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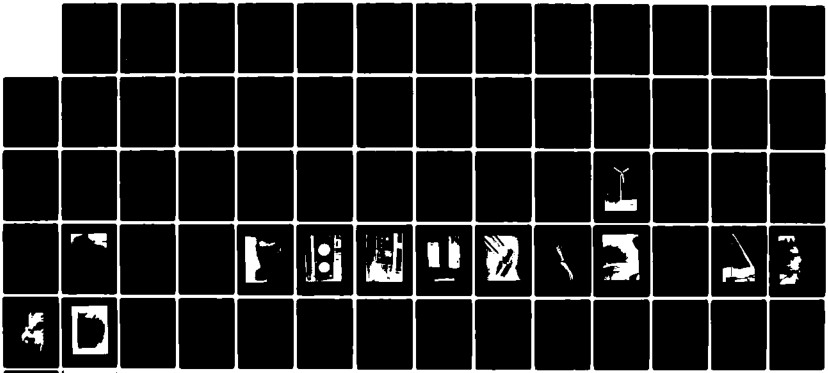

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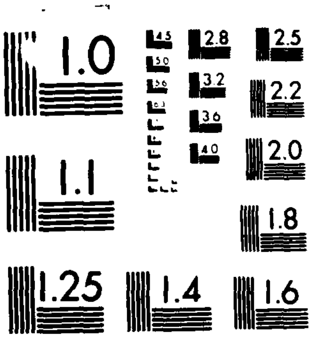

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NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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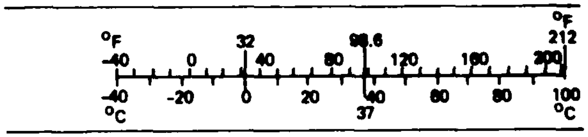
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the field evaluation of a 20-kW wind energy conversion system (WECS) installed in September 1978 at the Marine Corps Air Station (MCAS) Kaneohe Bay, Hawaii. The wind turbine generator chosen for the evaluation was a horizontal-axis-propeller-downwind rotor driving a three-phase, self-excited alternator through a step-up gear box. The alternator is fed into the base power distribution system through a three-phase, line-commutated-synchronous inverter using SCRs. The site has moderate wind conditions with

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This report describes the field evaluation of a 20-kW wind energy conversion system (WECS) installed in September 1978 at the Marine Corps Air Station (MCAS) Kaneohe Bay, Hawaii. The wind turbine generator chosen for the evaluation was a horizontal-axis-propeller-downwind rotor driving a three-phase, self-excited alternator through a step-up gear box. The alternator is fed into the base power distribution system through a three-phase, line-commutated-synchronous inverter using SCRs. The site has moderate wind conditions with an annual average windspeed of 12 to 14 mph, and the WECS turbine has a relatively high (29 mph) rated windspeed. The 20-kW WECS systems was primarily designed to obtain operating experience with, and maintenance information on, a 20-kW-sized WECS. This report describes in detail the experience gained and lessons learned during the field evaluation.

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APPENDIXES

INTRODUCTION

The Naval Civil Engineering Laboratory (NCEL), Port Hueneme, Calif., under the Naval Facilities Engineering Command's sponsorship, is investigating the application of wind power to generate electricity with small Wind Energy Conversion Systems (WECS) at Naval shore installations. This investigation follows an earlier study in which it was determined that WECS represents an economically viable means of displacing the use of fossil fuel sources of energy currently providing electrical power at Naval establishments -- both remote and unremote (Ref 1 and 2).

Results to date indicate that for wind-turbine-driven generators to produce electrical power competitively with diesel plants, a site must have an average annual windspeed of at least 12 mph. Of 325 existing major Naval shore establishments, 160 average annual windspeeds of 9 mph or greater. The data for most of these sites were collected at weather stations and near airports; local sites at these 160 facilities probably have wind conditions exceeding the required windspeed. At these facilities wind-generated power could replace conventional plant capacity, as well as save fuel, with suitable wind plant installations. Additionally, the WECS represents pollution-free, inexhaustible sources of energy. Further research, however, is required to determine the precise characteristics of locations suitable for WECS installations, and the appropriate system type, size, and configurations for these installations. At the present time, over 50 manufacturers are producing WECS with ratings from 1 to 60 kW, and large units in the 100 to 4,000 kW range are under development by the Department of Energy and private industry (Ref 3).

Because of the variable nature of the wind, most WECS operate at variable rotational speed and power output. The power conditioning methods and the hardware for converting the generator's variable output to match the electrical characteristics of building equipment, facilities, and power distribution grids are not as yet fully developed. The main problems associated with the WECS are the lack of mass production by the manufacturers and the meager amount of data on reliability and maintenance characteristics of the system. As part of the program to investigate the application of WECS at Naval shore establishments, NCEL installed a 20-kW system at the Marine Corps Air Station (MCAS) at Kaneohe Bay, Hawaii.

WECS Field Evaluation

The main objective of the evaluation at MCAS, Kaneohe Bay was to develop operational, maintenance, and reliability data on small, wind-powered systems. In particular, the objective was to identify any operational problems such as performance and efficiency of energy conversion from the wind, electromagnetic interference (EMI) problems with the Station grid or the communication gear in the proximity of the WECS, and any acoustical noise emissions. The wind turbine chosen for the evaluation was a horizontal-axis, downwind, 20-kW machine with an electrically controlled variable-pitch rotor and a three-phase, self-excited alternator. The alternator incorporates a rectifier that converts the variable voltage and frequency electricity produced by the variable speed rotor to direct current (DC) electricity. The rectifier's output is connected to a 20-kW synchronous inverter that accepts the DC power, converts it to 60 Hertz alternating current (AC) power, and feeds it into the grid network.

