Meteorological Field Measurements at Potential and Actual Wind Turbine Sites

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September 1982

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METEOROLOGICAL FIELD MEASUREMENTS AT
POTENTIAL AND ACTUAL WIND TURBINE SITES

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SUMMARY

Since 1976 the U.S. Department of Energy (DOE) has sponsored field measurement programs at a number of sites around the United States that appear promising for wind energy utilization. From time to time a site from this group has been chosen for installation of a large wind turbine for field testing. After the installation, the wind measurement activities are expanded to simultaneously record wind data from the meteorological tower and turbine performance data.

This measurement program has produced information, not only on wind characteristics in a variety of windy locations, but also on procedures for obtaining reliable and accurate wind measurements in harsh environments. In addition, with the availability of turbine data at some of these sites, this program has provided insight into the most appropriate measurement strategies at a potential wind turbine site so that estimates of machine performance and potential hazards to the machine can be obtained efficiently. This report summarizes these field measurement experiences.

Experience in this program has shown that unless the data logging equipment is given proper protection, a high percentage of data can be lost in severe weather conditions or high moisture environments due to failure of microprocessing components. In addition, although the more sensitive sensors can provide turbulence-scale information that may prove valuable for identifying hazards to machines, a certain amount of data recovery is sacrificed under icing or high wind conditions which can damage the more fragile types of sensors. Rigid calibration and maintenance procedures must be established to assure a successful program.

Statistical analyses of high-frequency data collected at sites with wind turbines have indicated that time-averaged sampling is preferable over instantaneous sampling. Although the instantaneous samples are adequate for climatological representativeness, time-averaged samples are more realistic for simulating turbine operations and for correlating wind speed measurements at the tower with turbine power output. A sampling scheme that records data averaged over several different time scales is prescribed.

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1. INTRODUCTION

This report provides an overview of experiences gained in a meteorological measurement program conducted at a number of locations around the United States for the purpose of site evaluation for wind energy utilization. The major emphasis of this report is to discuss the evolution of the measurement program from its inception in 1976 to the present day,^(a) to outline some of the major accomplishments and areas for improvement, and to present some conclusions on research utilizing data from this program that may be useful in future site evaluation exercises. We hope that, by sharing our experiences in undertaking field measurements in geographically dispersed and environmentally severe sites, others may benefit from the knowledge gained from this program.

(a) Summer of 1982

2. PROGRAM HISTORY

In 1976, the U.S. Department of Energy (then, the Energy Research and Development Administration) selected 17 candidate sites from among 64 proposals submitted by utility organizations. The candidate sites were those that showed promising wind energy potential and other site characteristics that qualified them for possible installation of large wind machines for field testing and utility operations. Following this selection, each site was eligible to receive a 48.8-m (160-ft) tall meteorological tower with two levels (9.1 m and 45.7 m) of wind speed and direction sensors. Data from these sensors were to be recorded on strip-chart recorders.

The data collection programs were started in December 1976 at most of the sites shown in Figure 1. At this time the measurement program was conducted by the National Aeronautics and Space Administration (NASA)/Lewis Research Center, which is the Department of Energy's (DOE) lead laboratory for developing large, horizontal-axis wind turbines for field testing. From time to time, one of the 17 candidate sites was to be selected for receiving a wind turbine. (Figure 1 shows that 5 of these original 17 sites were selected for field testing wind turbines. Four received the 200-kW MOD-0A machine, and one received the 2000-kW MOD-1 machine.) The selection of these turbine sites was done competitively by applying a number of criteria, including wind energy availability, site characteristics, and utility support. These selections occurred over a three-year period through 1979. Details of this program have been described by Renné and Sandusky (1979).

In late 1978, Pacific Northwest Laboratory (PNL), which is DOE's major laboratory for providing technical and management support in the area of wind characteristics for the Federal Wind Energy Program, assumed the responsibility of this measurement program. Like NASA, PNL also hired a subcontractor to perform all site maintenance and calibration responsibilities, and data processing functions. In addition, the subcontractor replaced all strip-chart recorders with digital cassette data loggers. This change-over was completed by the beginning of 1979.

FIGURE 1. The Candidate Site Program During the Period 1976-1978

In 1980 an additional 20 sites were added to the program. This was done in anticipation of a need for a larger variety of sites for field testing the next generation of large, horizontal-axis wind turbines. Ultimately, towers were installed at 18 of these 20 sites. Configuration of the measurement system at these new sites differed somewhat from those at the original 17 sites, as described in the next section. In 1981, after installation of large wind turbines at six sites (including the MOD-2 cluster at Goodnoe Hills, Washington), the emphasis of the DOE program was shifted from system development to technology research. Because of this, the candidate site program, which had also served to develop and apply techniques for analyzing wind resources and for prospecting for good sites, was curtailed. Measurements at most of the original 17 sites (with the exception of those having large wind turbines for field testing) were terminated. In 1982 the measurements at many of the newer sites continue under private support, with PNL continuing to provide assistance in data processing. Figure 2 shows the location of all candidate sites and their status as of early 1982.

3. DATA COLLECTION HISTORY

3.1 THE FIRST TWO YEARS

From its beginning in 1976 through September 1978, the Meteorological Validation Program (MVP), as the candidate site meteorological measurement program has been called, was managed for DOE by the NASA/Lewis Research Center, Cleveland, Ohio. NASA selected Western Scientific Services, Inc. (WSSI), of Fort Collins, Colorado, as its meteorological measurement contractor to install data acquisition equipment at 15 of the original 17 sites (Table 1). The other two sites, Kaena Point and Boardman, had data acquisition programs in progress, and thus installation of government equipment was not required. At each site where government equipment was installed, the system basically consisted of a 48.8-m (160-ft) Rohn^(a) 55G tower with MRI^(b) 1074 wind sensors at two levels. At the Ludington, Michigan, and Cold Bay, Alaska, sites the sensors were installed on existing towers. Data for each meteorological parameter were recorded as an analog signal on separate strip-chart recorders. At most sites, the sensors were installed at the 9.1-m (30-ft) and 45.7-m (150-ft) levels. At some sites the lower level was chosen to be 18.2 m (60 ft) to avoid effects on the measurements as a result of nearby obstructions. At Cold Bay, Alaska, the top-level sensor was mounted at the 21.8 m level on an FAA tower. At all sites, the tower was installed about 100 meters from where a wind turbine would actually be located.

