Meteorological Office).

After the Seattle meeting, an additional model was added to the program: the multi-level, time-dependent, hydrostatic model developed by Science Applications, Inc., called SIGMET. SIGMET has a different turbulence model than the other hydrostatic model, and it uses different numerical procedures in solving the equations of motion. The purpose for including SIGMET was to see if these modeling differences would make significant differences in simulated windfields.

Processed data were delivered to the various modeling groups on schedule and work began at the various modeling groups shortly after the first of the year. In early June 1980 a meeting was held to compare initial results and to iron out any problems in the work plan for the project. By the time of the meeting, simulations of the Oahu data set had been completed by the simpler models (NOABL and SAM). However, the more complicated models (SIGMET, the University of Virginia model and the U.K. Meteorological Office model) had not completed the Oahu simulations. The modelers were having more difficulty getting their simulations under way than they had anticipated, and by the end of September 1980, satisfactory results from the more complicated models had not been obtained.

Expected Progress During Next Reporting Period:

Modeling efforts will be completed by September 1981. A final report on the results is scheduled for FY 1982.

Reports and Publications:

None in FY 1980.

International Model Verification - SAI (2.1.2.2.4)

Contract No.: B-92947

Science Applications, Inc.
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1200 Prospect Street
La Jolla, CA 92038

Principal Investigator:

Richard M. Traci (714) 454-0642

Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To exercise the Science Applications, Inc. (SAI) NOABL and SIGMET complex terrain windfield models for Oahu, Hawaii; Nevada Test Site, Nevada; and Gotland, Sweden, and to compare results to site wind data for each of the regions.

Program Status:

The project was initiated in January 1980 and will continue through August 1981. The program represents a contribution to Annex II of the Implementing Agreement for a Program of Research and Development on Wind Energy Conversion Systems. A final report presenting model summaries and results for each of the selected cases will be prepared for delivery in July of 1981.

Progress During Reporting Period:

Under U.S. Department of Energy sponsorship (DOE contract DE-AC06-77ET20280) SAI has developed a WECS siting methodology that uses the NOABL and SIGMET numerical windfield models to describe mesoscale windfields based on available historical or field test data. Briefly, NOABL is described as a simplified physics, terrain conformal, objective analysis model and SIGMET is a primitive equation, terrain conformal, mesoscale meteorology model. The development, verification and application of these models, as well as other elements which constitute the siting methodology, have

been described in recent reports produced in the above referenced program. As a contribution to the Annex II program, these verification studies are being expanded to include the following:

- i) additional NOABL simulations and comparisons to data for Oahu, Hawaii, and Gotland, Sweden
- ii) long-duration (12 to 24 hours) SIGMET simulations and data comparisons for
  - Oahu, Hawaii, on August 2, 1976
  - Nevada Test Site, Nevada, on February 20, 1971
  - Gotland, Sweden, on November 23, 1978.

The bulk of the present work is represented by item ii, which involves demonstrating that SIGMET can be successfully operated for long-duration simulations and validating SIGMET predictions of diurnal variations in the windfield versus a relatively extensive data set for each of the regions.

During the present reporting period, each of the simulations indicated above has been set up and tested; the long-duration SIGMET simulations have been continued to the extent indicated:

• Oahu	August 2, 1976	from 0200 LST to 1600 LST
• Nevada Test Site	February 20, 1971	from 0400 LST to 1400 LST
• Gotland	November 23, 1978	from 0400 LST to 0600 LST.

Each of these simulations are "initialized" at the indicated local time using available sounding data and integrated forward-in-time accounting for the dynamic interaction of synoptic forcing, terrain forcing, atmospheric stability, boundary-layer turbulent mixing and solar/terrestrial radiation exchange. A typical result for the near-surface windfield is shown in Figure 1 for the Oahu simulation at 1600 LST (14 hours of simulation time). The figure indicates a rather dramatic modification of the approach flow in the southwest corner of the region believed due to the combination of thermal upwelling over the island and terrain/boundary layer interaction on the lee-side mountain range.

● windspeed contours (m/sec)

● wind vectors

FIGURE 1. Near-Surface (~ 20 m AGL) Windspeed Contours and Wind Vector Flowfield: SIGMET Simulation of Oahu, Hawaii at 1600 LST (Calculation Initialized at 0200 LST)

Expected Progress During Next Reporting Period:

All of the model simulations indicated above will be completed and detailed comparisons with data from each of the sites made. The model results and data comparisons will be described in a final report for inclusion in a report describing the overall Annex II program.

Reports and Publications:

None in FY 1980.

International Model Verification - University of Virginia (2.1.2.2.5)

Contract No.: B-92942

Department of Environmental Sciences
University of Virginia
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Principal Investigators:

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Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To compare windflow predictions from the University of Virginia mesoscale model (UVMM) with three other models - one prognostic and two diagnostic. At least three case studies for two different sites are planned. The numerical models are stressed by both fine horizontal resolution and rough topography.

Program Status:

The project was initiated in February 1980 and will continue through July 1981.

Progress During Reporting Period:

Early results from two-dimensional simulations suggested that the UVMM (a hydrostatic model) would be able to treat the relatively fine horizontal mesh (1.6 km) used for Oahu. This was confirmed by preliminary simulations using a three-dimensional version of the UVMM. However, coding problems persisted and this prevented further substantial progress during FY 1980.

Expected Progress During Next Reporting Period:

Complete the planned three-dimensional simulations for Oahu (both the tradewind and Kona case studies) and Gotland. A full 24-hour integration for the Oahu trade-wind day has already been achieved.

Figure 1 (from the simulation) shows a problem which arose. A perturbation developed along the eastern inflow boundary during the morning. By mid-afternoon the perturbation had amplified and contaminated the solution across much of the integration domain.

It was also noted that the zero-gradient inflow boundary condition caused a deceleration of the tradewind during the night. Therefore, new lateral boundary conditions will be formulated to preserve the persistent trade-wind flow. The boundaries will also be constructed so as to minimize the appearance and growth of undesirable perturbations.

Lastly, the University of Virginia is removing the time dependency from the vertical terrain-following coordinate. It is felt that the temporal dependence of the vertical coordinate is a source of numerical noise (i.e., instability).

Once the corrections are made, the three simulations will be run as agreed upon by the members of the Wind Energy Modeling Group. If funds permit, an additional simulation for Oahu which commences at sunrise may be made. This will permit a better comparison with the group in the United Kingdom, which has difficulty running its model beyond eight simulated hours.

Reports and Publications:

None in FY 1980.

Evaluate DOE Models (2.1.2.2.6)

Pacific Northwest Laboratory
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Principal Investigator:

Thomas R. Hiester (509) 375-6161 ext. 243

Objective:

To determine if documentation associated with the NOABL model provides an adequate description of how to implement and use the model.

Program Status:

This task was begun and completed in FY 1980.

Progress During Reporting Period:

The NOABL code was input to the DOE RL UNIVAC 1110 computer and successfully run. It was determined that the documentation was adequate to implement and run the model.

Reports and Publications:

None.

Sites for Wind Power Installations (C1a)

Contract No.: DE-AS06-77ET20292

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Contract Monitor:

William T. Pennell (509) 375-6161 ext. 200

Objective:

To verify wind-tunnel techniques for determining the influence of topography on the near-surface windfield.

Program Status:

This program was initiated in June 1975 and was completed with the submission of a final report (originally dated October 1979).

Progress During Reporting Period:

Oahu Island, Hawaii, is known to possess a rich wind power resource due to the prevailing trade wind boundary layer. Several wind energy conversion system (WECS) installations have been proposed for the Kahuku Point region. Although limited field measurements have now been performed at certain proposed sites, other wind power sites or regions may have greater local potential. The present study of wind tunnel tests over a Kahuku Point model is to extend the value of field results and to provide detailed information for WECS installations in this region. Field measurements were used to validate the wind-tunnel results at several selected sites.

A contoured model of the Kahuku Point area was prepared to an undistorted scale of 1:3840. Local terrain roughness due to topographic features was simulated. The approach flow over the model was adjusted to match a typical marine trade wind boundary layer.

For three different wind directions, which encompass the predominant directions from which the Pacific trade wind blows over the Kahuku Point region, measurements of wind speed and turbulence at proposed WECS sites and 40 additional grid locations were performed. These measurements were used to produce horizontal contour plots of relative wind power.

After careful examination of field measurement and wind tunnel test conditions, nineteen comparable data pairs were identified. The linear correlation between field and laboratory measurements of these data pairs was found to be 0.71. A correlation by rank of relative wind speed for these data pairs revealed a simulation at a level of 0.84.

To evaluate several currently proposed methods for speed-up prediction of flow over hills, one semi-empirical and one analytical technique were applied to several selected WECS sites. Comparison with the laboratory results indicates that both methods predict values which bracket typical topography amplification. Improvement in prediction of the approach flow appears to be the first step in reducing the uncertainty of the speed-up prediction.

Reports and Publications:

Chien, H. C., R. N. Meroney, and V. A. Sandborn. 1979. Sites for Wind Power Installations: Physical Modeling of the Wind Field Over Kahuku Point, Oahu, Hawaii. DOE/ET/20292-79/1, Colorado State University, Fort Collins, CO. Available from NTIS. (Also given as a paper at 3rd International Symposium on Wind Energy Systems, Copenhagen, Denmark, August 26-29, 1980.)

METEOROLOGICAL CHARACTERISTICS FOR DESIGN AND PERFORMANCE EVALUATION (2.2.1)

The objective of the Design and Performance Evaluation technical area is to examine the direct interaction between meteorological phenomena and a wind turbine. For FY 1980, the main efforts in Design and Performance Evaluation were:

- investigation of wind characteristics as experienced by a rotating blade of a WECS
- initiation of appropriate new measurements at a large wind turbine site
- characterization of fixed-point winds for different terrain or wind regimes
- quantitative estimation of probabilities of extreme events
- collection of wind characteristics for use in the design of wind turbines; this wind information, assessed, organized and presented by practicing turbine designers and atmospheric scientists, will be compiled by the end of FY 1981.

Also in FY 1980, the first effort was made to determine the accuracy of different uses of wind characteristics for performance evaluation, and advanced theoretical wind turbine experiments and a field study at a large turbine were undertaken.

FY 1981 will mark a distinct movement of emphasis toward availability of modern wind turbine considerations in characterizing the wind and relating wind measurements and analyses to accurate performance evaluation because of the FY 1980 program.

Atmospheric Criteria for Design of WECS (2.2.1.1.1)

Contract No.: B-23461

FWG Associates, Inc.
RR3 Box 331 or RR2 Box 271-A Lakewood Drive
Tullahoma, TN 37388

Principal Investigator:

F. Walter Frost (615) 455-1982

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To investigate derivation of theory and supporting data used by Frost, Long and Turner (1978).

Program Status:

Final report draft was submitted to Battelle and is being revised.

Progress During Reporting Period:

Graphical results of two-dimensional directional probabilities as a function of reference wind speed at the 10, 30, 50, 100, and 150 m levels and of surface roughness were given. These results are expected to provide reasonable engineering predictions at heights above local terrain disturbances to the wind. The bivariate model was then compared with some experimental data measured at the eight-tower array at NASA Marshall Space Flight Center's (MSFC) Atmospheric Boundary Layer Facility.

Improvements to the model were made by utilizing a multivariate probability distribution including all three wind speed components as well as cross-correlation terms. Integrated results using the multivariate model were compared with experimental data. The multivariate model was found to be more accurate in predicting probabilities than the bivariate model.