Currently, most commercially available WECS designs utilize horizontal-axis propellers to drive an electrical generator through a step-up gearbox. A growing number of researchers in wind energy systems think that the thrust toward horizontal-axis wind turbines exists only because of the aerospace industry's more extensive knowledge of propellers and that vertical-axis wind turbines would be more efficient. Several turbines such as the Darrieus and gyro-mill, of this type are available on the market today (Ref 4). The vertical-axis wind turbines have various advantages over the conventional horizontal-axis systems; for instance, the vertical symmetry eliminates the need for yaw control. The power is delivered at ground level and the supporting tower required is of simpler construction.

Among the various wind turbine designs, however, propeller systems are by far the most efficient for collecting wind energy. Figure 1 is a comparison of plots of power coefficient, $C_p(u)$, versus tip-speed-to-wind-speed ratio, λ, for five different wind turbine designs. For optimum conversion of wind power into mechanical power, most propeller rotors are designed to operate at a fixed value of λ. Typical values for λ range from 4 to 6 for most propeller systems. However, some attempts (Ref 5) have been made to develop WECS rotors with a high lift airfoil with values of λ as high as 10. Because of its higher efficiency values, horizontal axis WECS design was chosen for the evaluation at MACS, Kaneohe Bay. The downwind version of this design was chosen because it is self-yawing into the wind, and thus eliminates the need for a tail that results in a lighter system. Also, in the downwind version as opposed to the upwind version, deflection of the rotor blades due to wind forces is away from the tower.

Because of the variable nature of the wind, the rotor of a horizontal-axis wind turbine, without external speed controls, will turn at variable speeds. A generator driven by such a rotor will deliver electricity with variable voltage and frequency. It is possible to design a constant speed rotor by controlling the blade pitch, but as shown in Figure 2 (for a 5-kW WECS with a rated windspeed of 23 mph) the power coefficient or conversion efficiency for such a rotor will be less than that obtainable from the variable speed rotor during operation below the rated windspeed. This reduction in efficiency and, hence, power and energy output becomes significant at a location where, for the majority of time, the prevailing windspeed is less than the rated windspeed of the machine. Performance improvements of up to 20% are feasible by allowing the rotor's rpm to vary so that the tip-speed ratio remains constant and the rotor operates at or near its maximum power coefficient. A majority of the potential Naval shore establishments, it is believed, fall into this category; therefore, a variable speed rotor-driven generator was chosen for the field evaluation.

Power Conditioning Systems

Another important consideration in the choice of a WECS installation is the method of power conditioning used for utilization of power. Several methods of power conditioning with different design features were considered for the evaluation (Ref 6). The various methods considered were:

1. An alternator driven by a constant-speed DC motor.
2. A solid state inverter.*
3. A line-commutated synchronous inverter.
4. A field-modulated alternator.

The approximate costs and operating characteristics of the four power conditioning systems compatible with the 20-kW WECS demonstration are shown in Table 1. Clearly, the method utilizing a field-modulated alternator design is the least expensive, but a system of this type is not readily available. Also, due to the developmental nature of the system, little operating experience is available on this system. The solid state inverter system is the most expensive but has the highest reliability of all four systems. The DC motor driven alternator suffers from both high capital costs as well as high maintenance costs. The synchronous inverter system on the other hand has moderate cost and is readily available. The efficiency of all four systems is compared in Figure 3 which shows efficiency versus output power level through the system. The synchronous inverter system has the highest efficiency of all four systems at all power levels; hence, a line-commutated synchronous inverter was chosen for the evaluation.

The synchronous inverter chosen is a line-commutated system that when introduced between a variable voltage and DC power from the wind-driven generator, converts the DC power to AC at line voltage and frequency. The principle of operation of a synchronous inverter is discussed in Appendix A. In operation, if more power is available from WECS than is required by the load, the excess flows into the AC line where it can be used by other loads connected to the same distribution system. If less power is available than required by the load being served, the difference is provided by the AC line power. By interfacing a WECS with the base's power system, the need for storage is eliminated. The energy produced by the WECS allows a corresponding reduction in the fuel requirements at the point of base power generation.

The utility groups at the base have expressed considerable concern about the quality of power that is delivered by the WECS into the power distribution system. The term "quality of power" generally refers to the harmonic content of the WECS output power, although the term is often used to encompass other factors such as voltage control, frequency, generation availability, performance, and power factor. There are no rigid specifications for allowable total harmonic distortion for synchronous inverter systems for WECS. When the impedance of the WECS

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*Inverters are devices that convert DC power to AC power.

is properly matched to the impedance of the AC line, the total harmonic distortion of synchronous inverters can be kept within the tolerance range of typical loads on utility lines at military installations. Representative data from a harmonic analysis of the output current wave form from the inverter are shown in Table 2 (Ref 7). Although higher order harmonics in current may be as high as 11% in the case of the third harmonic, the fundamental amplitude contributes up to 98% of the total power. Next, the power factor for a synchronous inverter varies greatly with the available input power of the WECS. The best value of power factor (0.80) for the inverter occurs at or near its rated capacity, and the worst value (0.2) occurs at no load conditions. The power factor corrections can be easily made by adding capacitive reactance to the line. However, the applied capacitance must vary over the entire loading range of the inverter.

WECS Tower

All wind systems must be placed on an elevated supported structure, generally a tower. A variety of factors such as improvement in wind characteristics, cost, safety of traffic flow around the machine, aesthetics, and the amount of available land area influence the choice of a tower height and type for a WECS installation. The tower must be strong to support the weight of the wind turbine components and withstand wind-induced loads. A free-standing reinforce-concrete tower about 38 feet in height was chosen for the WECS installation, due to its lower cost, safety, and aesthetics.

WECS Location

The MCAS site at Kaneohe Bay has moderate wind conditions with windspeeds ranging from 12 to 14 mph, and the WECS turbine selected has a relatively high rated windspeed (29 mph). Hence, a WECS evaluation was done to gather operating experience and maintenance information on a 20-kW size WECS. This report describes in detail the experience gained and lessons learned from the field evaluation.