The towers were generally placed upwind in the prevailing wind direction of the proposed turbine location. The purpose of this arrangement was to ensure that the tower would measure the free-stream wind characteristics so that the data could be used for performance evaluation of the turbine if the site were selected to receive one. Table 1 provides information on the measurements at these sites during this phase of the program. As noted in the table, some utilities supplied their own meteorological systems, while others made their own towers available to the program.

(a) Unarco-Rohn, Inc., P.O. Box 2000, Peoria, IL 61601

(b) Meteorology Research, Inc., 464 Woodbury Road, Altadena, CA 91001

**TABLE 1. Pertinent Information About the 17 Candidate Sites
for Period December 1976 - September 1978**

Name of Site	Utility	Instrument Levels, m	Start of Measurements	Status of Measurements, 1982
Amarillo, TX	Southwestern Public Service	9.1, 45.7	March 1977	Equip. transferred to the U.S. Dept. of Agriculture
Augsburger Mt., WA	Bonneville Power Admin.	9.1, 45.7	December 1976	Terminated January 1978
Block Island, RI	Block Island Power Company	9.1, 45.7	December 1976	Continuing by DOE
Boone, NC	Blue Ridge Electric Membership Cooperative	18.2, 45.7, 83.8	December 1976	Terminated July 1981
Clayton, NM	City of Clayton	9.1, 30.0, 45.7	May 1977	Continuing by DOE
Cold Bay, AK	Alaska Bussell Elec. Co.	9.1, 21.8 ^(a)	August 1977	Terminated Sept. 1981
Culebra, PR	Puerto Rico Power Auth.	9.1, 45.7	March 1977	Continuing by DOE
Holyoke, MA	Holyoke Gas & Electric	18.2, 45.7	December 1976	Terminated Sept. 1981
Huron, SD	East River Electric Power Cooperative	9.1, 45.7	December 1976	Continuing by utility
Kingsley Dam, NE	Central Nebraska Pub. Power & Irri. District	9.1, 45.7	December 1976	Terminated August 1981
Ludington, MI	Consumers Power Company	18.2, 45.7 ^(a)	April 1977	Terminated October 1979
Montauk, Long Is., NY	Long Island Lighting Co.	18.2, 45.7	January 1977	Continuing by utility
Point Arena, CA	Pacific Gas & Elec. Co.	9.1, 45.7	January 1977	Terminated Sept. 1981
Russell, KS	City of Russell	9.1, 45.7	December 1976	Terminated August 1981
San Geronio Pass, CA	Southern California Edison	9.1, 45.7	December 1976	Continuing by DOE
Boardman, OR	Portland General Electric	9.1, 39.6, 70.1	January 1977 ^(c)	Continuing ^(d) by utility
Kaena Pt., HI	Hawaiian Electric Company	9.1, 45.7 ^(b)	December 1976	Terminated October 1979

(a) Tower supplied by utility.

(b) Meteorological equipment, data reports supplied by utility.

(c) Data collected by the utility since 1974.

(d) Data not supplied to DOE after September 1981.

Under cooperative agreements established between NASA and the participating utilities, utility personnel were required to inspect the site on a weekly basis, change the strip charts every other visit and return them to WSSI for reduction. Upon receiving the strip charts from the utilities each month, WSSI arranged to have the data reduced by hand and summarized into hourly average wind speed and direction, hourly turbulent intensity and wind direction standard deviation. WSSI also prepared monthly data reports. Because these 17 sites were involved in a competitive arrangement for receiving the first generation of wind turbines (totaling to four 200-kW MOD-0As and one 2000-kW MOD-1), the distribution of the data reports was limited to DOE, NASA/Lewis, PNL, and the utilities.

3.2 THE MEASUREMENT PROGRAM SINCE 1978

In 1978, PNL, located in Richland, Washington, and operated for the Department of Energy by the Battelle Memorial Institute (BMI), assumed the responsibility of the MVP from NASA/Lewis. PNL selected Environmental Systems Corporation (ESC) of Knoxville, Tennessee, to provide calibration, maintenance, and data reduction services at the 14 candidate sites which had DOE equipment. (Measurements were terminated at Bonneville Power Administration's (BPA) Augspurger Mountain site in January 1978 when a severe ice storm caused the collapse of the meteorological tower.) The Kaena Point and Boardman sites continued to be operated by their respective utilities.

In the fall of 1978, ESC installed Tower Systems^(a) instrument elevators and ESC CDL-700A digital cassette data loggers on each of the 14 towers. In a few cases the strip-chart recorders were retained as back-up systems. The data loggers were configured to record an instantaneous sample of each parameter once every two minutes. This allowed up to 17 days of data recording for each tape.

The data loggers were designed to operate unattended for two-week intervals using two 6-volt rechargeable batteries as a power source. At some sites

(a) Tower Systems, Inc., S. Hwy. 65, P.O. Box 308, Cambridge, MN 55008

where ac power was available, the dc battery supply was still used to supply power to the logger, but a trickle charger was attached to the battery to maintain a full charge at all times. This allowed the data logger to continue functioning even if there were a power failure at the site.