The trivariate model wind directional probability predictions were found to be more realistic than the bivariate predictions. The bivariate model showed the proper trend; however, it tended to overestimate the cumulative

probabilities. The multivariate model overestimated cumulative probabilities only within small angles. The model also allows for extreme wind directional fluctuations that occur only rarely. The experimental data were taken from a 10-minute time history samples and, therefore, do not include directional fluctuations, which occur at frequencies less than 0.01 Hz.

Scatter diagrams of cumulative probabilities, observed versus predicted for the trivariate model, are shown in Figure 1. The scatter diagrams show that the trivariate model makes realistic predictions of wind directional fluctuation probabilities. The rms differences of these two cases are 5 percent and 5.8 percent for level three and level four, respectively.

Estimates of the auto- and cross-correlations and the mean wind speed are all the information needed for this model. Estimates of the auto- and cross-correlations can be determined by sample tower data or by turbulence modeling with the use of the roughness parameter z_0 .

Expected Progress During Next Reporting Period:

The final report will be revised to include meaningful comparisons between bivariate and trivariate wind direction probability models.

Reports and Publications:

None in FY 1980.

FIGURE 1. Calculated Versus Observed Wind Directional Probabilities for the Trivariate Distribution Model

Wind Characteristics for Advanced Design of WECS (2.2.1.1.2)

Contract No.: DE-AT06-79ET23144

Oregon State University
Department of Mechanical Engineering
Corvallis, OR 97331

Principal Investigator:

Robert W. Thresher (503) 754-2535

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To determine which of the excitation sources in atmospheric turbulence are important in characterizing wind turbine system responses.

Program Status:

The project was began in July 1979 and is scheduled for completion in mid 1981.

Progress During Reporting Period:

A model for describing the statistical nature of the random field of turbulence over the rotor disk has been developed. The model incorporates uniform and gradient terms which vary with time, yielding nine turbulent inputs that drive the turbine excitations.

Models for two different sizes of three blade turbines have also been developed. These models include responses of both turbine and tower to the aerodynamic forces imposed by the mean and turbulent wind fields. Preliminary calculations have shown the importance of along-axis turbulent wind fluctuations and the longitudinal and vertical turbulent wind gradients. Comparisons have been made using frozen wake and equilibrium wake models. Side force, thrust, yaw moment and pitch moment responses are being investigated.

Expected Progress During Next Reporting Period:

The model comparisons will be completed, a full analysis of the machines' response to various turbulent fluctuations will be carried out, and a final report will be prepared.

Reports and Publications:

None in FY 1980.

Turbulence Characteristics Over Complex Terrain (2.2.1.1.3)

Contract No.: B-92870 and DE-AS06-78ET20560

Pennsylvania State University
505 Walker Building
University Park, PA 16802

Principal Investigator:

Hans A. Panofsky (814) 865-0478

John A. Dutton (814) 865-1534

Contract Monitor:

David C. Powell (509) 375-6161 ext. 304

Objective:

To characterize the wind at sites in complex terrain, typical of where WECS may reasonably be expected to be sited, in ways that will be directly applicable to WECS design or that will improve derived characteristics that will be applicable. Primarily, the analyses will be of speed and direction spectra, vertical profiles of wind, and probability distributions of wind speed and direction, mean and fluctuations.

Program Status:

This task began in FY 1979 and will continue into FY 1981.

Progress During Reporting Period:

The principal results of the research useful to wind turbine engineers are the qualitative comparison of turbulence spectral characteristics over complex terrain versus uniform terrain and turbulence rms values.

Spectra of the horizontal and vertical components of turbulence over three types of complex terrain were compared with those that are characteristic over flat land. The three terrain types were a) a coastal site, 70 m onshore from the coastline, b) on tops of hills and escarpments, and c) in rolling farmland near a mountain ridge. In the first and second cases the air travels from lesser roughness to greater roughness; in the third case the opposite occurs. In all cases it is found that in the

horizontal-component turbulence the high-frequency portions of the spectra reflect the "new" terrain roughness at the observation point, while the low-frequency turbulence "remembers" the upwind terrain condition longer.

Figure 1 compares average spectral energy of u-component turbulence over water with that over land 70 m downstream from the shoreline. The observations were made 2 m above the surface. Spectral densities at low frequencies were not affected by the change from the water surface to the rougher land surface; but at the high frequencies the spectral densities are significantly increased.

Figure 2 shows the effect at the top of a hill 170 m above the surrounding terrain. The upper graph is for the u-component; the lower graph is for the w-component. On each graph the two dashed curves, which represent turbulence at levels 9 m and 86 m above the ground at the top of the hill, show a marked deficiency in low-frequency energy compared to the solid curve, which is a model u-component turbulence spectrum for uniform terrain. The lower graph shows that for w-component turbulence, the same difference between hilltop spectra and uniform terrain spectra was not found.

Figure 3 shows the effect of decreased roughness as the turbulence travels from a mountain ridge out onto rolling farmland. The dashed and dotted lines represent spectra of onsite turbulence, while the solid line is the corresponding uniform terrain model. Here the low frequency turbulence "remembers" the greater upstream roughness; therefore there is relatively more low-frequency energy in the onsite turbulence than in the uniform terrain model. The lowest graph shows that the same observation does not hold for w-component turbulence.

Turbulence rms over complex terrain

Estimation of the rms usually starts from analysis of characteristics of ratios of the rms of the various velocity components to the friction velocity u_* . The friction velocity is defined by $\sqrt{\tau/\rho}$ where ρ is the air density and τ is the surface stress. Over uniform terrain, these ratios are constants for neutral conditions (2.4 for u, 1.9 for v and 1.3 for w). Variations of these quantities with atmospheric stability are well known.

FIGURE 1. Spectra at 2 m at Riso, Denmark - 1) Over Water, 2) Over Land 70 m From Shore

FIGURE 2. Normalized Spectra on Black Mountain, Australia. Solid lines are uniform terrain spectra by Kaimal.

FIGURE 3. Normalized Spectra in Stable Air Over Rolling Terrain Near State College, PA. Dashed lines are averages of spectra. Dotted lines represent range of spectra. Solid lines are uniform-terrain models.

The results show that the ratios of w to u_* were the same over simple and complex terrain. But for u and v these ratios are larger over farmland, particularly in air which had recently crossed the mountain ridge. In contrast, the ratios were smaller downwind of a coast and on the hill top.

Expected Progress During Next Reporting Period:

The final report providing wind characteristics at complex sites and some general criteria and methods for applying specific results to other terrain will be published.

Reports and Publications:

Dutton, J. A. et al. 1979. Statistics of Wind Fluctuations Over Complex Terrain. DOE/ET/20560-1, Pennsylvania State University, University Park, PA. Available from the National Technical Information Service.

Characteristics of Strong Downslope Wind (2.2.1.1.4)

Contract No.: DE-A106-79ET23115

NOAA
Wave Propagation Laboratory
Boulder, CO 80303

Principal Investigator:

Chandran Kaimal (303) 497-6263

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To collect and analyze wind turbulence data at the Boulder Atmospheric Observatory for testing wind statistics used in WECS design.

Program Status:

Data collection completed; draft report nearing completion.

Progress During Reporting Period:

Statistical analyses designed specifically for testing different gust models used in WECS design were performed on data collected during two high-wind cases observed at NOAA's Boulder Atmospheric Observatory. The two cases typify the downslope wind storms observed along the Front Range of the Rocky Mountains. Designated A and B, they represent widely different static stabilities. Case A was a typical Chinook produced by an intensification of east-west pressure gradient over the mountains. Wind speeds at 150 m exceeded 20 ms^{-1} and temperature gradient stayed very close to neutral. Case B resembled a Bora, which is a cold downslope wind of relatively short duration. Winds at 150 m exceeded 30 ms^{-1} , but a deep inversion persisted below 100 m.

The data set for this study consisted of wind speed and wind direction measurements from three heights on the tower (10, 50 and 150 m) in the form of data points spaced 1 second apart. From these data, several more time series were generated. The first operation involved bandpass filtering

to simulate the response of WECS to fluctuations in the wind speed and direction. Three passbands, each a decade wide, were used. The three filtered and the original unfiltered time series for the two cases, from all three heights, comprise the data base for the analyses.

The study produced an enormous array of plots and tables. Each time series yielded its own probability distributions, standard deviations, skewness and kurtosis. In addition, the time series were converted to gust variables appropriate to three gust models: 1) the velocity difference model, 2) the GUST 0 model and 3) the GUST 1 model. These variables, in turn, yielded yet another series of tables. The major challenge in this study was condensing information to make it accessible to WECS design engineers.

The analysis provided the following conclusions:

1. The computed gust parameters, when appropriately normalized, become insensitive to variations in static stability, height of observation and choice of bandpass filtering.
2. Bandpass filtering is essential for approximating Gaussian distribution in the original speed and direction time series.
3. A consistent relationship exists between the standard deviation of the speed and direction differences and the standard deviation of the original filtered time series.
4. Normalized gust statistics for GUST 0 and GUST 1 models show consistent relationships which are directly applicable to WECS design.

Expected Progress During Next Reporting Period:

Completion of the report.

Reports and Publications:

None in FY 1980.

Flow Through a Vertical Plane (2.2.1.1.5)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

J. Chris Doran (509) 375-6161 ext. 240

Objective:

To measure and characterize the two-dimensional space and time variations of the wind in a vertical plane, and relate these variations to the wind experienced by a rotating wind turbine.

Program Status:

The experimental apparatus at Hanford has been dismantled and no data are currently being taken. However, a large amount of data currently on tape has not been examined or organized for further studies. Several studies, using data from the array of anemometers, have been completed or are in progress.

Progress During Reporting Period:

A UC-60 report on fluctuating wind shears, based on the data obtained from the vertical plane array, is being prepared. An article on gust statistics, also based on the vertical plane array data, has been sent to the Journal of Applied Meteorology and is currently being revised. A UC-60 report on gust statistics has been completed and printed.

Expected Progress During Next Reporting Period:

Another journal article, on wind shear fluctuations, will be completed and sent to Solar Energy.

Data periods suitable for possible future analysis will be identified, the data will be reduced, converted to engineering units and written to tapes. A catalog of data, with a brief summary of important characteristics, will be prepared.

Reports and Publications:

Doran, J. C. and D. C. Powell. 1980. Gust Structure in the Neutral Surface Boundary Layer, sent to J. of Appl. Met.

Doran, J. C. and D. C. Powell. 1980. Gust Characteristics for WECS Design and Performance Analysis. PNL-3421, Pacific Northwest Laboratory, Richland, WA.

Doran, J. C. and D. C. Powell. 1980. "Gust Models for Design and Performance Analyses of Wind Turbines." In A Collection of Technical Papers. Proceedings of AIAA/SERI Wind Energy Conference, April 1980, Boulder, CO.

Wind Direction Change Characteristics (2.2.1.1.9)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

David C. Powell (509) 375-6161 ext. 304

Objective:

To derive spectra, probability distribution, standard deviation and gust characteristics of wind direction changes.

Program Status:

This is a new program this year and is expected to continue into FY 1981. A first draft of a report dealing with wind direction fluctuation characteristics was completed near the end of the year.