SYSTEM DESCRIPTION

The small WECS chosen by NCEL for evaluation at MCAS, Kaneohe Bay consists basically of a downwind-type 20-kW wind turbine and a synchronous inverter, both of commercial design (Ref 7 and 8). The wind turbine is comprised of a three-phase AC generator driven by a three-bladed rotor 24 feet in diameter. The system is mounted on a free-standing, steel, reinforced-concrete tower approximately 38 feet in height and is designed to produced 20 kW of power at a rated windspeed of 29 mph. The procedures for constructing the foundation are given in Appendix B. The system is currently configured to supply power to an instrumentation shop located at the Station. The WECS system, as currently installed, is shown in Figure 4. A plot of power output versus windspeed and a table relating windspeed to power coefficient and generator output are shown in Figure 5 and Table 3, respectively.

As seen in Figure 4, the wind turbine's rotor is a horizontal shaft. The blades are constructed of extruded aluminum. The nacelle, which houses the rotor shaft; gearbox; generator, located upwind from the rotor; control motor, and electrical control unit (ECU), located downwind from the rotor, is free to yaw about its vertical axis as directed by the wind forces. The cut-in speed of the machine (the speed at which the rotor begins turning) is approximately 8 mph. Once the rotor is turning, its rotational speed is governed by the areodynamic forces up to a windspeed of 29 mph. At that point, the ECU commences to feather the blades. The feathering is done variably up to a windspeed of 50 mph (the cut-out speed of the machine) at which point the blades are pitched completely parallel to the wind direction and the wind no longer exerts any lifting force on the face of the blades. Safety features included in the system are a manual override shutdown control and centrifugally actuated drag brakes on the blade tips which provide redundance to the ECU control.

The rotor drives a three-phase AC generator through a standard shaft-mounted reducer gearbox. Figure 6 is a schematic drawing of the wind plant setup at MCAS, Keneohe Bay. The generator incorporates a rectifier that converts the variable voltage and frequency electricity produced by the variable speed rotor to nearly constant DC electricity. At the rated windspeed, the generator, as configured, delivers 220 volts of DC power.

Next, the electricity passes through a line commutated inverter. The wind turbine installed at MCAS, Kaneohe Bay is interconnected with the base utility system through a synchronous inverter. The hardware design for this inversion technique utilizes the AC grid as the storage reservoir in addition to using it for fixing both the voltage and frequency of the power available in the wind. As shown in Figure 6, the system takes the rectified output of the three-phase AC generator through the inverter system and feeds it to the existing grid lines. The inverter system design accepts the DC power from the generator, converts it to AC, and feeds it into the grid lines. The load connected to the lines obtains power at the voltage and frequency fixed by the grid lines. If, at any instant, the generator produces more power than is required by the load, the excess flows into the grid network, but if the generator output is less than the load requires, the difference is provided by the grid lines. Hence, the grid acts as a limitless storage medium for the small-capacity wind generator, and the load served by this arrangement - the instrumentation shop - receives constant voltage and frequency power as desired. Some of the features of the synchronous inverter are discussed below:

1. Voltage, current, and current slope controls permit matching the load demand to the power available from the WECS, thereby maximizing the energy extracted. In a wind system, the power available in the wind varies with the cube of the windspeed. The inverter's controls permit loading the WECS to convert the available energy in the wind to within 80 percent of energy that could be extracted under ideal conditions.

2. The inverter's efficiency at WECS's rated output is estimated to be about 98% for the three-phase system installed at MCAS, Kaneohe Bay.

3. The no-load power draw for the inverter is typically less than 0.5% of its rated capacity, thereby maximizing the net energy production of the WECS.

4. A DC contactor energized by the AC lines automatically disconnects the DC source from the AC lines during utility outages and automatically reconnects it when the AC power is restored. This feature ensures the safety of a utility lineman while servicing a broken powerline to which the inverter is connected.

5. The input and output fuses are installed in the synchronous inverter to protect internal wiring, the DC source, and the AC lines from severe overload conditions.

In early December 1980, a 27 kV-A two-winding isolation transformer was incorporated into the WECS between the inverter and grid. Its purpose is to prevent any backflow of power and to protect the inverter and other electrical components of the system. Its design employs a 240-v delta-primary and a 208-v wye secondary.

As seen in Figure 6, wattmeters are located at various places throughout the circuit. These meters provide a portion of the data required by the test objectives. The wattmeter in the line between the generator and the inverter measures the DC power provided to the inverter by the generator. The wattmeter between the grid network and the inverter is a two-way meter which measures the power flowing from the grid network to the load and the power delivered from the synchronous inverter to the grid line. The wattmeter located in the line immediately adjacent to the load measures the AC demand of the load on the system. A detailed description of these and all other data collection devices can be found in the Instrumentation section of this report.

Test Site and Conditions

The installation of the 20-kW WECS at MCAS, Kaneohe, was completed in late September 1978. The site was chosen because it was felt that this installation and its windspeeds are characteristic of other Naval installations potentially suited for wind energy application. Location of the WECS on Oahu is shown in Figure 7. Figure 8 is a United States Geological Survey quadrangle map of the air station, and Figure 9 is a larger scale aerial photograph of the WECS vicinity. The site labeled "Kaneohe 45" marks the location of the system. With the exception of 70-foot Pako Hill (see Figure 8) located on the spur in the northwest quadrant, the area is relatively flat. The terrain is characterized by sand dunes partially covered by low vegetation. In Figure 9, a number of radar domes and one-story buildings located near Kaneohe 45 are visible.

A long-term windspeed estimated for the site based upon results of a siting study is presented in Reference 9. Using the results of a windpower survey conducted from 13 to 21 July 1978, the annual mean windspeed at the site at an elevation of 45 feet was estimated to be 14.5 ± 1.5 mph. (The hub height of the wind turbine is approximately 38 feet.) This estimate was made using several methods that relate windspeed at the site to windspeed at the neighboring Marine Corps weather station, (long-term windspeed frequencies are available at this station). As shown in Figure 8, the weather station (designated PHNG) is located at the southwest corner of the MCAS runway about 1.2 miles southwest of the WECS. Other methods and results of the siting survey are summarized below.