A goal of 90% data recovery at each site was established for this program. Achieving this goal was challenging since, unlike other programs with similar goals, there were generally no back-up recording systems at the sites, and often the sensors and loggers could only be checked once weekly by utility personnel. In general, data recovery decreased during the winter months when severe weather hampered performance of the sensors and loggers.

In late 1979 and early 1980, the number of candidate sites was greatly expanded following the selection of 20 utility organizations who were to receive meteorological measurement equipment. In 1980, PNL's new subcontractor, Engineering-Science (E-S) of Arcadia, California, arranged for installation of meteorological measuring equipment at 18 of these new sites, and at the same time continued to maintain the original sites in the program. At the new sites, three levels of Climet^(a) wind speed and direction sensors were installed at the 9.1-, 30.0-, and 45.7-m levels. A new model of the ESC data logger was used, although the sampling procedure remained identical to that at the original sites. A Tri-EX^(b) instrument elevator system was installed on the 48.8-m (160-ft) Rohn 55G tower at these new sites.

In 1981, as the Federal Wind Energy Program was transformed from a systems development program to a technology research program, measurements were concluded at most of the original candidate sites where five years of data had been collected. In 1982, after one year of data collection had been completed at the sites selected in 1980, the utilities were offered the DOE equipment that had been installed on their sites by the DOE in exchange for their commitment to maintain the equipment and provide data to DOE through PNL. Many of the sites opted for this transfer, although measurement

(a) Climet Instrument Co., P.O. Box 151, Redlands, CA 92373

(b) Tri-EX, Inc., 7182 Rasmussen Ave., Rd. 76, Visalia, CA 93277

programs were terminated at a few sites in January of 1982. Table 2 provides pertinent information about the sites that were selected in 1980, and includes the Kahuku, Hawaii, MOD-OA site.

TABLE 2. Pertinent Information About the 18 New Candidate Sites
(All Instrument Levels at 9.1 m, 30.5 m, and 45.7 m
Unless Otherwise Noted)

<u>Name of Site</u>	<u>Utility</u>	<u>Start of Measurements</u>	<u>Status of Measurements, 1982</u>
Big Sable Point, MI	Consumers Power	January 1981	Continuing by utility
Bridger Butte, WY	Intermountain Consumers Power	September 1980	Continuing by utility
Cape Blanco, OR	Coos-Curry Electric	November 1980	Terminated October 1981
Diablo Dam, WA	Seattle City Light	December 1980	Continuing by utility
Finley, ND	Sheyenne Valley Electric Coop.	October 1980	Continuing by utility
Fort Sill, OK	Department of Defense	September 1980	Terminated January 1982
Ilio Point, Molokai, HI	Molokai Electric	January 1981	Continuing by utility
Kahua Ranch, Hawaii, HI	Hawaiian Electric Light Company	February 1981	Continuing by utility
Kahuku, HI	Hawaiian Electric Company	September 1980	Continuing by utility
Livingston, MT	Montana Power	September 1980	Continuing by utility
Meade, KS	City of Meade	July 1980	Continuing by utility
Minot, ND	Verendrye Electric Coop.	October 1980	Continuing by utility
Nantucket, MA	Nantucket Electric	November 1980	Terminated January 1982
Provincetown, MA ^(a)	New Bedford Gas & Electric	January 1981	Continuing by utility
Romero Overlook, CA	Department of Water Resources	October 1980	Continuing by utility
San Augustin Pass, NM	El Paso Electric	November 1980	Continuing by utility
Stratton Mountain, VT	Vermont Electric	January 1981	Terminated January 1982
Tucumcari, NM	City of Tucumcari	November 1980	Continuing by utility
Wells, NV	Wells Rural Electric	October 1980	Terminated January 1982

(a) Top level sensor is at 42.7 m.

NOTE: Two-minute instantaneous values of wind speed and direction recorded at all
levels.

4. DATA COLLECTION PROCEDURES

During the past four years when PNL conducted the measurement program at the candidate sites, the following procedures were established for performing maintenance, calibration, and data reduction by PNL's subcontractor. These procedures were followed until June 1981 when PNL assumed all site maintenance and calibration and data processing responsibilities. Procedures now followed by PNL are described at the end of this section.

4.1 CALIBRATION AND MAINTENANCE

The subcontractor provided routine calibration and maintenance services, as well as emergency maintenance services, at each site that received DOE equipment. For example, when a utility representative reported a sensor or logger failure, the subcontractor proceeded to the site within 72 hours to correct the problem (in some instances, the problem could be identified and corrective procedures implemented by discussing the situation with the utility representative over the telephone).

The subcontractor also performed calibrations at each of the sites. Annually, calibrations included changing all sensors with precalibrated spares. Quarterly onsite calibrations of all electronics were performed. The precalibrated wind speed sensors were calibrated in a wind tunnel. (WSSI utilized the Colorado State University wind tunnel facilities at Fort Collins, Colorado; ESC used the NOAA Atmospheric Turbulence and Diffusion Laboratory (ATDL) wind tunnel at Oak Ridge, Tennessee; and E-S used the wind tunnel facilities at MRI, Inc., Altadena, California). All calibrations were traceable to standards established by the National Bureau of Standards.

4.2 SITE MAINTENANCE, DATA EDITING, AND REDUCTION

At the operational sites, a representative of the utility visited the tower site weekly and changed the cassette tape in the data logger every other week, except at turbine sites where cassettes were changed weekly. Before June 1981, the data-filled cassette was mailed to PNL's subcontractor.

The utility representative also visually inspected the tower and sensors, checked the performance of the logger, replaced the rechargeable batteries as needed, and filled out a site inspection form that was also mailed to the subcontractor or PNL. Completion of the site inspection form was an important part of both the maintenance and data editing portion of the program. On this form the utility representative was asked to note existing meteorological conditions occurring at the site as well as readings from the various data channels of the data logger. This information aided the subcontractor and PNL meteorologists in determining if a possible equipment failure had occurred or appeared likely and the approximate time during the month the problem occurred. The latter information was valuable in processing and editing the data from the cassette tape.