Progress During Reporting Period:

Wind directional data from the PNL vertical plane array were processed, analyzed and interpreted. The analyses were those producing probability functions, power spectra and gust parameters, all of single point wind direction data. These were interpreted in the draft report. The draft also contained an interpretation of analysis of data from the 1968 turbulence data-taking experiments performed in Kansas by personnel of the Air Force Cambridge Research Laboratory. This interpretation revealed a considerable distribution of the rms of wind direction fluctuations that is not taken into account in current models, but which is critical in estimating exceedance probability of large and extreme fluctuation magnitudes.

Expected Progress During Next Reporting Period:

The draft report will be revised, then reviewed both internally and externally. A final report will be written for publication in FY 1981.

Reports and Publications:

None in FY 1980.

Topical Reports on Atmospheric Criteria for WECS Design (2.2.1.1.10)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

James R. Connell (509) 375-6161 ext. 210

Objective:

To develop basic topical reference documents on wind and other atmospheric characteristics for use in WECS design. There is a strong need for accurate, concise, and applicable documents that provide basic wind and other atmospheric characteristic information for WECS design. These documents, containing current best estimates, emanate from studies under the task Atmospheric Criteria for Design (2.1.2.1.1). They will provide the bases for topical segments of a handbook as they are completed.

Program Status:

This program began in FY 1980 and is expected to continue in an evolutionary manner over the next few years.

Progress During Reporting Period:

Fluctuating vertical shears of wind speed have been measured using an array of towers. The statistical distributions of these shears are compared with formulas proposed by other researchers and good agreement is found. A comparison of Fichtl's formula for $\sigma_{\Delta u}$, the standard deviation of the fluctuating shears, with a more empirical one proposed by Ramsdell (1978) shows that the latter is consistent with the former under the proper conditions.

$\sigma_{\Delta u}$ is also shown to be strongly affected by τ , the averaging time used for the shear measurements. Increasing τ from 0.2 seconds to 4 seconds can decrease $\sigma_{\Delta u}$ by 25% or more; the precise amount seems to depend on the vertical separation of the two measuring points.

The probability of occurrence of extreme shears in speed is discussed. Directional shears are not treated here. Fluctuating shears two or more times larger than the mean values are shown to be readily obtainable, and

their likelihood increases as the mean measuring height increases if Δz is held fixed. These results are applicable for slightly unstable to neutral conditions over level, homogeneous terrain, and in the surface boundary layers. At greater heights (e.g., >150 m) and in stable stratifications, the behavior of fluctuating shears is not yet known. The normal distribution gives a useful lower bound on shear probabilities, but seriously underestimates the likelihood of large shear values.

A simple model relating $\sigma_{\Delta u}$ to the correlation coefficient between velocity fluctuations at two levels has also been derived.

Expected Progress During Next Reporting Period:

A number of reports on wind characteristics for design of wind turbines are in progress both within the PNL and by subcontractors. This task is expected to continue in FY 1981 under the title of Compendium of Wind Characteristics.

Reports and Publications:

None in FY 1980.

Wind Shear in the Nocturnal Boundary Layer (2.2.1.1.11)

Contract No.: DE-AT06-79ET23116

Oregon State University
Department of Atmospheric Science
Corvallis, OR 97331

Principal Investigator:

Larry J. Mahrt (503) 754-4557

Contract Monitor:

David C. Powell (509) 375-6161 ext. 304

Objective:

To document occurrence of wind shear for use in assessment of wind machine fatigue.

Program Status:

The project was initiated in February 1979 and the data collection completed September 30, 1980.

Progress During Reporting Period:

Wind shear data at wind turbine heights from several sites are reviewed and new data are documented in terms of total and component shear. A variety of atmospheric scenarios may combine to give large persistent shear. Among these, strong boundary layer stability is foremost. It occurs with strong nocturnal surface cooling, in low-level frontal and subsidence inversions, and in thunderstorm outflows. Strong shears resulting from surface radiation inversions are particularly evident over the High Plains where dry air and high altitude combine to result in strong radiational cooling. Terrain is also an important influence on shear, but it is not well understood and is very site specific.

Expected Progress During Next Reporting Period:

Completion of a supplemental report.

Reports and Publications:

Mahrt, L. and R. C. Heald. 1979. Analysis of Strong Nocturnal Shears for Wind Machine Design. DOE/ET/23116-79/1, Oregon State University, Corvallis, OR. Available from NTIS.

Handbook on Meteorological Guidelines for WECS (2.2.1.1.12)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

James R. Connell (509) 375-6161 ext. 210

Objective:

To construct a single, concise, current volume containing the characteristics of wind and other atmospheric properties for use in design of WECS.

Program Status:

This task was initiated in late FY 1980 and continues into FY 1981.

Progress During Reporting Period:

A workshop was held on September 29 and 30 in Seattle, Washington, to obtain representative input from the major WECS designing components of the U.S. Department of Energy. The workshop objective was to discuss aspects of wind characteristics related to the design of WECS. Rocky Flats, NASA-Lewis Research Center and Sandia representatives attended, as well as personnel from companies designing large and small WECS, and researchers from universities. Horizontal axis as well as vertical axis interests were also represented. By design, the meeting was small (17 total attendees) and was a working meeting. Broadly, the topics discussed included the wind turbine design process and details of atmospheric characteristics for the design of wind turbines.

Expected Progress During Next Reporting Period:

Since this meeting was held the last 2 days of the fiscal year, the minutes of the meeting, actually a summary of all the sessions which were recorded and transcribed, will be published in FY 1981. In FY 1981 this task will be merged with 2.2.1.1.10 in a task titled Compendium of Wind Characteristics.

Reports and Publications:

None in FY 1980.

Wind Characteristics at an East Coast Island Site (2.2.1.1.13)

Contract No.: DE-AC06-79ET23007

Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Principal Investigators:

Robert E. Akins (703) 961-4574

Henry W. Tieleman (703) 961-6891

Contract Monitor:

David C. Powell (509) 375-6161 ext. 304

Objective:

To document the wind characteristics at an Atlantic coastal location with particular emphasis on the properties of discrete gusts.

Program Status:

The program was completed on September 30, 1980. Reviews have been completed of two technical reports and they are in the final stages of publication.

Progress During Reporting Period:

This program was separated into two tasks: one to document the wind environment at a mid-Atlantic coastal site, with particular emphasis on the variability of wind characteristics as a function of wind direction, and a second to study the discrete gust structure at the same location. The data used in both tasks were obtained as a part of an experimental research program conducted by Dr. H. W. Tieleman as a portion of a NASA grant to study the micrometeorology at Wallops Island, Virginia.

Two distinct flow regimes exist at the Wallops Island site. Offshore winds occur in the winter and spring with an upwind fetch over land. In the summer months the prevailing winds are onshore, approaching the tower used in the study over water. Detailed flow information for all wind directions have been summarized. The typical upwind terrain features as

a function of wind direction are shown in Figure 1. Averages of important flow parameters, such as vertical distribution of mean velocity, turbulence intensities and turbulence integral scales, were computed for wind-direction sectors with near-uniform upwind terrain. Figure 2 contains typical results for the longitudinal turbulence intensity at five levels. The wind-direction sectors correspond to Figure 1. Spectral densities of the three velocity components for the prevailing northwesterly and southerly winds were computed and are considered in detail in the report for this task. The experimental results indicate that the nonuniformity of upstream surface conditions, the non-neutral thermal stratification and the presence of appreciable low-frequency velocity fluctuations have a pronounced effect on the surface flow. Consequently it is impossible to define a single model which describes the flow at this location even under moderately strong conditions.

FIGURE 1. Upstream Terrain Features at Wallops Island, VA as Function of Wind Direction Sector

FIGURE 2. Average Longitudinal Turbulence Intensity at Wallops Islands, VA as a Function of Wind-Direction Sector

In addition to the summary of the wind characteristics at Wallops Island, the discrete gust structure was also studied. Detailed three-dimensional wind measurements obtained using hot-film anemometers were available from the NASA-sponsored program. Three definitions of discrete gust structure were used and the differences between the definitions were considered. Data were analyzed for two distinct flow regimes, onshore and offshore. These correspond to wind directions between 60 and 170° and 240 to 300°, respectively, in Figure 1. The analysis used gusts based on mean-level crossings, slope changes and a fixed 3-second average. The slope change definition provides the most complete description of the discrete gust structure. Typical results for the number of gusts-per-minute based on the slope change definition are shown in Figure 3. The results are shown as a function of mean wind speed at a fixed elevation. Data are included for all three components of both onshore and offshore winds.

FIGURE 3. Gusts Per Minute as a Function of Mean Wind Speed, Slope Change Definition

In all instances the number of gusts per unit time increased with mean wind speed and turbulence intensity and decreased with increasing height. The duration of the gusts increased with height and mean wind speed. The amplitude of the gusts decreased with height and increased with turbulence intensity. In some instance it may be possible to predict the amplitude of discrete gusts directly from the turbulence intensity.

Reports and Publications:

Tieleman, H. W. 1980. Wind Environment at a Mid-Atlantic Coastal Site for the Design and Evaluation of Wind Turbines. DOE/ET/23007-80/1, Virginia Polytechnic Institute and State University, Blacksburg, VI. Available from NTIS.

Akins, R. E. 1980. Gust Structure Analysis for WECS Design and Performance Analysis. DOE/ET/23007-80/2, Virginia Polytechnic and State University, Blacksburg, VI. Available from NTIS.

Icing on Wind Energy Systems (2.2.1.1.14)

Contract No.: DE-AC06-79ET23170

Desert Research Institute
University of Nevada
P.O. Box 60220
Reno, NV 89506

Principal Investigator:

T. Hoffer (702) 972-1676

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To characterize the special particulate content of wind as it relates to icing, abrasion, debris damage, and corrosion of WECS placed in locations where these deleterious processes may occur. The characteristics will be presented in ways readily applicable to WECS design.

Program Status:

This project was initiated in FY 1980 and will last for 1 year. The final report is expected to be published in FY 1981.

Progress During Reporting Period:

The use of wind energy as an alternative means of meeting energy needs has become increasingly attractive with the advent of the present energy crisis. Technological advances in the design and production of wind energy systems have resulted in a variety of available systems that can supply the needs of both the large corporation as well as the private citizen. In addition to the technological aspect, meteorological studies to determine wind availability and the feasibility of installing a wind energy system in certain areas are also being pursued. However, in determining such a feasibility, the availability of wind is not the only aspect to be considered. An assessment of nature's erosive forces and the stresses and strains that a system is likely to encounter during operation must also be determined.

A particularly important aspect to consider before installation of a wind energy system is the potential for atmospheric icing. Destructive wind icing occurs in many areas of the continental United States and riming is particularly common at the higher elevations. When accompanied by strong winds, excessive ice buildup on a wind turbine and its supporting structure will incapacitate it and can cause structural failure if such conditions were not anticipated.

A study of atmospheric icing, however, is not a straightforward task since the observation and reporting of icing are not routine. A limited record of such measurements is available for the more severe ice storms occurring in the vicinity of urban areas; however, the dependability of such measurements is questionable. Very few measurements are published for mountain locations where the availability of wind is often optimum for a wind system installation. Until field measurements are done at the proposed site of a wind energy system, an analysis of the icing potential must necessarily be based on existing data.

A source of such data is the network of meteorological recording stations within the continental United States that collect meteorological measurements both at the surface and aloft. This task is meant to produce procedures for analyzing this data to determine the maximum possible icing to be expected at specified locations. Although atmospheric icing can result from a wide range of meteorological conditions, icing due to widespread freezing rain (i.e., glaze) or riming is specifically discussed as these conditions are most commonly observed.