In addition to the data collected at the site's 45-foot elevation, wind data were collected by instrumentation deployed for various time intervals at 30-foot elevations at the WECS site and at five other locations in the surrounding area. These locations are shown in Figure 9. Data collected at the location denoted "Kaneohe 30" were used to determine how the windspeed varies with height at the site. "Kaneohe Beach 1" and "Kaneohe Beach 2" data were used to determine the strength of the undisturbed tradewinds as they come ashore; and the possibility of wind channeling by Pako Hill was examined at "Kaneohe Beach 3." Instrumentation deployed at "Kaneohe Line Up" and "Kaneohe Line Down," (located upwind and downwind, respectively, from the WECS site), were used to determine if the 12-foot high buildings located adjacent to the site would seriously affect the wind turbine's output during tradewinds. Using the data collected at these locations, the survey revealed the following wind characteristics for the area:

1. The vertical wind gradient at the site is rather large because upwind buildings (approximately 12 feet in height) retard the winds to a height of at least 30 feet. This deficiency is evident to a distance of 20 building heights downwind.

2. No signs of any wind acceleration from a channeling effect by Pako Hill were found; instead the wind near the hill seems to decelerate.

3. The undisturbed tradewinds lose their surface layer momentum rapidly as they come ashore. The strongest wind in the lowest layers is, therefore, found close to the beach. If the site chosen for the wind turbine installation had been on the shore rather than at the site selected, an increase in energy production of more than 20% might have been realized. Long electrical cables between the turbine and the load would, however, result in excessive voltage drop and power dissipation. Also considerable increase in salt spray, and therefore corrosion, would offset the advantage of stronger winds at this location.

4. Estimates of long-term site windspeeds were made using a number of statistical relationships between hourly speed observations at the chosen site and those at the permanent station, PHNG. Based on the estimated windspeed frequency distribution, the average output of the 20-kW wind turbine installed is estimated to be 4 ± 1 kW. This corresponds to an annual power output of about 30,000 kW hours, assuming a plant efficiency of about 90%. With the use of the instantaneous power curve for the wind turbine (Figure 5) and the seven methods used in the survey to relate windspeed at the site to windspeed at PHNG, annual cumulative power output for the turbine is plotted in Figure 10.

Test Objectives

Since the state of small WECS technology is still at an early stage, the main thrust of both past and present testing has been directed toward the systematic collection of data that will provide answers to some key questions, about this alternate source of energy. Much work must still be done before such questions as the following can be answered.

1. The generic characteristics of sites at which WECS can provide energy economically.
2. Geographical locations of these sites.
3. Optimum rotor diameter and generator size required for a WECS installation at a given site.
4. Type and design of a rotor required for optimum extraction of windpower at a site.
5. Type of generator required for a given application.
6. Type of power conditioning method and hardware.
7. Reliability and maintainability considerations.
8. Environmental impact considerations.
9. EMI interference with military communications.

There are several types of data being collected on a periodic basis at the WECS evaluation site. A discussion of the data items can be found along with the listing in the TEST RESULTS section.

INSTRUMENTATION

This section describes the data collection instruments being used in the WECS evaluation at MCAS, Kaneohe. A connection diagram showing the relative location of the various instruments in the system is given in Figure 11. Various instruments are described in detail in the material that follows.

Anemometer

The anemometer used in the field evaluation is the Bendix Aerovane Wind Transmitter, Model 120. It is a dual purpose instrument for measuring wind speed and wind direction, and is shown in Figure 12. The transmitter is 30 inches long, weighs approximately 13 pounds, and is mounted on a 40-foot galvanized-steel tower with a tubular mast. The system operates on 115-v AC, 60-Hertz power and does not emit radio-frequency interference.

Windspeed is measured by a three-bladed impeller fastened to the armature of a tachometer magneto located in the nose of the instrument. The rotational speed of the magneto is directly proportional to the windspeed; thus, the voltage signal generated by the magneto is a function of windspeed. This voltage signal is electrically transmitted to a remotely located voltmeter which is calibrated to indicate windspeed in miles per hour for visual observation.

Wind direction is measured by a streamlined vane coupled to the rotor of a type 1 HG synchro. The synchro electrically transmits the vane position to a remotely located companion synchro which moves a pointer on a wind direction dial. Windspeed and wind direction are displayed on the Bendix Model 135 Aerovane Indicator. This type of anemometer requires a 115-volt, 60-Hertz power for its operation.

Indicator

The Model 135 Bendix Aerovane Indicator being used in the evaluation is an electrical device designed to provide constant visual indication of windspeed and direction (see Figure 13). The indicator is used in conjunction with the transmitter which furnishes the windspeed and direction inputs. The indicator is 7 inches high, 17-1/2 inches wide, 11-1/4 inches deep, and weighs approximately 25 pounds. It is mounted in a rack along with other data collection instruments as shown in Figure 14 and operates normally in an ambient temperature range of 40°F to 120°F. The indicator requires a 115-volt, 60-Hertz, power source for its operation. The specifications of the windspeed and direction measuring units (the anemometer and the indicator) are given below:

Windspeed

- Range:
  - Miles per hour: 0 to 100 mph
  - System accuracy: ± 1%
  - System threshold: 2 mph or less (nominal)
- Input:
  - Miles per hour: 0.1056 volt/mph (nominal)
- Output: Visual, 4-inch diameter indicator

Wind Direction

- Range: 0 to 360°
  - Accuracy: ± 3° (nominal)
  - System threshold: 3 mph or less (nominal)
  - Input: Angular position voltage from 115 volt, 60 Hertz synchro
  - Output: Visual, 4-inch diameter indicator

Autodata Nine Data Acquisition System

The data acquisition system chosen for the field evaluation is a standard analog-to-digital data logger with an arithmetic averaging option of data channels. The system is capable of monitoring up to 256 channels either continuously or at discrete time intervals ranging from 1 minutes to 99 hours. The data logger is also designed to compute and record mean of the measurements taken on any set of channels. The arithmetic averaging options are programmable through the system front panel oy simply entering the channel number to be averaged and the desired averaging period. The averaging period can be varied from 1 minute to 99 hours in steps of one-minute increments. During this evaluation, the data logger is being used to record windspeed and direction, ambient temperature, or output from the generator, inverter output and the load demand. All the data channels except the wind direction are being averaged over a period of 15-minute and 1-hour intervals, respectively. The Autodata Nine System performance specifications are operational as follows:

Recording Speed - 24 readings per second with accuracy independent of voltage magnitude.