PNL's subcontractor utilized a computer program to convert the data on the cassette data tapes to engineering units. These data were then edited by a computer program to determine if

- time was less than 2358 and increments were in steps of two minutes
- Julian date recorded on the tape was within the expected range for the month and increments each day
- recorded wind speeds did not change by large values for succeeding two-minute scans, or over each hour
- wind speed values increased with height
- the recorded wind direction did not vary by more than 60° with wind speeds greater than 5 mph.

If any of these conditions occurred, an appropriate message was printed out along with the particular scan in question and a meteorologist reviewed this listing to determine if the data should be changed or coded as missing. Later, PNL requested the subcontractor to code as missing values the obvious bad data and to flag questionable data by a lettering scheme that was coded along with each data scan within the magnetic tape. Once the data were properly edited, they were put on a nine-track tape, a copy of which was forwarded to PNL for analysis.

The subcontractors were also required, as part of their quality assurance program, to perform a routine "dummy data analysis" on all computer programs that were involved in data processing. This procedure would document that the individual computer programs were performing as expected. This technique is commonly used in quality assurance procedures involving data collection at nuclear reactor facilities (Sandusky and Conley 1979).

4.3 DATA REPORTING

When the edited monthly nine-track data tape was received at PNL, it was put into a data analysis program, which provided summaries of pertinent wind characteristics at each candidate site. These summaries were incorporated into monthly candidate wind turbine site data reports, which were forwarded to NASA/Lewis, DOE, and each participating utility, thereby allowing an assessment of the wind energy potential at the sites. These reports contained information on

- sensor performance
- monthly means of wind speed and wind direction
- maximum recorded two-minute wind speed value at each level
- mean hourly wind speed and direction versus time-of-day
- a frequency distribution of wind speed
- cumulative frequency distribution of wind speed
- wind speed persistence frequency
- average power law exponent by wind direction
- turbulence intensity versus wind direction
- wind rose plot.

In addition, annual and five-year candidate wind turbine site data reports are published (Sandusky and Renné 1981a, 1981b; Sandusky et al. 1982), which are available from the National Technical Information Service (NTIS). These reports differ from the monthly data reports in that the two-minute data are first used to create hourly averages before the final analyses are made. This is required because of the vast amount of two-minute data collected at the sites over a period of a year. Data from the 17 original sites have also been summarized by Sandusky and Buck (1981).

4.4 QUALITY ASSURANCE

A Quality Assurance (QA) program, similar to that required by the United States Nuclear Regulatory Commission (USNRC), was established for the MVP. The objectives of the QA program were to ensure that all procedures for calibration, maintenance, and data reduction were carefully followed and results documented. The QA program required, for example, that PNL subcontractors verify that the engineering units created from the cassette data tapes were accurate conversions of the sensor output values as recorded on the tapes. A key element of the QA program was the filing of Nonconformance Reports, which documented the apparent time and type of any component failure and the steps taken to remedy the situation.

PNL's subcontractors designated a QA officer who ensured that all QA procedures were strictly followed. The QA officer was not directly associated with the calibration, maintenance, and data reduction activities and therefore retained a more independent, unbiased perspective of the program.

4.5 CURRENT PROGRAM AND DATA BASE DEVELOPMENT

In June of 1981 all site maintenance and calibration procedures and data processing functions were taken over by PNL. This was done in anticipation of a phase-out of the candidate site program. The calibration and maintenance activities were assumed by PNL technicians; however, the utility personnel who visited the sites periodically also contributed significantly to routine maintenance activities. For example, since the instrument elevator systems allowed the sensors to be brought down to ground level for routine change-out, and PNL supplied spare data loggers to each utility, it was simple for utility personnel to replace and return any damaged equipment to PNL for repairs. This also greatly reduced down time. Although data recovery rates have suffered somewhat since the 72-hour emergency maintenance procedure was discontinued (rates that had been upwards of 90% dropped to below 80% in some cases), these procedures have permitted conservation of program funds without drastic losses in usable data.

Perhaps the biggest advantage in this revised program management format has been in processing and reporting the data. The current data processing procedure, which has been in place at PNL since June 1981, bypasses the need to translate the cassette tapes onto a nine-track tape. Instead, as the cassettes are received at PNL from the participating utilities, they are read directly into a computer system and stored on a disk. The editing and processing are performed routinely as one step; when a monthly file of data has been assembled, a monthly data analysis report can be produced. This procedure has greatly increased processing efficiency, decreased the turnaround time for producing individual monthly reports, and has allowed the creation of a comprehensive candidate site data base. This data base has proved invaluable for performing special analyses and for responding to numerous data requests.

The data editing procedure was streamlined so that data were edited, coded as missing if required, and converted to engineering units by one computer program. This procedure, which had been suggested by the PNL subcontractors, was required because of the large volume of data to be processed once all sites were operational. As the data were processed, any values changed to a missing code were listed as part of the program. These listings were reviewed by a PNL meteorologist to determine if any "good" data were being incorrectly changed to a missing code. Generally, the above condition only occurred when abnormal time-of-day or Julian day data were recorded on the cassette tape. In this case the PNL meteorologist, using the text editor of the computer, could locate the abnormal data scan and delete that scan or change the incorrect value. Since the original data, stored as a binary file, remained on disk, the editing and engineering conversion procedure was repeated and subsequent outputs from the program were again reviewed by the meteorologist. Thus, the editing procedure for some individual tapes required several iterative review and reprocessing steps.