Since the physical processes are different, the procedures for predicting maximum glaze ice and rime are being studied individually. The icing associated with glaze storms is computed using the hourly rainfall data coincident with documented reports of severe glaze storm occurrences. Reported ice thicknesses are not depended upon but instead are estimated through the rainfall data. This is a unique approach for the study of icing associated with glaze storms and avoids the subjective aspect of the thickness measurements reported. Icing due to rime is being analyzed for a mountain site using meteorological sounding data for the atmospheric

layer up to and including the 10,000-ft level. The sounding data used were for a site typically upwind from the mountain location. Rime is predicted for conditions of orographic lifting and cloud formation at subfreezing temperatures. The extent of riming is computed from the cloud water content.

Models are being developed to simulate the maximum possible ice buildup on an exposed surface using the rainfall and cloud water data as input. Two models are considered, one for the static case, namely a stationary collection surface, and one for the dynamic case, namely a rotating collection surface. In both cases, all of the water (i.e., supercooled water) available for icing is assumed to accrete as ice and, therefore, no further ice buildup can be attained.

In addition to the maximal dynamic and static icing loads, comparative icing values based on an attempt to simulate actual field conditions are also being investigated. Included are assumptions of droplet splashing and water drainage for the glaze cases and atmospheric mixing during orographic lifting for rime cases.

This study is being directed towards finding the total mass of ice that the wind energy structure would have to be capable of withstanding during a riming episode. Certainly, the blades will not accumulate as much ice as the dynamic model predicts, since they would stop rotating. The importance of dynamic linear model lies in predicting the mass of ice/unit time that the blades must indeed be capable of shedding if the windmill is to continue operating in the normal mode. Any ice accumulation on the blades will have a deleterious effect, either in decreased efficiency or in an imbalance that can be transmitted through the entire system as mechanical shock. Statistical fluctuations will occur in the riming rate so that the blades must be capable of shedding more mass at some times.

The actual load as calculated by the static model may be smaller than the computed value for several reasons. First, the ice may fracture and fall from the structure due to stresses, and second, the shape of the collection surface changes with time (particularly with riming) causing a change in the collection efficiency.

These calculations are intended to show maximum probable riming rates. The structural design should reflect at least the realistic rate since these rates certainly can be achieved.

Expected Progress During Next Reporting Period:

This task should be completed early in FY 1981. It will be concluded with the publication of the final report, which will provide some tools for the prediction of icing or riming at a potential candidate site.

Reports and Publications:

None in FY 1980.

Physical Analysis of Wind Speed Distribution Functions (2.2.1.1.15)

Contract No.: DE-AC06-79ET23114

Science Applications, Inc.
2860 S. Circle Drive, Ste 2224
Colorado Springs, CO 80906

Principal Investigator:

C. Eugene Buell (303) 576-0786

Contract Monitor:

J. Chris Doran (509) 375-6161 ext. 240

Objective:

To determine the appropriate parameters needed to describe the PDFs for wind speed as are represented by the data, the conditions under which one or more of the parameters may be neglected, and the effects of terrain features and instrument height on the values of these parameters.

Program Status:

The project was initiated April 1979. The data collection was completed in FY 1980 and a report is to be submitted in mid FY 1981.

Progress During Reporting Period:

Since the Weibull distribution is not a physically acceptable distribution function for scalar wind speed and since even the wind speed data itself is frequently bimodal it is suggested that a mixture of two generalized Rayleigh distributions (a thoroughly acceptable distribution) be used to describe the distribution of scalar wind speed.

Data from meteorological towers at Patrick AFB, Florida, the Hanford Meteorological Station, Washington, Cape Kennedy (NASA), Florida, and White Sands Missile Range, New Mexico, were analyzed in some detail and the variation of parameters as a function of anemometer height was determined. Data from meteorological towers at nuclear power plant sites were analyzed for those cases where anemometers were located at two or more levels. Data were provided by PNL from locations in the northwestern U.S. at which the anemometer had been located at two different elevations

and the wind speed frequency tabulated separately at the different levels. In all of these cases the variation of the parameters entering the distribution function was determined as a function of height. It was found that insofar as the empirical distribution function remained of the same type from level to level, the parameter variation was reasonably well described by the frequently applied power law with the exception of the mixing proportion of the two components of the mixture of the two generalized Rayleigh distributions used.

The effect of the site exposure on the parameters of the empirical distribution function is reported for locations near Boston, Massachusetts, Washington, DC, Bridgeport and New Haven, Connecticut, and Tucson, Arizona. It was found, as expected, that site exposure was important in determining the parameters of the mixture.

Diurnal changes in the empirical distribution function parameters at Washington, DC, and Montgomery and Mobile, Alabama, are also reported.

The two components of the mixture, each a generalized Rayleigh distribution, may be described as one that dominates the distribution of the lower scalar wind speeds and one that dominates the higher speeds, called herein the low speed and high speed components of the mixture. In any particular case, one of these mixture components may be absent. Also one or both of these components may reduce to an ordinary Rayleigh distribution or even to a degenerate (spike) distribution.

In the case of the tower data it was found that the low speed component of the mixture was dominant at the lower anemometer elevations while at the higher elevations the high speed component became dominant.

With regard to the type of distribution that appeared in the two mixture components, it may be said that the more varied the conditions included in the data collection the simpler the two mixture components. Thus, yearly data (which is affected by the annual and diurnal variation) tends frequently to be an ordinary Rayleigh distribution.

In the case of tower scalar wind speed, the high speed mixture component at the upper levels is usually a generalized Rayleigh while that at the lower levels tends to be an ordinary Rayleigh.

At "sheltered" locations, i.e., those located on terrain noticeably lower than the surrounding hilltops, the low speed mixture component is strongly dominant and tends to be an ordinary Rayleigh or even degenerate distribution. At "exposed" locations, i.e., those located at roughly the general hilltop level, the high speed component is dominant and tends to be a generalized Rayleigh distribution.

As far as the annual variation of the parameters and the type of distribution appearing in the mixture components are concerned, the low speed component is more frequent in summer and the high speed component more frequent in winter. The type of distribution function for these mixture components seems to be more or less consistent as far as seasonal variation is concerned. The generalized Rayleigh distribution function appears more frequently in the monthly distribution function than it does in the annual data.

The diurnal variation of parameters and the distribution types is more extreme than the annual variation. As expected, the early morning scalar wind speed distribution is dominated by the low speed component, which tends to be an ordinary Rayleigh distribution and very frequently can be described as degenerate (a "spike" at zero wind speed, calm). The afternoon winds are dominated by the high speed component, which is most frequently a generalized Rayleigh distribution.

Expected Progress During Next Reporting Period:

A report on this research will be provided to PNL in FY 1981.

Reports and Publications:

None in FY 1980.

Wind Measured From a Rotating Blade (2.2.1.1.16)

Contract No.: B-92618

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

Principal Investigator:

Virgil A. Sandborn (303) 491-8551

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To evaluate, design, build, test, and perform studies of wind characteristics with a rotating-boom, hot-film anemometer apparatus.

Program Status:

The program was initiated in July 1980 and is currently extended to May 1981.

Progress During Reporting Period:

A rotating-boom apparatus was developed to test transient anemometer measurements on rotating systems. The apparatus consists of a counter-balanced helicopter blade mounted vertically at the top of a walk-up scaffold. The blade is rotated by a variable speed, one-half horsepower, electric motor. The system is designed to operate over a range of rotation speeds from less than 10 to approximately 100 revolutions per minute. Either hot-wire or hot-film anemometers can be mounted at the tip of the blade. The anemometers will sense both the normal and vertical wind components approaching the rotating blade. Battery-powered, constant-temperature anemometers can be mounted to the counter-balance side of the boom. The output of the anemometers is taken off the rotating shaft by a series of slip rings. A photograph of the system is shown in Figure 1.

FIGURE 1. Photograph of the Rotating Boom

A preliminary set of measurements was made using dual hot-wire probes mounted on the end of the helicopter blade. Figure 2 shows typical output traces obtained with a hot wire.

FIGURE 2. Output Voltage From a Hot Wire Operating on the Rotating Boom

The output is dominated by relative velocity affect between the wind and the arm rotation. The energy contained at the rotational speed of the arm was approximately two orders of magnitude greater than any other frequency. The energy of the fluctuations decreases quickly for frequencies greater than the rotation speed.

Expected Progress During Next Reporting Period:

During the early part of FY 1981, analysis of data collected in FY 1980 will be undertaken. Various functions will be investigated such as turbulence spectra versus rotation speed, coherence through the disk of rotation and spectral shift due to rotation. These analytical studies will be documented in a final report.

Reports and Publications:

None in FY 1980.

Doppler Lidar Measurements of Winds Experienced by Wind Turbine Blades (2.2.1.2.2)

Contract No.: B-92620

Wave Propagation Laboratory
Environmental Research Laboratories, NOAA
Boulder, CO 80303

Principal Investigator:

Freeman F. Hall (303) 497-6312

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To measure the winds experienced by wind turbine blades using a remote sensor, an infrared Doppler lidar, at the Boulder Atmospheric Observatory tower site.

Program Status:

The program was initiated in September 1980 and the measurement phase was completed shortly thereafter. Data analysis continued during the fall of 1980.

Progress During Reporting Period:

The continuous-wave, infrared, Doppler lidar, using a CO₂ laser and a homodyne detection technique, was set up at the 300 m Boulder Atmospheric Observatory tower. A scanning mirror mechanism was developed and mounted onto the tower carriage so that when the carriage was elevated at a height of 30 m, the vertically directed lidar beam, reflected from the nutated scanning mirror, placed the measurement volume some 50 m from the tower, rotating in a circle some 10 m in diameter. Based on the tower wind instruments, the nutating mirror was directed so that the scanning lidar beam looked into the wind as it blew toward the tower. A number of data runs were recorded in sections of 20 minutes each. On evaluating the signal-to-noise ratios obtained, 5 of the 20-minute sections were chosen for data evaluation. Both nocturnal, stably stratified, and diurnal, convectively unstable, conditions were available for analysis.

Expected Progress During Next Reporting Period:

Wind measurements will be analyzed using a Fast Fourier Transform Doppler processing algorithm, and time series of the winds so measured will be spectrally analyzed. The spectrum of wind energy measured with the lidar will be compared with that measured using the sonic anemometers on the tower. The two different types of spectra will be compared to determine what differences may exist between the spectra measured using the disk of rotation (simulating the winds loading a wind turbine blade) and the fixed sensors on the tower.

Reports and Publications:

None in FY 1980.

Measurement Methods for Performance Evaluation (2.2.1.2.4)

Contract No.: DE-AC06-79ET23164

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

Principal Investigator:

C. Byron Winn (303) 491-6783

Contract Monitor:

James R. Connell (509) 375-6161 ext. 210

Objective:

To develop a minicomputer (HP9845B)-based data acquisition system with supporting software for wind energy conversion systems and test the system on a Darrieus machine at Colorado State University.

Program Status:

The project was initiated in September 1979 and the final report will be submitted in mid FY 1981.