Digitizing Technique - Voltage to frequency converter. Input voltage is integrated over one period of power frequency. Uses no filter.

Voltage Ranges - Full scale ranges of ± 100 mV, ±1 v, and ± 10 v.

Voltage Limit - Algebraic sum of voltages between any two input leads must not exceed 250 v.

Resolution - 1% of full scale.

Dynamic Range - 12,000 counts minimum.

Input Impedance - 1,000 megohms per volt.

Overload Recovery - Error on first reading following 1,000% overload is less than 0.10% of full scale at maximum scan rate.

Zero Stability - Fully automatic zero on every reading; no zero calibration required.

Voltage Measurement Performance of Autodata Nine

Initial Calibration Accuracy - ± 0.005% full scale at calibration temperature of 25°C.

Time Stability - Initial calibration accuracy ± 0.01% reading per month for first six months and improving to ± 0.005% reading per month thereafter.

The above performance specifications define individual "worst case" error contributions. Individual errors are not directly additive as their instantaneous values differ in amplitude and polarity. A realistic and verifiable specification of overall system voltage measurement performance is given in Table 4. The overall system measurement accuracy based upon Normal Probability Distribution of individual errors is found to be around 99.73% of all voltage measurements. Tolerances of error shown in Table 4 are specified for analog voltage input to digitized output after one-hour warmup under the following operating conditions:

- Ambient temperature 25 ± 5°C.
- ± 10% power variation.
- System scanning a fully loaded mainframe (40 channels) at the maximum rate.
- Any two adjacent input channels, A and B; where A is a voltage equal to 1,000% overload and B is the measurement test channel.
- With 100-V peak-to-peak AC signal at the power line frequency applied as a common-mode voltage to the low side of the measurement test channel with 1,000 ohms source unbalance.
- System scanning in the continuous mode at the maximum rate.

RS 232 Tape Recorder. An RS 232 tape recorder was selected to record the field data on magnetic tape. The tape recorder is designed to handle the digitized output of the data logger on magnetic tape, which is compatible with most computers.

Wattmeters. As shown in the wiring diagram (Figure 11), there are three wattmeters being employed in the demonstration at MCAS, Kaneohe Bay to collect the data specified in the test objectives. The meter in the line between the generator and the inverter measures the DC power supplied to the inverter by the generator. The meter between the inverter and the grid network in a bi-directional AC type and it measures the AC power supplied to the grid by the inverter as well as the power used from the grid during low wind conditions. All meters are watt-hour and wattmeter types utilizing Hall-effect power transducers as input elements. The watt-hour indications are based on the absolute volts and amperes. The specifications for the wattmeters are presented in Table 5.

TEST RESULTS

The 20-kW WECS chosen for the field evaluation at MCAS, Kaneohe Bay, was installed in late September 1978. Since that time, numerous technical problems with the operation and reliability of the system have been encountered. While most of these problems were corrected in the field (by NCEL personnel with support from MCAS personnel), a portion of these problems was caused by the WECS being nonoperational for approximately 14 months of the 27-month duration of the field evaluation. However, several modifications have improved the performance of the system. One of the objectives of the field evaluation was to establish an operational data base from which further refinements of wind plant configuration as well as improvements in WECS operation and reliability, could be realized. The experience gained in determining solutions to these numerous problems was extremely valuable. A summary of the WECS evolution, including brief descriptions of the operational, reliability, and maintenance problems encountered since installation, follows.

EVOLUTION OF THE WECS INSTALLED AT MCAS, KANEOHE BAY

1978

Late September: WECS was installed.

Late October: During a period when Kaneohe Bay received approximately 7 inches of rain, rainwater entered the rotor hub and ECU. The limit switches in the control motor were badly corroded; as a result, the rotor blades jammed in a completely feathered position. WECS was down. The corroded limit switches are shown in Figure 15, and the limit switches were extensively damaged.

1979

January. The ECU was replaced and the WECS was up. While performing repairs on the WECS, it was observed that the wind pressure switch's connecting tubing was badly corroded (Figure 16). This corrosion was attributed to the electrochemical effect due to dissimilar metals being in contact (the aluminum pressure switch and the steel tubing). Also, the anemometer tower guy wire (steel) was badly corroded at the anchor point as shown in Figure 17. The corrosive atmosphere at the site is due to salt and high humidity in the prevailing winds. The corrosion problem at the guy wire was corrected by using a plastic-coated guy wire for the anemometer tower.

Late April: ECU was found not operating. It was suspected that a short in the bridge network and an open induction coil (T2 #1882) in the ECU was responsible for the failure. Other problems, such as blown fuses in lines, were also encountered. The turbine was very resistant to movement in yaw. Excessive noise was emanating from the front horizontal shaft bearing. The ECU circuit breaker was found open. Tape recorder was nonoperational. The necessary repairs were performed as follows: replaced the ECU and the bridge network; ordered a new coil from the manufacturer; oiled the yaw bearing; greased the horizontal shaft bearing; reset the circuit breaker; replaced the tape recorder; and made various modifications. A 150-volt varistor was placed across the 150-volt DC supply and grounded to the ECU. The AC utility wattmeter output changed from 8 volts DC full scale to 7.5 volts DC full scale.

May 7: Autodata Nine indicated a power failure. Part of the tape was missing. The Autodata Nine was reset.

May 9: The turbine was making a knocking noise.

May 14: In spite of very good winds the preceding two days, the counter showed no power flow into the grid.

June 4: The magnetic tape machine was nonoperational; repairs were made.

June 12: Heavy gusty winds caused a loud noise in turbine when it attempted to yaw.