Another innovation that has taken place in the program since June of 1981 has been the installation of remote data transfer systems at some of the sites. These systems store up to 32 hours of hourly data collected at the site, then transmit the data over existing phone lines to a printer or to the

computer system at PNL. A total of nine units were installed at sites where phone lines were readily available by early 1982, including the MOD-OA turbine installation sites identified in the next section.^(a) With the implementation of an automatic dial-up system in the computer, it is possible to maintain a daily file of current data in the computer. This allows for more efficient identification of any problems with the sensors at the sites and allows the data to be used in other wind energy studies, such as wind forecasting studies, where rapid access to the data is required.

(a) Except at the Culebra, Puerto Rico, site

5. TURBINE INSTALLATION SITES

From time to time a candidate site was selected for receiving a large DOE horizontal-axis wind turbine for a cooperative field testing program operated by NASA/Lewis and the utility. Five sites were selected for these first-generation wind turbine experiments during the first two years of the program. These sites, and the type of wind turbine, are summarized in Table 3.

TABLE 3. Large Turbine Installation Sites for Field Testing Selected During the Period 1976-1979

<u>Site</u>	<u>Turbine</u>
Clayton, NM	MOD-OA (rated at 200 kW)
Culebra, PR	MOD-OA
Block Island, RI	MOD-OA
Kahuku, HI ^(a)	MOD-OA
Boone, NC	MOD-1 (rated at 2000 kW)

(a) Data from Kaena Point, Hawaii, were used for the selection in 1978, but for logistical reasons the site was moved to the Kahuku Hills, about 30 km to the northeast.

In 1978 and early 1979, special modifications to the data acquisition system were made at these turbine sites. At two of the operational MOD-OA sites (Clayton, New Mexico, and Block Island, Rhode Island), a third level of sensors was installed on the towers at the 30-m (100-ft) level (hub height). In addition, the original MRI 1074 wind sensors were replaced with more sensitive Climet Model 011-3 wind speed and Model 012-15 wind direction sensors. The use of these sensors allowed for more detailed turbulence studies at these sites when the loggers were operated at their high-speed data collection rate (one sample every two seconds). This sampling rate has been utilized periodically for research purposes.

At the Clayton, New Mexico, MOD-0A site, a special array of meteorological towers has been installed to perform additional turbine performance and stress studies on the machine. This research program is also being conducted as part of PNL's Wind Characteristics Program Element (WCPE), but is not directly a part of the MVP.

Another modification to the data acquisition program at the MOD-0A sites was that turbine output parameters (alternator power output, nacelle yaw error, and wind speed and direction from the nacelle anemometer) were recorded simultaneously with the meteorological tower data. This allowed detailed analysis of the turbine's performance and response to the free-stream meteorological conditions at the site.

A 48.8-m (160-ft), free-standing meteorological tower was installed at the Kahuku, Hawaii, MOD-0A site, and data collection began in September 1980. The tower is 60 m southeast of the turbine. Collection of meteorological data began in late September 1980. At this site, as at the other MOD-0A sites, turbine output parameters were recorded simultaneously with the meteorological tower data.

At the Boone, North Carolina, site, the tower was extended to 85.3 m (280 ft) in the summer of 1978 so that a warning light could be installed above the MOD-1 blade tip, 83.8 m (275 ft) above the ground. A third level of sensors was installed at the 76.2-m level on the tower. At this site, as at the other MOD-0A sites, the MRI 1074 wind sensors were replaced with Climet sensors. Turbine output parameters were not recorded on the data logger.

When the candidate site program was expanded in early 1980, the Goodnoe Hills, Washington, site was selected to receive the cluster of three MOD-2 2500-kW wind turbines, which represent the second generation of wind turbine technology developed by DOE and NASA/Lewis. The measurement program at this site was greatly modified to meet the needs of the numerous test procedures that have been planned for this facility. Description of this program is beyond the scope of this report.

6. SUMMARY OF FIELD EXPERIENCE

A detailed summary of the data collected in this program cannot be given here. Reports of annual summarized data have been prepared and are listed as references. However, to provide an idea of the type of wind resource that exists at each of the sites, Table 4 summarizes the mean annual wind speed at the 45.7-m level at all sites involved in this program since its beginning. Since the actual data collection period varied from site to site, the reader should refer to Tables 1 and 2 to determine when the measurements started and ended at each site.

The basic purpose of this program was to obtain wind resource data at promising sites to determine their suitability for operating and field testing large wind turbines. Given this objective, the program was originally designed to obtain reliable data that would document, in climatological terms, the wind resource. Considerations of such parameters as the detailed turbulence structure of the atmosphere and the thermal structure as it relates to stability were beyond the scope of this program. For this reason, the sampling scales were kept long, and highly responsive sensors were sacrificed for rugged and durable equipment.

As the program evolved, however, the need for more refined turbulence data became apparent because of possible structural problems the machines might encounter. Therefore, the more rugged equipment used earlier in the program was replaced by more responsive sensors. In addition, as the size of the program increased, a more automated approach for data collection was required, and the strip-chart recorders were replaced by digital cassette data loggers.