Progress During Reporting Period:

Samples from power and wind speed were collected and further processed (real time) to plot the power curve and gustiness coefficient as a function of wind speed. The algorithm used for the curve fit of data was based on a piecewise linear approximation of the power curve. The graph was divided into analysis modules and each module was curve fitted based on the linear model:

$$P_j = P_{jo} + D_{pj} (W_{\text{bar}} - W_{jo}) + K_j G \quad (\text{for } j\text{th module})$$

where: P_j = estimate of power for a given wind speed
 P_{jo} = power at midpoint of a module
 D_{pj} = slope
 W_{bar} = averaged wind speed
 W_{jo} = wind speed at the midpoint of module
 G = gustiness
 K_j = gustiness coefficient.

The system was tested on a Darrieus wind turbine at the Colorado State University dairy farm and data were collected.

A flow chart illustrating the processing used in the system is shown as Figure 1. Sample output of the system is shown in Figure 2.

FIGURE 1. Real Time Data Acquisition Flow Chart

$W_{min} = 10$ mph

$W_{max} = 40$ mph

Data File = DATA2 & DATA3

Samsize = 3

NSAM = 2000

Code = "WIND3"

FIGURE 2. Gustiness Coefficient vs. Wind Speed

Expected Progress During Next Reporting Period:

A report on this research will be provided to PNL in FY 1981.

Reports and Publications:

None.

METEOROLOGICAL CHARACTERISTICS FOR WECS OPERATIONS (2.2.2)

Meteorological Characteristics for WECS Operations was divided into two areas in FY 1980: forecast technology and utility applications. The work in forecast technology included the processing and analysis of data for the verification of all wind forecasts produced to date, providing interim reports on the forecast verification results and examining short-term (0-3 hr) wind forecasting techniques. The utility application efforts consisted of a study to investigate the sensitivity of the economic impact of wind turbine generation to wind speed sampling frequency, wind turbine performance model, and wind speed forecasting accuracy. The initial phase of the study consisted of calculating the expected output of the Boeing MOD-2 wind turbine using various MOD-2 performance models driven by wind speed data sets representing different sampling frequencies.

Wind Forecast Verification (2.2.2.1.1)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigators:

A. H. Miller (509) 375-6161 ext. 202

A. R. Olsen (509) 376-4213

Objective:

To produce a statistical analysis of the results of a number of prior contracts to subjectively forecast wind speed and direction at 12 sites around the country.

Program Status:

This program was initiated late in FY 1979 with some software for the analysis of data already written. In FY 1980 all of the subjective forecast data were processed and software to produce graphics were written for inclusion in a report to be published in FY 1981. The analysis of the data is ongoing.

Progress During Reporting Period:

During this reporting period several data sets were processed on the computer for incorporation into a report. The data were stratified by site, time period, contract organization and even forecaster.

The validity of the interpretation of the results is subject to question since no one contract organization forced its forecasters to follow any "rules". The stratifications performed however, should differentiate the forecast techniques and provide a reasonable estimate of the state-of-the-art.

Expected Progress During Next Reporting Period:

A report on the apparent state-of-the-art of remote wind forecasting is planned for FY 1981. This report will conclude the forecast validation effort.

Reports and Publications:

None in FY 1980.

International Wind Forecasting Verification Program (2.2.2.1.2)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To define criteria for an international wind-forecasting verification program and to provide wind forecasts with corresponding observations to determine the reliability of wind forecasts for WECS observations.

Program Status:

The program was established in 1976 by the International Energy Agency (IEA). Work began in May 1979 with a "kick-off" meeting of meteorologists from participating nations. The draft final report was outlined during a second meeting in June 1980.

Progress During Reporting Period:

In January 1980, wind forecasts, corresponding observations as well as background information on the forecasting technique, were sent to Sweden. During June 1980, a second technical meeting was held during which forecast verification results were examined and an outline for the final report was drafted jointly by representatives from Sweden, the U.S., and Germany. The U.S. was tasked with supplying some further information regarding its wind forecasting method, the forecasting sites and the integration of WECS into U.S. utility grids. This information was provided and incorporated into the draft final report.

Expected Progress During Next Reporting Period:

Review of the draft final report will be performed upon receipt from Sweden. This review should conclude U.S. participation in this subtask of the IEA agreement unless additional work is recommended by the IEA board following its review of the final report.

Reports and Publications:

None.

Wind Forecasts for WECS Operation by MOS (2.2.2.1.3)

Contract No.: DE-AI06-79RL10046

NOAA-Techniques Development Laboratory
National Weather Service
Silver Springs, MD 20910

Principal Investigator:

David B. Gilhousen (301) 427-7768

Contract Monitor:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To examine the reliability and accuracy of wind forecasts produced by the Model Output Statistics (MOS) approach for nine wind turbine generator (WTG) sites.

Program Status:

The project was initiated in June 1979. The draft final report was received in June 1980; however, the need for rewriting and reformatting portions of the report will delay publication until FY 1981.

Progress During Reporting Period:

Production was completed on all forecasting equations for speed and direction forecasts as well as probabilistic and deterministic forecasts. The equations were tested on 11 months' independent data. Unique error trends were noted at several sites. The locations exemplifying regular diurnal wind speed variations often have winds that are more accurately forecast 21 to 24 hours in advance than 12 to 15 hours.

The draft final report, entitled "Development and Testing of Automated Wind Forecasts for Wind Turbine Generator Sites," was received, reviewed and returned to the contractor for changes prior to publication.

In addition to the draft final report, tapes and microfiche containing both forecast developmental and verification data were received.

Expected Progress During Next Reporting Period:

The final report will be published when appropriate changes have been incorporated. Furthermore, the detailed forecast verification and developmental data received will permit a more in-depth study (by PNL) of the reliability of MOS wind forecasts as applied to the operation of large WECS.

Reports and Publications:

None in FY 1980.

Real Time Subjective Wind Forecasts (2.2.2.1.4)

Contract No.: B-87040

Murray and Trettel, Inc.
414 West Frontage Road
Northfield, IL 60093

Contract No.: B-87038

General Weather Center
910 Fisher Building
Detroit, MI 48202

Contract No.: B-23098

ACCU-Weather
619 W. College Avenue
State College, PA 16801

Contract No.: B-87039

Global Weather Services
P.O. Box 6053
Leawood, KS 66206

Contract No.: B-87037

Freese-Notis Weather
1453 N.E. 66th Avenue
Des Moines, IA 50313

Principal Investigators:

John P. Murray (M&T) (312) 446-7800
Lyle E. Brosche (GWC) (313) 871-3511
Joel N. Meyers (A-W) (814) 237-5801
Victor E. Cook (GWS) (913) 642-7373
Charles Notis (F-NW) (515) 289-1314

Contract Monitor:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To produce subjective wind forecasts using real-time data typically available to the operational forecaster.

Program Status:

This project was concluded at the end of October 1979 (FY 1980). An analysis of the results is ongoing (see 2.2.2.1.1).

Progress During Reporting Period:

The final month's forecasts were made at 11 sites. Qualitative evaluation of the forecasts produced evidenced an increase in skill at a number of sites by a number of forecasters.

Reports and Publications:

Informal reports outlining the personnel qualifications of the forecasters, and any techniques they found useful, though not verified, for specific sites have been received. Any useful information from these reports will be included in the formal verification report (see 2.2.2.1.1).

Wind Forecast Integration Into Utility Operation (2.2.2.2.1)

Contract No.: B-93474

JBF Scientific Corporation
2 Jewel Drive
Wilmington, MA 01887

Principal Investigator:

Martin Goldenblatt (617) 657-4170

Contract Monitor:

Harry L. Wegley (509) 375-6161 ext. 299

Objective:

To examine the sensitivity of the economic impact of wind turbine generation to wind speed sampling frequency, wind turbine performance model, and wind speed forecasting accuracy.

Program Status:

The project was initiated in March 1980 and a draft final report will be submitted in the fall of 1980.

Progress During Reporting Period:

The initial phase of the study consisted of calculating the expected output of the Boeing MOD-2 wind turbine using various MOD-2 performance models driven by wind speed data sets representing different sampling frequencies.

Two-minute wind speed data, measured in 1979 at the DOE meteorological tower located in the San Geronio Pass, California, were used in performing this study. The data were applied to four different simulation methods for calculating MOD-2 performance:

1. A time-dependent performance simulation of machine operation that calculates power output from the 2-minute wind data and includes control logic for startup and shutdown, yawing, and system time constants. For each hour, the 2-minute power calculated is integrated to obtain the average hourly power output.

2. An integrated hourly performance model that calculates machine output every 2 minutes. Hourly power output was calculated by integrating 2-minute power output over each hour.
3. An hourly sampled wind speed performance model that uses the last 2-minute wind speed sample taken every hour to represent the hourly wind speed. This method is similar to that used when using SOLMET wind speed data.
4. An hourly averaged wind speed performance model that uses hourly averaged 2-minute wind speed samples in calculating hourly machine output.

The hourly MOD-2 outputs defined by the four techniques were used as load modifiers in defining the net load that must be serviced by the conventional utility generating sources. On this study net loads were calculated for the 1995 Los Angeles Department of Water and Power (LADWP) generating system assuming a 10 percent WTG penetration. These loads were applied to a production cost simulation to estimate LADWP's 1995 annual cost of generation. The results were then used in establishing the sensitivity of LADWP's annual production costs and WTG value to the particular technique used in calculating hourly wind turbine generation.

The second phase of the study consisted of examining the impact wind forecasting accuracy would have on LADWP operation and costs. The objective of this phase was to observe the impact of wind speed forecasting accuracy on LADWP production costs in an effort to define realistic goals for wind speed forecasters.

The following results were obtained from the analysis performed in this study. Caution must be exercised in generalizing these results since they were obtained by analyzing a single utility under very specific assumptions.

- Using three different nontime-dependent methods for calculating hourly WTG performance resulted in less than a 3 percent difference in the calculated MOD-2 capacity factor. Similarly, the WTG life-cycle value calculated also varied by less than 3 percent for the three nontime-dependent models used.

- Averaging 2-minute power output computations for each hour does not appreciably (less than 3 percent) change MOD-2 capacity factor, single-year production cost savings, or life-cycle value from that calculated using wind speed samples taken once every hour.
- Modeling machine performance with a time-dependent simulation and using 2-minute wind speed data does change the MOD-2 capacity factor, production cost savings, and life-cycle savings from those calculated using the three static performance models. Using the time-dependent simulation decreased MOD-2 performance by approximately 13 percent. This resulted from a combination of increased machine downtime and a decrease in the time the WTG is computed to be operating at rated capacity.
- The ability of LADWP to accurately forecast wind speeds (WTG power) may decrease its operating costs 20 percent.
- The ability of LADWP to accurately forecast wind speeds (WTG power) can decrease its dependency on oil-fired generation.

Expected Progress During Next Reporting Period:

Following a PNL and DOE review the final report will be published in mid-FY 1981.

Reports and Publications:

None in FY 1980.

SITE SELECTION SUPPORT (2.3.1)

Work in this technical area during FY 1980 focused on completion of the documentation of the Goodnoe Hills MOD-2 site selection work, and continuing with the selection of additional candidate sites. These sites would receive meteorological measurement equipment, wind measurements would be taken for at least 1 year, and these measurements would be analyzed by PNL and used for assisting DOE in future wind turbine site selection work.

Techniques for improving the analysis of data and displaying large quantities of information in a concise format will continue to be developed. These techniques should assist the decision-makers in the selection process.

Candidate Site Selection Support (2.3.1.1)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

David S. Renné (509) 375-6161 ext. 258

Objective:

To develop and implement technical procedures for candidate and wind turbine site selection in support of DOE's large wind turbine test program, and to document the results of DOE's selection decisions.