June 13: The turbine was still noisy when attempting to move in yaw.

June 15: The turbine shut down due to a power outage.

June 18: A new coil T2 #1882 was installed, but the turbine was still down.

June 19: Turbine was put back on line, and the timer on the Autodata Nine was reset.

June 27: Turbine was still very noisy when yawing.

June 28: The synchronous inverter was nonoperational. The inverter was returned to operation and the Autodata Nine was reset.

July 9: The turbine again made a loud noise. The suspicion was that the noise was coming from the hub. Excessive noise was also coming from the turbine when it attempted to yaw. The Autodata Nine was not giving line feeds.

July 10: The turbine was put in emergency feather and could not be feathered with manual control. The inverter and power were secured.

Early August: The turbine was removed from the tower to check and replace the damaged bearings. The control motor housing was found to be very loose at the hub (Figure 18). After removing the motor housing and disassembling the hub, it was found that the gears were broken. The hub and horizontal shaft were shipped to the manufacturer for repair. The ECU and 350 3-1/2-in. and 360 2-11/16-in. bearings were replaced in addition to a new modified bearing on the vertical shaft. The loud noise emission was caused by the motor housing being loose from the rotor. As a result, the gears inside the housing were misaligned and that caused the rotor imbalance.

November 16: The turbine was replaced on the tower after the hub was repaired. The components in the power supply of the inverter were repaired because it would short out when output was greater than 10 amperes (approximately 250 volts).

November 19: The inverter was returned to operation. Batteries in the Autodata Nine were replaced. WECS was operating.

<u>1980</u>

March 5: The ECU was replaced. The turbine was no longer making noise, however, the inverter was still blowing fuses. The inverter was checked and had two damaged SCR's. Also, a GE-D41K1 transistor was out and a 20-ohm resistor in the CKT was open. All were replaced, and the inverter was returned to operation.

March 6: The inverter continued to blow fuses. The main trigger control cards were sent to the manufacturer for a checkout.

April: The turbine was taken off line due to continuing problems with the fuses in the inverter. Plans were made to incorporate an isolation transformer between the grid and the inverter to prevent any backflow of power and, hence, protect the inverter and other electrical components of the system.

Early December: The isolation transformer was incorporated, and the turbine was put back on line. Salt in the air caused some corrosion of the blade attachment points and the bolts in the rotor hub. In addition, following this long period of nonoperation, the yaw control bearing had frozen and had to be repaired. Some minor rust spots on the horizontal shaft were also noticed. The slip ring on the generator had some uneven wear problems.

The main goal of the WECS field testing was to develop operational, maintenance, and reliability data on windpower systems. In particular, the purpose of the field evaluation was to identify any operational problems, such as performance and efficiency of energy conversion from the wind, interference (both electrical and electromagnetic in nature) with the station grid or the communication gear in the WECS proximity, and any acoustical noise emission. As noted above, the WECS installation was marked with numerous operational and reliability problems, but these problems have provided NCEL with many opportunities to gain firsthand knowledge of the myriad ramifications of wind energy conversion systems. At these opportunities and throughout the testing period, both visual and instrumentation data collection has been ongoing. Considerable information has been gathered to date, and yet much information is still outstanding.

Discussion of the data collected to date are presented in outline format based on the test objectives.

WECS PERFORMANCE

Climatological Data

Windspeed and Direction. Instantaneous readings (several per second) of windspeed and direction were being made throughout the tests. Average windspeed was computed every 15 minutes, 1 hour, and 24 hours using the averaging option on the Autodata Nine Data Acquisition System. Data collected to date indicate that the average windspeed at the site is approximately 13 to 14 mph and that, approximately 70% of the time wind is from the northeast.

Ambient Air Temperature. The climate at MCAS, Kaneohe Bay is very mild and the air temperature normally ranges from 70° to 80°F. As a result, the effect of temperature changes on air density are negligible.

Salt Concentration. No measurements were made to record salt concentrations in the air. However, the heavy salt deposits observed on the guy wires and other exposed structures in the vicinity of the WECS site indicated high salt concentrations in the air.

Operating Data

Rotor. Effect on rotor performance of:

1. Aerodynamic flutter. None was observed.
2. Gyroscopic forces due to sudden yawing. None of significance were observed.
3. Centrifugal forces. Not of sufficient strength to cause any damage to the system.
4. Rotor-tower dynamic interaction. The natural frequency of the tower was significantly less than the rotational speed range of the rotor.

As for the effect of blowing sand, dust, and salt air on the rotor, blowing salt air caused some corrosion of the blade attachment points and the bolts in the rotor hub, especially during the period of April to December 1980 when the system was not operating. There was no blowing sand and dust observed at the site.

Sound meter readings for acoustical noise emission were taken at several locations 30 feet and 50 feet downwind from the rotor and at three locations immediately upwind from the rotor. A reading was also taken directly below the rotor where the maximum reading of 80 decibels was recorded.

Drive System. The drive system performed well. Friction in the gearbox did not cause any overheating problems. No significant problems due to temperature were noticed that affected performance and required alignment.

Electrical Generator.

1. Output versus windspeed characteristics. Figure 19 is a plot of generator DC output as a function of wind speed versus kW DC produced by the generator. The data points were collected over a 2-day period, 22 and 23 January 1979, and averaged at 20-minute intervals. Table 6 lists the data points used for the graph.

2. Interaction of generator with control system and rotor dynamics. Interaction with the control system was very good. Control of blade pitch-angle in high winds greater than 25 mph was excellent.

3. Electrical and aerodynamic losses. Generator efficiency was measured by dividing generator output (DC) by available power in the wind. The data collected on 22-23 January 1979 (see Table 6) were used to establish the average generator efficiency for this period which was approximately 34%. Twenty-six 20-minute interval averages are recorded. The average generator output is 6.57 kW. The windspeed averages 19.9 mph, making the average available power in the wind 19.54 kW.

No direct measurements were made for estimating the rotor aerodynamic losses. A well-designed WECS has an overall efficiency of about 42%. Based upon a measurement value of 34% for the WECS, the aerodynamic losses are estimated as 19%.