These changes allowed for a much more refined data collection system. For example, the loggers had the capability to collect one-second samples, and the highly responsive anemometers were capable of providing detailed turbulence data. However, the basic objective of the program was still to collect climatological-type data, and the responsive characteristics of the data

TABLE 4. Average Annual Wind Speed, m/s at the
45.7 m Level at 36 Candidate Sites

Name of Site	Annual Average Wind Speed, m/s at 45.7 m				
	1977	1978	1979	1980	1981
Amarillo, TX	8.3	8.0	7.6	9.1	7.7
Auspurger Mt., WA	8.6	---	---	---	---
Big Sable Pt., MI	---	---	---	---	8.8
Block Island, RI	7.4	7.4	7.0	7.7	7.4
Boardman, OR	5.9(a)	4.8(a)	5.4(a)	5.6(a)	5.4(a)
Boone, NC	8.0	7.0	7.8	8.3	8.4
Bridger Butte, WY	---	---	---	---	8.5
Cape Blanco, OR	---	---	---	---	7.9
Clayton, NM	7.4	7.4	7.3	7.3	7.2
Cold Bay, AK	9.6(b)	8.3(b)	7.1(b)	7.1(b)	6.4(b)
Culebra, PR	6.9	7.1	7.4	6.7	7.1
Diablo Dam, WA	---	---	---	---	5.6
Finley, ND	---	---	---	---	9.4
Fort Sill, OK	---	---	---	---	9.2
Holyoke, MA	7.2	7.1	6.5	7.0	5.8(c)
Huron, SD	6.7	6.6	6.5	6.5	7.4
Ilio Pt., Molokai, HI	---	---	---	---	10.9(c)
Kaena Pt., Oahu, HI	8.0	8.4	7.2	---	---
Kahua Ranch, Hawaii, HI	---	---	---	---	11.3(c)
Kahuku, Oahu, HI	---	---	---	---	8.4(c)
Kingsley Dam, NE	6.8	7.0	6.2	6.3	6.2
Livingston, MT	---	---	---	---	8.0
Ludington, MI	7.6	N/A	---	---	---
Meade, KS	---	---	---	---	8.0
Minot, ND	---	---	---	---	8.3
Montauk, NY	7.2	7.4	6.7	7.2	7.0
Nantucket, MA	---	---	---	---	9.1
Point Arena, CA	6.7	6.8	6.4	6.0	7.1(c)
Provincetown, MA	---	---	---	---	9.7
Romero Overlook, CA	---	---	---	---	6.1
Russell, KS	7.5	7.5	7.0	6.8	7.1
San Augustin Pass, NM	---	---	---	---	8.6
San Geronio Pass, CA	7.9	8.1	7.2	8.1	7.1
Stratton Mt., VT	---	---	---	---	11.4(c)
Tucumcari, NM	---	---	---	---	8.7
Wells, NV	---	---	---	---	7.9

(a) 39.6 m

(b) 21.8 m

(c) Data recovery less than 40%

collection system were only utilized under special circumstances. Additional tradeoffs became apparent as the more sensitive equipment and automated data logging systems were installed. In most cases, windy sites are also sites with harsh environments, and the geographical diversity of this program included a wide range of severity in climates. At sites in tropical and temperate coastal environments, salt spray and excessive moisture challenged the capability of the circuitry of the data logging equipment. At other sites, icing was a frequent wintertime problem, causing repeated failure of the more sensitive cup-and-vane-type anemometers (icing at some sites was so severe that even the rugged equipment used earlier in the program was occasionally damaged and in one case icing caused the failure of a tower). At some sites, wintertime temperatures could be so cold that the microprocessors in the unheated data logging equipment would fail. Because of the remoteness of the sites, it was often difficult for anyone to visit them more than once a week--this occasionally resulted in lost data, since equipment could fail during the time no one was at the site, and the failure would not be detected until the next visit. The remoteness of some sites also resulted in occasional vandalism of the equipment.

Despite these problems, which would be inherent in any data collection program, we were able to obtain a relatively high data recovery rate at most sites. A key factor in this was the cooperation of the utility personnel, who often checked the tower more frequently than required, performed maintenance on their own, and often provided additional security around the tower to minimize vandalism and to increase safety. Much was learned about operating sensitive data logging and anemometry systems in harsh environments through this program, as well as more appropriate ways to sample the data for wind turbine site evaluation. Based on these experiences, the next section lists the major recommendations we can offer at this time on future site evaluation measurement programs.

7. RECOMMENDATIONS FOR FUTURE SITE EVALUATION PROGRAMS

7.1 TOWER AND EQUIPMENT CONFIGURATIONS

Based on our experiences in the Meteorological Validation Program, we offer the following recommendations for equipment installations at sites being evaluated for large wind turbine utilization:

- If possible, measurements at least as high as the hub of the machine should be obtained. One, and preferably two additional levels, should be installed to allow data to be extrapolated to the hub height or higher, and to provide important information on the vertical shear characteristics at the site.
- Nevertheless, it is preferable to keep the height of the tower below 62 m (200 ft), since the Federal Aviation Administration (FAA) requires a beacon light on towers higher than this (in some cases, a beacon light would be required even for shorter towers, and after the turbine is installed a beacon light might be required at the height of the blade tip). The operation of the beacon lights requires ac power and, at least early in the site evaluation stage, electrical power may not be available at the site.
- The climatological conditions at the site should be considered before ordering equipment. If severe gustiness or icing is possible, more rugged sensors should be utilized (at the expense of the capability to obtain long-term, high-resolution turbulence data). If severe moisture could be a problem, special instrument enclosures and circuitry designs should be considered to assure that the data logging equipment stays absolutely dry and operational. If severe cold is a problem, the data logging equipment should be placed in a heated enclosure, or some type of resistance heat element installed in the enclosure.
- It is preferable to install towers at locations where icing conditions are minimized. However, if icing is a problem at a chosen location,

special care should be taken in the tower installation to ensure that a heavy load of ice will not buckle the tower or cause a guy wire to break loose. In the MVP, some problems were encountered with standard guy grips at sites where severe icing was experienced. Water would work its way inside the grip during thaws, and then expand and loosen the grip during refreezing. The grip should be designed to eliminate this problem.

- Although it is preferable to power the data loggers with ac power, in many cases none will be available. Some type of reliable onsite battery charging system should be a part of the equipment, such as solar cells or windchargers. (These were not available in this program, but would have simplified the utility personnel's weekly procedures.)
- Some type of remote data transfer system is recommended (using telephone lines, communications satellites, or telemetry) and a system to automatically incorporate the data into a computer data base is recommended. This will greatly improve data recovery rates and allow for more efficient site maintenance procedures. Nevertheless, it is still recommended that local people be utilized as much as possible to maintain a visual check on the equipment. An onsite data logger should still be used as a backup recording system.