Program Status:

This program is a continuation of earlier technical support roles PNL has provided DOE for large machine site selections. In previous years PNL has assisted DOE in the selection of the MOD-1 site at Boone, North Carolina, the MOD-0A site at Kahuku, Hawaii, and the MOD-2 site at Goodnoe Hills, Washington. The role of supporting DOE in the candidate and turbine site selection process will continue as long as DOE develops large wind turbines for field testing and plans to install these turbines at utility-proposed sites, selected on a competitive basis.

Progress During Reporting Period:

In January 1980, DOE selected about 20 new candidate sites to receive meteorological measurement equipment. The selection was made from about 52 proposals submitted in response to a PON which was developed and distributed by PNL in FY 1979. During the selection process PNL reviewed and screened proposals, provided technical summaries, estimated the wind energy potential at each proposer's site, advised the federal evaluation panel, DOE site selection board, and DOE site selection official, and documented the results of all the proceedings.

During FY 1979 PNL also assisted DOE in the selection of the MOD-2 wind turbine cluster site at Goodnoe Hills. During FY 1980 PNL assisted in the presentation of the Site Selection Boards recommendations to the Site Selection Official, assisted in preparing a site selection statement, and assisted in debriefing sites that proposed but did not receive the MOD-2.

Expected Progress During Next Reporting Period:

Technical procedures for improving site selection methods will continue to be developed, including statistical and numerical techniques and computer graphics displays of technical results. PON's and site selection master plans for the MOD-5 and MOD-6 will be developed as the development of these machines proceeds.

Reports and Publications:

None.

Statistical Studies of Site Wind Characteristics (2.3.1.1A)

Contract No.: DE-AS06-76ET20383

Northwestern University
Evanston, IL 60201

Principal Investigator:

Ross B. Corotis (312) 492-3453

Contract Monitor:

David S. Renné (509) 375-6161 ext. 258

Objective:

Statistical analyses of site wind data are conducted through application of previously derived programs to PNL-supplied site wind data. An investigation of time-averaging techniques, specifically the effects of averaging time and sampling rate, has the objective of leading to the most economical data recording procedures.

Program Status:

This task is completed.

Progress During Reporting Period:

Statistical analyses of a high-frequency wind speed data tape collected at Clayton, New Mexico, and supplied by PNL have been performed and results compared with those from 20-second data collected at Northwestern University. The effect of time-averaging techniques utilizing such statistical quantities as mean, standard deviation and autocorrelation have been investigated. Both averaging time and sampling rate have been studied in determining the sensitivity to alternative data collection schemes.

The appropriate wind characteristics are those that correlate most highly with turbine output. However, if the data may be used for studies such as turbulent forces on the blades, then data appropriate to that purpose must also be considered. It is most desirable to collect wind data at more than one point in space, so that spatial averaging effects may be included. For economy of data collection costs, as well as to assess the wind shear effect, data may be collected at multiple heights on a single meteorological tower.

The use of an on-site microprocessor allows the collection of both instantaneous and time-averaged wind data. A mechanical anemometer has a response time on the order of 1 second, which should be short enough to represent "instantaneous" wind speed for most wind turbine applications. The Northwestern and Clayton data also suggest that it would be desirable to have a 5-second average and a 60-second average wind speed. These three pieces of data can adequately represent the practical shift in wind speed characteristics with averaging time. A study of the Clayton autocorrelation graphs confirms the sufficiency of 1-second, 5-second, and 60-second averaging times in summarizing the shift in correlation pattern. A study of the variances and autocorrelations from the Northwestern data also indicates the desirability of a 10-minute and 60-minute average, especially to summarize autocorrelation shifts.

The Clayton autocorrelation graphs indicate that the autocorrelation decays relatively smoothly for lags up to 60 to 90 seconds, and then fluctuates without any strong trend. This means that samples more than 60 to 90 seconds apart have almost as high a correlation as samples 5 to 10 minutes apart, and therefore the latter sampling interval would not result in a significant loss of usefulness as compared to 2-minute sampling. The Northwestern data indicate that for 1-minute average wind speeds, sampling rates of 6 per hour or higher all give similar autocorrelation functions. Based on these preliminary results it is recommended that data be sampled once every 10 minutes. It is possible to record 5 pieces of information every 10 minutes with the same amount of tape as required for an instantaneous wind speed every 2 minutes. For each 10 minute period, one 1-second "instantaneous" wind speed, one 5-second average wind speed, one 60-second average wind speed, and one 10-minute average wind speed can be recorded. In addition, the variance for all the 5-second values in each 10-minute period can be computed and recorded. The continuous 10-minute averages permit computation of all longer term averages that are a multiple of 10 minutes (for example, 30-minute and 60-minute averages).

Expected Progress During Next Reporting Period:

Additional analysis may be done when additional high speed turbine site data become available.

Reports and Publications:

Corotis, R. B. 1980. Application of Statistical Techniques to Wind Characteristics at Potential Wind Energy Conversion Sites. DOE/ET/20283-2, Northwestern University, Evanston, IL, 172 pp. Available from NTIS.

Corotis, R. B. 1980. Handbook for the Application of Statistical Techniques to Wind Characteristics at Potential Wind Energy Conversion Sites. DOE/ET20283-3, Northwestern University, Evanston, IL, 27 pp. Available from NTIS.

Corotis, R. B. 1980. "Confidence Interval Procedures for Wind Turbine Candidate Sites." Journal of Solar Energy. 24(5):427-434.

Application of Refined Techniques for Estimating Wind Characteristics at
Candidate Sites (2.3.1.2)

Contract No.: B-23149

SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Principal Investigator:

Chandrakant M. Bhumralkar (415) 326-6200

Contract Monitor:

David S. Renné (509) 375-6161 ext. 258

Objective:

To refine a diagnostic model of low-level windflow over complex terrain,
and to apply the model to seven wind turbine sites in the United States.

Program Status:

The work was initiated in March 1979 and was completed in April 1980.

Progress During the Reporting Period:

The basic structure of the windflow model (COMPLEX) was described previously by Bhumralkar et al. (1980). The model uses wind observations from National Weather Service stations in the area of interest. In the present contract the model was improved by

- use of digital terrain data
- use of the geostrophic wind (computed from pressure data) to represent the flow at the top of the boundary layer
- use of variable density in the vertical
- introduction of a curved boundary-layer top.

The method was applied to data for seven candidate wind turbine sites in the United States for 1977. At these same sites, wind measurements were made on towers at a level 46 m above ground under the auspices of PNL (Wendell et al. 1978; Renné and Sandusky 1979). The observations for four of the sites were used to "tune" the model, i.e., to provide guidance

in selecting the parameters that control the depth of the boundary layer and the shape of the boundary-layer top. The results are shown in the first four rows of the following comparison of simulated and measured wind speeds (annual averages for 1977).

At the remaining sites, computations were made without tuning. The results (shown in the last three rows of the tabulated comparison) are of good accuracy.

Site	Speed (ms^{-1})		Difference
	Measured	Simulated	
Boone, NC	8.0	8.1	+0.1
San Geronio, CA	8.0	7.2	-0.8
Block Island, RI	7.5	7.0	-0.5
Clayton, NM	7.6	5.8	-1.8
Ludington, MI	7.9	7.2	-0.7
Holyoke, MA	7.3	7.4	+0.1
Huron, SD	6.9	6.7	-0.2

Expected Progress During Next Reporting Period:

In FY 81 we expect to further improve the method, and to apply the revised model to ten additional wind turbine sites in the United States.

Reports and Publications:

Endlich, R. M., F. L. Ludwig, C. M. Bhumralkar, and M. A. Estoque. 1980. A Practical Method for Estimating Wind Characteristics at Potential Wind-Energy Conversion Sites. PNL-3808, Pacific Northwest Laboratory, Richland, WA.

SITE METEOROLOGICAL MEASUREMENTS (2.3.2)

During FY 1980, PNL continued work on collecting, analyzing and reducing meteorological data collected at the DOE candidate sites. In conjunction with this effort, PNL, in addition to data reports, produced graphical reports for the MOD-0A sites on machine output parameters, such as alternator power output, yaw error, and nacelle anemometer wind speed and wind direction values. These reports also included plots of nacelle wind speed versus tower wind speed and turbine power output versus tower wind speed. Both data reports and MOD-0A site reports were produced on a monthly basis.

This technical area also supported the installation of meteorological data acquisition systems at new candidate sites chosen by DOE in FY 1980. This includes systems for the Kahuku MOD-0A site in Hawaii and the Goodnoe Hills MOD-2 site in Washington.

Meteorological Measurement Program (2.3.2.1)

Contract No.: B-92790

Air Quality & Atmospheric Sciences Group
Engineering-Science (ES)
125 West Huntington Drive
Arcadia, CA 91006

Environmental Systems Corp. (ESC)
200 Tech Center Drive
Knoxville, TN 37906

Principal Investigators:

Dennis P. Becvar (213) 445-7560 (ES)
Thomas B. Carlson (615) 688-7900 (ESC)

Contract Monitor:

William F. Sandusky (509) 375-6161 ext. 343

Objective:

The objectives of this program are: a) to conduct meteorological measurements at potential and actual wind turbine sites selected by DOE, b) to provide meteorological data acquired at sites to PNL, and c) to install and operate meteorological data acquisition systems for new candidate sites selected by DOE in January 1980 and the Kahuku MOD-0A turbine that was constructed in FY 1980.

Program Status:

The contract for routine and emergency maintenance of the data acquisition systems (ES) was initiated in December 1979 and continued through September 30, 1980. The contract for installation of the meteorological tower at the Kahuku MOD-0A site (ESC) was initiated in February 1980 and completed in September 1980.

Progress During Reporting Period:

During June and July 1980, a 160-ft free-standing tower was erected at the Kahuku MOD-0A site. The tower will be used to acquire meteorological data to be used in evaluation of the turbine constructed at the site during FY 1980.

Routine maintenance, along with quarterly calibrations, were performed at each site to ensure data validity. Emergency maintenance visits were also performed to replace, or repair, failed equipment and restore the site to operation and to maintain a 90% data recovery rate. On an annual basis the sensors were calibrated in a wind tunnel.

Cassette data tapes were sent by the utility representatives to ES for processing. The data were then processed, edited, and compiled into composite nine-track data tapes for transmission to PNL. With all sites in operation, about 46.8 million data points are collected each year.

During FY 1980 installation of the towers and data acquisition system for the new candidate sites began. By October 1980, five sites were operational. Data acquisition also began at the Kahuku MOD-OA site.

All installations, maintenance actions, calibrations, and data reduction activities were conducted under a rigorous quality assurance program for this project. Narrative reports describing the progress of this project were provided monthly by the subcontractors to PNL.

Expected Progress During Next Reporting Period:

The maintenance and calibration services will continue as needed. The installation of the equipment at the new candidate sites will continue and be completed in FY 1981.

Reports and Publications:

None.

Candidate Site Data Reports (2.3.2.2)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

William F. Sandusky (509) 375-6161 ext. 343

Objective:

To document, on a monthly basis, the pertinent wind data collected from the meteorological measurement equipment installed at each of DOE's candidate wind turbine sites.

Program Status:

Monthly data reports have been prepared for each candidate site since 1976 and are continuing.