4. Overload and overspeed characteristics. The system has accepted overload well; its overspeed protection (i.e., electronically controlled blade pitch) performed as required. The air brakes located at the blade tip controlled rotor overspeeding between zero and full load conditions.

5. Short and no load effects on the generator operation. No problems were observed.

6. Effect of temperature, humidity, and water on the various connections and on performance. Temperature and humidity have had no observable effects; however, early in the evaluation (October 1978) rainwater from a heavy storm entered the rotor hub. The limit switches in the control motor were corroded and caused the components of the ECU to overload and the rotor blades jammed completely in the feathered position. The ECU had to be replaced.

7. Quality of power (i.e., the extent of harmonics generated). The instrumentation shop at the Communications Station, which receives power from the WECS experienced little or no problems due to generated harmonics.

8. Ease of installation. Installation of the WECS generator required use of cranes and specialized crews (Figure 20). The grouting of the tower in the foundation is shown in Figure 21 (the tower is wedged in place for a quick setting grout). Although specialized installation equipment and personnel are generally available at most facilities, installation of the hub assembly is a relatively complex and time consuming matter (Figure 22).

A minor difficulty was encountered during installation of the hub assembly for the WECS at the site. During placement of the vertical shaft in the tower, the sleeve fitting was severely bent and had to be replaced. This was due to an improperly sized hole in the top of the tower. The hole was remachined, and no further problems were encountered. Figure 23 shows the damaged sleeve fitting.

9. Accessibility for service and maintenance. For the same reason described in no. 8, maintenance of the generator is not a simple matter. Circuit breakers are located in the hub assembly, and a bucket truck is required to reach them.

Controls.

1. Sensitivity and stability of controls to windspeed and direction and rotor rotational speed. The main problem throughout the evaluation has been the unreliability of the ECU. It has been replaced three times: once in October 1978 following the intrusion of water into the control motor, once in August 1979, and once in March 1980 due to the ECU's inability to feather the blades as required.

2. Effect of temperature, humidity, water, and dust on operation. Temperature, humidity, and dust have had no effects on operation of the controls. However, the control motor in the ECU was damaged by intrusion as previously described.

3. Starting (cut in), restarting, and shutdown including full or partial feathering characteristics. The ECU was unreliable and caused the main problem throughout the evaluation. The ECU was unable to feather the blade as required.

4. Simplicity and reliability of control system design. The control system design is neither simple nor reliable. The ECU is a complex and very sensitive unit and has been replaced on three occasions.

Tower.

1. Isolation of resonant frequency to minimize rotor-tower interaction. The natural frequency of the tower was significantly less than the rotational speed range of the rotor.

2. Rotor-tower wake interaction for downwind rotors. When there was a sudden change in wind direction, the rotor experienced a rapid movement in yaw and consequently a rapid movement from a wind regime into a regime of no wind. Results of this created aerodynamic noise and the associated blade fatigue.

3. Ease of installation. Installation of the tower presented no major problems.

4. Tower shape and appearance. Public reaction to the appearance of the tower was very favorable.

5. Tower stability. Due to the persistence of the prevailing tradewinds at the site, the rotor is aligned in the same direction much of the time and, furthermore, experiences many movements this same direction. As a result, the tower has developed a slight set in this direction. To date this has created no serious problems; however, should the condition worsen, shims may be required to level the hub assembly and horizontal shaft.

Synchronous Inverter.

1. Interfacing characteristics of synchronous inverter with self-excited type generator. To date, there have been no problems at this interface.

2. Efficiency and electrical losses. Inverter efficiency is measured by dividing the sum of net kilowatts displaced from the load (load demand - power drawn from the utility) and power supplied to the utility by WECS by generator output. Using the data collected on 22 and 23 January 1979, (see Table 5, the average inverter efficiency was approximately 91%. (Twenty-six 20-minute interval averages are recorded. The averages of the load demand and power drawn from the utility averages are 7.89 and 3.47 kW respectively, making the average net killowatt displaced from the load 4.42 kW. The average power supplied to the utility by WECS is 1.58 kW. The average of the generator output is 6.57 kW.)

3. Quality of power output. See the data regarding the power quality of the synchronous inverter installed at MCAS, Kaneohe Bay.

4. EMI considerations. No electromagnetic interference with the communication gear at Kaneohe from the WECS has been reported.

5. Design capable of optimum conversion of wind power into electricity. The design is very efficient for converting wind energy into electricity over short intervals. Due to various failures, not enough performance data have been collected to establish this factor on a long-term basis.

6. Relative ease of interfacing with station grid. In March 1980, the synchronous inverter began blowing fuses. Damaged SCRs and transistors were found. Even after replacing these parts, the inverter continued to blow fuses. Because the number of wires leading into the inverter did not match the number leaving the inverter, it was decided that using an isolation transformer the system would rectify this problem. The isolation transformer was installed early December 1980 and no further problems have been observed.

Maintenance Data

Rotor.

1. Adequacy of bonds and fasteners and the blade's attachment connections to the rotor hub. Other than the corrosion of the blade attachment points and the bolts in the rotor hub during the period of April 1980 to December 1980, when the WECS was down, no inadequacies have been observed.

2. Blade fatigue cracks. No fatigue cracks have been observed in the rotor blades.

3. Resistance to corrosion of various components. Some corrosion was evident at the blade attachment points and on the bolts in the hub, but no serious instances of corrosion were observed.

4. Ease of repair or replacement of various components. As previously mentioned, access to the rotor requires the use of specialized equipment and personnel. These resources are generally not available at remote Naval establishments.

Drive System.

1. Lubrication and servicing requirements. No special requirements.

Controls.

1. Lubrication and servicing requirements. No special requirements were noted.

2. Ease of replacement or repair. Very difficult to perform any repairs to the controls in the field. It usually requires sophisticated maintenance shop facilities; i.e., the hub assembly was damaged in May 1979 and had to be remachined. After the hub was redesigned by the manufacturer, it was reassembled in the field.