7.2 SAMPLING AND DATA PROCESSING PROCEDURES

In Section 5 we discussed an expanded data collection program at the turbine installation sites. One feature of this program is to provide better guidelines on data collection procedures at sites where turbines could be installed, so that the data base more closely resembles the turbine operating logic. Detailed analysis of data collected at these sites has begun, and at this time we can offer the following preliminary recommendations on data collection procedures (see also Renné and Corotis 1981, Corotis 1982):

- The two-minute instantaneous samples provide an adequate sampling scheme for climatological purposes. However, they do not resemble the logic used by the wind turbines for start-up/shut-down procedures.

- For machine performance evaluation, some type of data averaging is appropriate. A suggested sampling rate of once every 10 minutes is made, with the following pieces of information recorded:
 - a 1-second average wind speed
 - a 15-second average wind speed (experience has shown that this correlates well with turbine performance)
 - a 1-minute average wind speed (correlating with the sampling procedure followed at routine National Weather Service Stations)
 - a 10-minute average wind speed (for machine operating procedures)
 - the variance of all 15-second averages within the 10-minute average
 - maximum wind gust during the 10-minute sampling period.

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APPENDIX

INFORMATION ON THE LOCATION AND EXPOSURE OF THE
METEOROLOGICAL EQUIPMENT AT EACH OF THE CANDIDATE SITES

TABLE A.1. Pertinent Information on the Location and Exposure of the Original 18 Candidate Sites^(a)

<u>Name of Site</u>	<u>Location</u>	<u>Reference USGS Map</u>	<u>Site Exposure</u>
Amarillo, TX	7 mi NE of Amarillo	Pleasant Valley, Mayer, TX (7.5')	Open grassland; site lies between 2 power plants to N and S
Augspurger Mt, WA	7 mi W, 2 mi N of Hood River, OR	Hood River, OR (15')	Open clearing in forest of 40-ft trees
Block Island, RI	1/2 mi E of town on Harbor Road	Block Island, RI (7.5')	Hilltop in rolling grassland
Boone, NC	1 mi N of Boone on Howard Knob	Boone, NC (7.5')	Forested ridgetop, 40-ft trees
Clayton, NM	3/4 mi SW of Clayton	Clayton, NM (7.5')	Open grassland
Cold Bay, AK	FAA tower, Cold Bay, AK	Cold Bay, AK (60' x 120')	Airport location, low bldgs. nearby
Culebra, PR	2 mi N of town	Culebra and Adj. Is. (6' x 11')	Top of hill, few shrubs and low trees
Holyoke, MA	4 mi N of Holyoke near Mt. Tom	Mt. Holyoke, MA (7.5')	Forested ridgetop, 50-ft trees
Huron, SD	4.2 mi NE Huron	Huron NW, SD (7.5')	Open grassland, slightly rolling
Kingsley Dam, NE	6.5 mi NE of Ogallala off SR 61	Ogallala, NE (7.5')	Rolling prairie, large lake to NW
Ludington, MI	5 mi S of Ludington	Ludington, MI (15')	Cliff with scattered 50-ft trees
Montauk, LI, NY	3/4 mi N of Montauk on Ocean Science Lab. site	Montauk Pt., NY (7.5')	Rolling sand dunes, bldgs. to NE
Point Arena, CA	7 mi N of town of Pt. Arena, 1 mi W of SR 1	Pt. Arena, CA (7.5')	Flat grassland, 50-ft cliff 1/4 mi W
Russell, KS	2.5 mi S of Russell off US 281	Homer, KS (7.5')	Flat prairie
San Geronio Pass, CA	9 mi NW of Palm Springs	Desert Hot Springs, CA (7.5')	Flat desert, hill 1 mi W
Boardman, OR	10 mi SSW of Boardman off Tower Road	Ells, OR (7.5')	Open, flat prairie
Kaena Pt., HI	32 mi NW of Honolulu	Kaena, HI (7.5')	Ridgetop with scattered shrubs, surrounded by cliffs except NE
Kahuku, HI	2.5 mi NW of Kahuku	Kahuku, HI (7.5')	On hilltop, MOD-OA 200 ft to the N

(a) Includes Kahuku, which replaced Kaena Pt.

TABLE A.2. Pertinent Information on the Location and Exposure of the 18 New Candidate Sites