Progress During Reporting Period:

Monthly data reports for each site were prepared. Annual data reports for the periods October 1978 through September 1979 and January 1979 through December 1979 were prepared and transmitted to DOE, NASA, and the participating utilities.

A magnetic data tape of hourly data for each site for the period October 1978 through December 1979 was transmitted to the National Climatic Center in Asheville, North Carolina, for archiving and general public availability.

Various data requests by other DOE subcontractors engaged in wind energy research were filled.

Expected Progress During Next Reporting Period:

Formal annual data reports for calendar years 1979 and 1980 will be prepared, published and transmitted to the National Information Technical Service (NTIS) for public dissemination.

Monthly data reports will continue to be prepared for existing sites, as well as for the new candidate sites once the sites become operational.

Reports and Publications:

Monthly and annual data reports are provided to DOE, NASA and the participating utilities.

Turbine Site Data Reports (2.3.2.3)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

William F. Sandusky (509) 375-6161 ext. 343

Objective:

To present graphical displays relating machine turbine parameters to meteorological data collected from the tower.

Program Status:

This reporting is currently under way for the MOD-OA turbines at Clayton, New Mexico, Culebra, Puerto Rico, and Block Island, Rhode Island.

Progress During Reporting Period:

Monthly reports are prepared and transmitted to NASA. These reports allow NASA to evaluate the theoretical power performance curve of the MOD-OA turbines based on hourly data. Information provided in the report allows NASA to compare wind speeds recorded on the turbine nacelle and the meteorological tower.

Expected Progress During Next Reporting Period:

Monthly data reports will continue to be prepared for the Clayton, Culebra, and Block Island MOD-OA turbine sites, as well as the Kahuku MOD-OA turbine and Goodnoe Hills MOD-2 turbines once the appropriate electronics have been installed.

Reports and Publications:

Monthly reports for the Clayton, Culebra, and Block Island MOD-OA turbines are provided to NASA.

LARGE MACHINE SITE EVALUATION (2.3.3)

After a large machine is installed at a candidate site for field testing purposes, the meteorological measurement program at the site is expanded to acquire information for performance evaluation of the machine. Turbine output parameters, such as alternator output, yaw error, and nacelle wind speed and direction are recorded on the same data logger as the meteorological tower parameters. Often, additional levels of sensors are installed on the tower. Special analysis programs are developed to present the data, and monthly data reports comparing free-stream meteorological data with turbine performance are published.

MOD-2 Site Evaluation Program (2.3.3.3)

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

Principal Investigator:

David S. Renné (509) 375-6161 ext. 258

Objective:

The objective of this program is to develop an advanced meteorological data acquisition system at the Goodnoe Hills site by incorporating the needs of the various researchers involved in this program. The system is to be designed to support performance evaluation, wake studies, and resource verification studies at Goodnoe Hills.

Program Status:

Shortly after the Goodnoe Hills site was selected, PNL was selected to participate on a research review panel, in the area of wind characteristics, for all field research to be performed at Goodnoe Hills. As a part of this role, PNL developed a task of installing a meteorological data acquisition system at the site, as well as coordinating other research. This role will continue throughout the test program, which will last 2 years once the machines become operational, estimated to be May 1981.

Progress During Reporting Period:

During FY 1980, a 350-ft meteorological tower was installed and instrumented by PNL at the site. In addition PNL participated in developing an overall site research plan, which includes wake studies, environmental studies, and cluster performance studies. Other members of the group developing this plan are NASA/Lewis, BPA, Boeing, and SERI.

A physical model of the Goodnoe Hills site was also made by PNL. Flow visualization and vertical profile studies of the area were made by inserting the model in a water flume at PNL. Photographic and laser Doppler anemometry measurements were used.

Expected Progress During Next Reporting Period:

A central data acquisition system will be designed which will simultaneously record turbine output parameters from the three turbines and meteorological parameters from the BPA 200-ft and PNL 350-ft towers.

Once the data acquisition system becomes operational, PNL will undertake research tasks relating to wake studies and performance evaluation.

Field studies will be conducted throughout the year. Monthly data reports will be published. In addition, a narrated motion picture of the flow visualization of the physical model of the Goodnoe Hills will be made.

Reports and Publications:

None in FY 1980.

REFERENCES

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- Hiester, T. R. and W. T. Pennell. 1981. The Meteorological Aspects of Siting Large Wind Turbines. PNL-2522, Pacific Northwest Laboratory, Richland, WA.
- Renné, D. S. and W. F. Sandusky. 1979. "Meteorological Measurements at DOE's Candidate Wind Turbine Sites." Paper presented at the International Expert Meeting, Boone, NC, 26-27 September, 1979.
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- Wendell, L. L., J. R. Connell, W. T. Pennell, D. S. Renné, and H. L. Wegley. 1978. Annual Report of the Wind Characteristics Program Element for the Period July 1977 Through July 1978. PNL-2545, Pacific Northwest Laboratory, Richland, WA.

APPENDIX A

MANAGEMENT OVERVIEW OF THE
WIND CHARACTERISTICS PROGRAM ELEMENT

APPENDIX A
MANAGEMENT OVERVIEW

The Wind Characteristics Program Element (WCPE) involves both management and technical efforts. The management effort has three primary roles:

- Program Planning--formulating and integrating plans for research tasks conducted by PNL and contractors of PNL and DOE.
- Contract Administration and Control of Research Tasks--preparing procurements, such as RFPs, reviewing unsolicited proposals, preparing and awarding contracts, and monitoring technical progress, financial status and contractual commitments.
- Reporting research progress--preparing weekly, monthly, quarterly and annual technical progress and administrative reports.

To accomplish these management functions, PNL has organized the WCPE into three technical areas and four staff functions. The three technical areas are: 2.1 Wind Energy Prospecting, 2.2 Support for Design and Operation and 2.3 Site Evaluation. The staff areas are: Finance, Subcontracts, Management Support and Technical Information Management Support. Technical work conducted by PNL is designed primarily to fill gaps between and to consolidate the results of contractor efforts.

A Program Development Plan (PDP) is prepared for DOE by the Program Manager and the Program Area Leaders. The PDP defines the program's research priorities and establishes tasks and milestones designed to produce the wind characteristics information needed by wind turbine designers, planners and potential users of wind turbines. Tasks conducted by contractors are monitored and the results assimilated under the direction of the Program Area Leaders. The Program Area Leaders also direct the PNL technical tasks, which help to focus contractor and PNL results on specific needs. The Program Area Leaders are also responsible for the publication of research results in a format and style appropriate to the needs of the user community. A comprehensive monthly progress report is prepared and submitted to DOE to allow detailed tracking of the program established in the PDP.

Funding

The funding history of the Wind Characteristics Program Element at PNL is shown in Table A-1. For the period shown, the funding averaged about 11% of the total budget of the Federal Wind Energy Program. The following sections contain financial information for the program during FY 1980. This information includes subcontracts and budget outlay.

TABLE A-1. Funding History

	Thousands of Dollars						
	<u>FY76</u>	<u>T Q(a)</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>	<u>FY80</u>	<u>FY81</u>
Wind Characteristics	700	699	1,900	2,320	2,700	4,614	4,325
Site Evaluation (MVP)				600	1,400		
Total	700	669	1,900	2,920	4,100	4,614	4,325

(a) Transition quarter

(b) Wind characteristics and site evaluation (MVP) combined in FY 1980.

FY 1980 SUBCONTRACTS, MAJOR PROCUREMENTS
AND CONSULTING AGREEMENTS

During FY 1980 the following subcontracts, major procurements, and consulting agreements were executed within the Wind Characteristics Program Element:

<u>FIRM</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
Marlatt and Associates	2.1.1.2.2	\$ 21
NUS Corporation	2.1.1.2.7	88
GEOMET	2.1.1.2.8	73
Environmental Research and Technology, Inc.	2.1.1.2.9	99
Western Scientific Services, Inc.	2.1.1.2.10	98
Environmental Research and Technology, Inc.	2.1.1.2.11	3
Institute for Storm Research	2.1.1.2.12	90
Western Scientific Service, Inc.	2.1.1.2.13	80
Aerovironment, Inc.	2.1.2.1.2	2
FWG Associates	2.1.2.1.12	6
Science Applications, Inc.	2.1.2.2.4	120
Tower Systems, Inc.	2.2.1.1.5	46
Midwest Communications	2.2.1.1.5	33
JBF Scientific Corporation	2.2.2.2.1	65
SRI, International	2.3.1.2	8
Tower Systems, Inc.	2.3.2.1	7
Engineering-Science	2.3.2.1	754
Puerto Rico Water Resources	2.3.2.1	1
Environmental Systems Corporation	2.3.2.1	65
Cosme Tower Service	2.3.2.1	3
Environmental Systems Corporation	2.3.2.1	73
Commonwealth Association Environmental Services	2.3.2.1	3
Research Service Bureau	2.3.3.1	54
Approach Fish	2.3.3.3	1
Northwest Marketing	2.3.3.3	16
Total Firms		1809

<u>UNIVERSITY</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
University of Virginia	2.1.1.1.1	\$ 43
New Mexico State University	2.1.2.1.3	10
University of Virginia	2.1.2.2.5	76
Penn State University	2.2.1.1.3	55
Colorado State University	2.2.1.1.5	11
Oregon State University	2.3.2.1	<u>2</u>
Total Universities		197

<u>GOVERNMENT</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
National Climatic Center - Tape Purchase Order	2.1.1.2.2	\$ 26
National Climatic Center - Tape Purchase Order	2.1.1.4	4
National Climatic Center - Tape Purchase Order	2.1.1.4	40
NOAA/ERL-Wave Propagation Laboratory	2.2.1.2.2	20
Other	2.2.1.1.12	<u>2</u>
Total Government		92

<u>CONSULTING AGREEMENT</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
Dr. Neil Cherry/Lincoln College, Canterbury, New Zealand	2.1.1.4	\$ 25
Richard Traci/SAI	2.1.2.2.4	2
Dr. M.A. LeMone/NCAR	2.1.2.8	1
G.H. Fichtl	2.2.1.1.1	4
Workshop Consulting Agreements (15 Individuals)	2.2.1.1.12	5
PON Review Consulting Agreements:	2.3.1.1	
Dipak Sengupta/Univ. of Michigan		3
Michael Changery/NOAA		1
Marjorie Greene/HARC		2
J. Donald Brown	2.3.1.2	5
Dr. Ross B. Corotis/Cedar Assoc.	2.3.1.2	<u>17</u>
Total Consulting Agreements		<u>65</u>
Total		<u>\$2163</u>

The \$2163K in subcontracts, major procurements and consulting agreements within the WCPE were placed in the following categories:

<u>CATEGORY</u>	<u>No.</u>	<u>AMOUNT (K's)</u>	<u>%</u>
Small Firm	14	\$ 523	25
Large Firm	11	1286	59
University	6	197	9
Government	5	92	4
Consulting Agreement	<u>10</u>	<u>65</u>	<u>3</u>
Total	<u>46</u>	<u>\$2163</u>	<u>100</u>

FY 1980 BUDGET OUTLAY

In FY 1980 Pacific Northwest Laboratory had a total Budget Outlay for the Wind Characteristics Program Element of \$4675K. FY 1980 costs incurred were \$4614K or 98.7%. A detail of those costs is shown below.

<u>COSTS</u>	<u>AMOUNT (K's)</u>
PNL:	
Labor and Overheads	\$1766
Materials and Supplies	33
Travel	87
Services (Computer, Duplicating, Graphics, Photography, Technical Editing, Word Processing)	<u>345</u>
PNL TOTAL	2231

Outside PNL:

<u>FIRM</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
Development Planning and Research Associates	2.1.1.1.2	\$ 1
Marlatt and Associates	2.1.1.2.2	13
GEOMET	2.1.1.2.3	83
Global Weather Consultants	2.1.1.2.6	51
NUS Corporation	2.1.1.2.7	88
GEOMET	2.1.1.2.8	68
Environmental Research and Technology, Inc.	2.1.1.2.9	96
Western Scientific Services, Inc.	2.1.1.2.10	56
Environmental Research and Technology, Inc.	2.1.1.2.11	2
Institute for Storm Research	2.1.1.2.12	75
Western Scientific Services, Inc.	2.1.1.2.13	50
Aerovironment, Inc.	2.1.2.1.2	20
Flow Industries	2.1.2.1.5	(1)
FWG Associates	2.1.2.1.12	6
Science Applications, Inc.	2.1.2.2.2	22
Science Applications, Inc.	2.1.2.2.4	64

<u>FIRM</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
FWG Associates	2.2.1.1.1	2
Tower Systems, Inc.	2.2.1.1.5	46
Midwest Communications	2.2.1.1.5	19
Science Applications, Inc.	2.2.1.1.15	10
Weather Services, Inc.	2.2.2.1.4	1
Freese Notis Weather	2.2.2.1.4	3
Gen. Weather Center	2.2.2.1.4	1
Murray and Treetle, Inc.	2.2.2.1.4	2
Accu-Weather	2.2.2.1.4	1
JBF Scientific Corporation	2.2.2.2.1	59
Simpson Weather Association	2.2.2.2.2	6
SRI, International	2.3.1.2	24
Tower Systems, Inc.	2.3.2.1	7
Engineering-Science	2.3.2.1	405
Environmental Systems Corporation	2.3.2.1	3
Environmental Systems Corporation	2.3.2.1	65
Cosme Tower Service	2.3.2.1	3
Tri-Ex Tower	2.3.2.1	37
Environmental Systems Corporation	2.3.2.1	73
Commonwealth Association Environmental Services	2.3.2.1	3
Research Service Bureau	2.3.3.1	54
Approach Fish	2.3.3.3	1
Northwest Marketing	2.3.3.3	16
Total Firms		1535

<u>UNIVERSITY</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
University of Virginia	2.1.1.1.1	56
University of Virginia	2.1.1.1.1	39
University of Alaska	2.1.1.2.4	135
University of Hawaii	2.1.1.2.5	44
Oregon State University	2.1.2.1.1	73

<u>UNIVERSITY</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
New Mexico State University	2.1.2.1.3	\$ 50
University of Virginia	2.1.2.2.5	33
Oregon State University	2.2.1.1.2	86
Penn State University	2.2.1.1.3	55
Colorado State University	2.2.1.1.5	8
Oregon State University	2.2.1.1.11	40
Oregon State University	2.3.2.1	<u>2</u>
Total Universities		621

<u>GOVERNMENT</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
National Climatic Center - Tape Purchase Order	2.1.1.2.2	\$ 26
National Climatic Center - Tape Purchase Order	2.1.1.4	4
National Climatic Center - Tape Purchase Order	2.1.1.4	40
NOAA/Wave Propagation Laboratory	2.1.2.1.7	25
NOAA	2.2.1.1.4	44
NOAA/ERL-Wave Propagation Laboratory	2.2.1.2.2	20
NOAA/Tech. Dev. Lab.	2.2.2.1.3	15
Other	2.2.1.1.12	<u>2</u>
Total Government		176

<u>CONSULTING AGREEMENT</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
Dr. Neil Cherry/Lincoln College. Canterbury, New Zealand	2.1.1.4	\$ 12
Richard Traci/SAI	2.1.2.2.4	2
Dr. M.A. LeMone/NCAR	2.1.2.8	1
G.H. Fichtl	2.2.1.1.1	4
Workshop Consulting Agreements (15 Individuals)	2.2.1.1.12	4
PON Review Consulting Agreements:	2.3.1.1	
Dipak Sengupta/Univ. of Michigan		3
Michael Changery/NOAA		1
Marjorie Greene/HARC		2

<u>CONSULTING AGREEMENT</u>	<u>WCPE TASK</u>	<u>AMOUNT (K's)</u>
J. Donald Brown	2.3.1.2	\$ 5
Dr. Ross B. Corotis/Cedar Assoc.	2.3.1.2	<u>17</u>
Total Consulting Agreement		<u>51</u>
Total Outside PNL		<u>2383</u>
Total WCPE		<u>\$4614</u>

A summary of FY 1980 WCPE costs by task is shown below.

<u>AREA</u>	<u>PNL AMOUNT (K's)</u>	<u>NON-PNL AMOUNT (K's)</u>	<u>TOTAL</u>	<u>%</u>
<u>Technical</u>				
2.1.1 Resource Assessment	\$ 472	\$ 939	\$1411	30
2.1.2 Siting Methodologies	<u>297</u>	<u>295</u>	<u>592</u>	<u>13</u>
2.1 Wind Energy Prospecting	769	1234	2003	43
2.2.1 Meteorological Characteristics for Design and Evaluation	339	340	679	15
2.2.2 Meteorological Characteristics for Operations	<u>136</u>	<u>88</u>	<u>224</u>	<u>5</u>
2.2 Support for Design and Operations	475	428	903	20
2.3 Site Evaluation (excluding 2.3.8)	<u>668</u>	<u>721</u>	<u>1389</u>	<u>30</u>
Total Technical	<u>1912</u>	<u>2383</u>	<u>4295</u>	<u>93</u>
<u>Adminstration</u>				
2.1.8 Wind Energy Prospecting - Administration	124	0	124	3
2.2.8 Support for Design and Operations - Administration	120	0	120	3
2.3.8 Site Evaluation - Administration	<u>75</u>	<u>0</u>	<u>75</u>	<u>1</u>
Total Administration	<u>319</u>	<u>0</u>	<u>319</u>	<u>7</u>
Total WCPE	<u>\$2231</u>	<u>\$2383</u>	<u>\$4614</u>	<u>100</u>

A summary of FY 1980 WCPE costs by type of contractor is shown below.

<u>CATEGORY</u>	<u>AMOUNT (K's)</u>	<u>%</u>
PNL	\$2231	48
Outside PNL	2207	48
Government	<u>176</u>	<u>4</u>
Total	<u>\$4614</u>	<u>100</u>

FY 1980 BUDGET AUTHORITY

In FY 1980, PNL had a total Budget Authority of \$6195K for the Wind Characteristics Program Element. This included \$4705K Budget Authority authorized in FY 1980 and \$1490K Budget Authority carry over from past fiscal years.

The Budget Authority at PNL was distributed as follows.

<u>Area</u>	<u>AMOUNT (K's)</u>	<u>%</u>
PNL	\$2231	43
Outside PNL	2814	54
Government	<u>176</u>	<u>3</u>
Total	<u>\$5221</u>	<u>100</u>

APPENDIX B

PUBLISHED REPORTS

WIND CHARACTERISTICS PROGRAM ELEMENT (WCPE)

LIST OF PUBLICATIONS

October 1980

Pacific Northwest Laboratory
Richland, Washington 99352

- (a) Available from National Oceanic and Atmospheric Administration, National Climatic Center, Federal Building, Asheville, NC 28801
- (b) Available from the American Meteorological Society, 45 Beacon Street, Boston, MA 02108. The price is \$25.00 for non-AMS members, and \$20.00 for AMS members. Postage and handling is \$1.25 additional.
- (c) Available from the U.S. Government Printing Office, Superintendent of Documents, Washington, DC 20402. The price is \$6.50 which includes postage and handling. The stock number is 061-000-00446-7.

Reports given UC-60 distribution and available from:

National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

NTIS Customer Service Phone: (615) 576-1304

<u>Pages</u>	<u>NTIS Selling Price</u>
001-025	\$4.00
026-050	4.50
051-075	5.25
076-100	6.00
101-125	6.50
126-150	7.25
151-175	8.00
176-200	9.00
201-225	9.25
226-250	9.50
251-275	10.75
276-300	11.00

The WCPE is coordinated for DOE/Wind Energy Systems Division of the Office of Solar Power Applications by Pacific Northwest Laboratory, Richland, WA 99352. The attached listing has been prepared by:

Judith M. Proud

Phone: FTS 444-4177

Commercial: (509) 376-4177

LIST OF TECHNICAL REPORTS DONE BY PNL AND ITS SUBCONTRACTORS FOR THE
WIND CHARACTERISTICS PROGRAM

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- Freeman, B.E. April 1976. Mathematical Modeling of Topographic Effects on Wind Energy Systems. (Paper) BNWL-SA-5935, Science Applications, Inc., La Jolla, CA 92037, Microfiche.
- Freeman, B.E. May 1976. A New Wind Energy Site Selection Methodology. SAI76-614-LJ (NSF Grant), Science Applications, Inc., La Jolla, CA 92037, 233 pp.
- Meroney, R.N., et al. July 1976. Sites for Wind Power Installations: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence. ERDA/NSF/00702-75/1, Colorado State Univ., Fort Collins, CO 80523, 88 pp.
- Justus, C.G., et al. August 1976. Wind Energy Statistics for Large Arrays of Wind Turbines (New England and Central U.S. Regions). ERDA/NSF-00547/76/1, Georgia Inst. of Technology, Atlanta, GA 30332, 126 pp.
- Justus, C.G., et al. August 1976. Reference Wind Speed Distributions and Height Profiles for Wind Turbine Design and Performance Evaluation Applications. ORO/5108-76/4, Georgia Inst. of Technology, Atlanta, GA 30332, 103 pp.
- Wentink, T., Jr. August 1976. Wind Power Potential of Alaska: Part II - Wind Duration Curve Fits and Output Power Estimates for Typical Windmills. RLO/2229-112-76/1, Univ. of Alaska, Fairbanks, AK 99701, 89 pp.
- Corotis, R.B. November 1976. Stochastic Modeling of Site Wind Characteristics. ERDA/NSF-00357/76/1, Northwestern Univ., Evanston, IL 60201, 305 pp.
- Meroney, R.N., et al. December 1976. Sites for Wind Power Installations: Wind Tunnel Simulation of the Influence of Two-Dimensional Ridges on Wind Speed and Turbulence--Tabulated Experimental Data. RLO/2438-76/1, Colorado State Univ., Fort Collins, CO 80523, 68 pp.
- Freeman, B.E., et al. December 1976. Development of a Wind Energy Site Selection Methodology. RLO/2440-76/4, Science Applications, Inc., La Jolla, CA 92037, 150 pp.
- Elderkin, C.E., J.V. Ramsdell. January 1977. Semi-Annual Report of the Wind Characteristics Program Element for the Period April 1976 Through December 1976. BNWL-2220 WIND-2, Pacific Northwest Laboratory, Richland, WA 99352, 89 pp.
- Verhulek, M.G. March 1977. Summary of Wind Data from Nuclear Power Plant Sites. BNWL-2220 WIND-4, Pacific Northwest Laboratory, Richland, WA 99352, 339 pp.
- Orgill, M.M. May 1977. Survey of Wind Measurement Field Programs. BNWL-2220 WIND-3, Pacific Northwest Laboratory, Richland, WA 99352, 57 pp.
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