Name of Site	Location	Reference USGS Map	Site Exposure
Big Sable Point, MI	8 mi N of Ludington, MI	Manistee, MI (15')	Low rolling sand dunes
Bridger Butte, WY	5.6 mi SW Ft. Bridger, WY	Ft. Bridger, WY (7.5')	Flat, barren mesa, cliffs 200 ft to W and S
Cape Blanco, OR	5 mi NW Port Orford, OR, off Cape Blanco Hwy.	Cape Blanco, OR (15')	Open clearing in rolling woodland, exposed to ocean toward NW
Diablo Dam, WA	1/4 mi W of Diablo Lake Resort in North Cascades N.P.	Ross Dam, WA (7.5')	Heavily forested (40-ft trees) hilltop
Finley, ND	NW corner Finley AFB, 1.5 mi W of Finley, ND	Finley, ND (7.5')	Open grassland, bldgs. 500 ft to E
Fort Sill, OK	S end of Army Base (3 mi N of Lawton, OK)	Fort Sill, OK (7.5')	Flat, open grassland
Ilio Pt., HI	18 mi NW of Kaunakakai on NW end of Molokai	Ilio Pt., HI (7.5')	Opening, with scattered shrubs, cliffs to E and NE
Kahua Ranch, HI	10 mi NW of Waimea, Island of Hawaii	Kawaihae, HI (7.5')	Rolling grassy ranchland
Livingston, MT	2.8 mi E of Livingston, MT	Livingston, Mission Mt. (7.5')	Slightly rolling, ranch land, rising hills to S
Meade, KS	1.9 mi ENE of Meade	Meade, KS (7.5')	Flat grassland and cornfields
Minot, ND	16 mi S of Minot on radar base	Minot Quadrangle, ND (15')	Hilltop in rolling prairies; large bldgs. to NE
Nantucket, MA	5.9 mi ESE town of Nantucket	Siasconset, MA (7.5')	Open field; shrubs to N, bldg. to immediate N
Provincetown, MA	0.7 mi W of Provincetown	Provincetown, MA (7.5')	Flat clearing in woodland (30-ft trees)
Romero Overlook, CA	26 mi E of Gilroy; 1/2 mi N S.R. 152 at Pacheco Pass	Pacheco Pass, CA (7.5')	Partially wooded (30-ft trees) ridgetop
San Augustin Pass, NM	20 mi NE of Las Cruces	Orgar, NM (7.5')	Steep, westward-facing barren slope
Stratton Mt., VT	38 mi NW of Brattleboro, VT, on Stratton Ski Area	Londonderry, VT (15')	Heavily wooded (40-ft trees) mountain top
Tucumcari, NM	3 mi SW at Tucumcari	Tucumcari, Liberty Mesa, NM (7.5')	Barren, flat hilltop
Wells, NV	20 mi ESE of Wells	Pequop Summit, NV (7.5')	Slightly rolling ridges; high complex terrain to S and N

AMARILLO, TX

101°44.76'W

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET

AUGSPURGER MT., WA.

121°40.78'W

45°44.40'N

45°44.40'N

121°40.78'W

SCALE 1:62 500

CONTOUR INTERVAL 80 FEET
 DOTTED LINES REPRESENT 40-FOOT CONTOURS
 DATUM IS MEAN SEA LEVEL

BIG SABLE POINT, MI

CONTOUR INTERVAL 20 FEET
DOTTED LINES REPRESENT 10-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS 578 FEET

BLOCK ISLAND, R.I.

71°34.33'W

119°50.37'W

BRIDGER BUTTE, WY

110°28.75'W

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

CAPE BLANCO, OR

CONTOUR INTERVAL 40 FEET

DATUM IS MEAN SEA LEVEL

DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER

SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER

THE AVERAGE RANGE OF TIDE IS APPROXIMATELY 5 FEET

CLAYTON, N.M.

103°10.23' W

36°26.58' N

36°26.58' N

103°10.23' W

SCALE 1:24 000

COLD BAY, AK

162°43.24'W

162°43.24'W

SCALE 1:250000

CONTOUR INTERVAL 200 FEET

CULEBRA, P.R.

65°18.55'W

65°18.55'W

SCALE 1:30 000

DIABLO DAM, WASHINGTON

121°6.78' W

121°6.78' W

97°52.39'W

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

FORT SILL, OK

98°27.18'W

98°27.18'W

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

157°14.92'W

DATUM IS MEAN SEA LEVEL

DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER.
THE MEAN RANGE OF TIDE IS APPROXIMATELY 2 FEET

HOLYOKE, MA.

72°34.63'W

42°18.23'N

42°18.23'N

72°34.63'W

SCALE 1:25 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

HURON, SOUTH DAKOTA

98°8.59' W

98°8.59' W

CONTOUR INTERVAL 5 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

KAHUKU PT, HAWAII

157°59.67'W

157°59.67'W

SCALE 1:24000

KAHUA RANCH, HAWAII

155°47.03' W

155°47.03' W

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
 DATUM IS MEAN SEA LEVEL
 DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER
 SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
 THE AVERAGE RANGE OF TIDE IS APPROXIMATELY 2 FEET

KINGSLEY DAM, NEB.

101°39.75'W

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
 DOTTED LINES REPRESENT 5-FOOT CONTOURS
 DATUM IS MEAN SEA LEVEL

LIVINGSTON, MT

110°30.02'W

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

LUDINGTON, MI

86°26.59'W

43°53.15'N

I C H I G A N

LAKE ELEVATION 580

TOWER

43°53.15'N

86°25.59'W

SCALE 1:62500

MEADE, KS

100°18.46'W

SCALE 1:24000

CONTOUR INTERVAL 10 FEET
 DOTTED LINES REPRESENT 5-FOOT CONTOURS
 DATUM IS MEAN SEA LEVEL

MINOT, ND

MONTAUK, NY

71°57.48'W

NANTUCKET, MASSACHUSETTS

POINT ARENA, CALIF.

123°43.29'W

38°55.50'N

38°55.50'N

123°43.29'W

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET

DOTTED LINES REPRESENT 20-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 4 FEET

PROVINCETOWN, MASS.

70°11.98'W

70°11.98'W

SCALE 1:25 000

CONTOUR INTERVAL 10 FEET

DATUM IS MEAN SEA LEVEL

DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER

SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER

THE MEAN RANGE OF TIDE IS APPROXIMATELY 9 FEET

ROMERO OVERLOOK/ PACHECO PASS AREA, CA.

121°13.17'W

121°13.17'W

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 10-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

RUSSELL, KANSAS

98°51.39' W

SCALE 1:24000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

SAN AUGUSTIN PASS, N. MEX.

106°33.93'W

106°33.93'W

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

SAN GORGONIO PASS, CA

116°34.83'W

116°34.83'W

SCALE 1:24000

STRATTON MOUNTAIN, VT

TUCUMCARI, NM

103°44.75'W

103°44.75'W

WELLS, NEVADA

114°34.65' W

114°34.65' W

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

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