3. Blade pitching mechanism adjustment requirements. No adjustments have been required since its installation.

4. Frequent checking of the overspeed and braking system, cut in - cutout system, and rotor lockout for servicing. Other than the inability to feather the rotor blades due to the frequent problems incurred by the ECU, no special problems have been encountered.

Electrical Generator.

1. Maintenance of the connections such as slip rings and generator terminals. The slip rings corroded easily and required frequent cleaning.

2. Lubrication and servicing requirements of the bearings. No extra requirements.

3. Accessibility and ease of repair or replacement. As previously mentioned, the generator does not afford easy access.

4. Long-term integrity of connections and windings. No special problems have been encountered.

Tower.

1. Adjust generator holding clamp. No adjustment has been necessary.

2. Protection against corrosion of various components of the tower. All components are made of concrete and they are not subject to corrosion.

Maintenance of Adequate Lightning Protection. No maintenance problems have occurred.

Reliability, Maintainability, and Availability Data

The WECS set-up at Kaneohe primarily utilized prototype components that, for the most part, are in early stages of development. Consequently, the WECS set-up was not operational a good deal of the time because of the repairs and design modifications that had to be performed for improving the system performance. Hence, it was not possible to collect the reliability and maintenance data on the WECS set-up. Some preliminary information on type and frequency of critical failures is listed below.

Number of Critical Failures (WECS Producing No Electrical Power Due to Component Failure). To date, five critical failures have occurred.

Times Before Critical Failure. To date, times before failure are 45, 90, 40, 100, and 30 days. This gives a Mean Time Between Failure (MTBF) of 61 days for the overall system date.

Times to Repair. As refinements of the system are incorporated, greater attention will be given to accurately measuring the time spent in the following categories of downtime.

1. Logistic time. The sum of time intervals during which the WECS is not capable of providing electrical power because replacement parts must be obtained from outside sources.

2. Awaiting outside help time. The sum of time intervals during which the WECS is not capable of providing electrical power because outside assistance is required.

3. Administrative time. The sum of time intervals during which the WECS is not capable of providing electrical power but no corrective maintenance is being performed and no outside help or external replacement parts are needed.

4. Corrective maintenance time. The sum of time intervals during which repair, part replacement, alignment, or adjustment is undertaken in order to correct a failure, and the WECS is not capable of providing electrical power. Mean Time to Repair (MTTR) is defined as the arithmetic average of all corrective maintenance times

The administrative times tended to be relatively long because a majority of the failures occurred during periods of high winds. At these times, safety of the maintenance personnel precluded any repair actions at the WECS hub where many components with relatively high probabilities of failure are housed.

Availability. Availability is defined as the probability that the WECS will be capable of providing electrical power at any random point in time. It is calculated as:

$$A = \frac{\text{Uptime}}{\text{Uptime + Downtime}}$$

Power Output Data

Generator Efficiency. The average generator efficiency for this period was approximately 34% (see Table 5).

Synchronous Inverter Efficiency. The average inverter efficiency was approximately 91%, based on the data collected on 22 and 23 January 1979 (see Table 5).

1. Generator output. The average generator output was 6.57 kW.

2. Net power displaced from load (load demand - power drawn from utility). Figure 24 is a graph of load demand in kilowatts versus time of day for a typical demand day at the Communications Station. Power drawn from the utility averaged 3.47 kW.

Overall System Efficiency. Generator efficiency X inverter efficiency = 34% X 91% = 31% for 22-23 January 1979 as shown in Table 5.

Instantaneous Power Output of Wind Turbine. These data can be found in Table 5.

Long-term Power Output of the WECS. In the 30-day period, from 4 June to 3 July 1979, 1,094 kW-hr of electricity were displaced from the load by the WECS. This represents an annual rate of 13,128 kW-hr.

Percentage of Power Required by Load Supplied by the WECS (Goal Was Displacement of 20%). In the 30-day period, 4 June to 3 July 1979, approximately 19% of the load demand was supplied by the WECS.

CONCLUSIONS

1. Installation of WECS of this design requires the use of specialized equipment and personnel (resources generally not available at remote Naval establishments). The use of these specialized resources is also expected to be required for a majority of required system maintenance actions because many of the system components that have a relatively high probability rate of failure are housed in the nacelle.

2. Since its installation in late September 1978, numerous technical problems with the operation and reliability of the system have been encountered. While most of these problems were corrected in the field, the WECS was nonoperational for approximately 14 months of the 27-month field evaluation. Several modifications have improved the system, and NCEL has gained much experience from these problems.

3. Test results have indicated that there are no significant interference (EMI) or noise problems for a WECS of this size (25-foot rotor).

4. The major problem throughout this evaluation has been the unreliability of the ECU. It was replaced three times -- once in October 1978 following intrusion of water into the control motor, once in August 1979 and again in March 1979 due to the ECU's inability to feather the blades as required.

5. A 27-kVA isolation transformer was incorporated into the WECS between the inverter and grid in December 1980 because of the problem with blown fuses on the synchronous inverter. The purpose was to protect the inverter and other electrical components of the system. No further problems have been observed.

6. The rotor is aligned in a north-northeasterly direction because of the tradewinds and experiences many movements into this direction. As a result, the tower has developed a slight set in this direction. This condition has created no serious problems; however, should it worsen, shims may be required to level the horizontal shaft.

7. Data collected to date indicate that the average windspeed at the site is approximately 13 to 14 mph and that approximately 70% of the time the wind is from the northeast.

8. Using data collected on 22 and 23 January 1979, the average efficiency of the generator, synchronous inverter, and the total system for this period was approximately 34%, 91%, and 31%, respectively. (These efficiency values for various components of the WECS are close to what is feasible within the present state-of-the-art.)

9. From 4 June to 3 July 1979, 1,094 kW-hr of electricity was displaced from the load by the WECS. This represents an annual rate of 13,128 kW-hr, which corresponds to approximately 19% of the load demand.

10. The WECS installed at MCAS Kaneohe Bay has exhibited an MTBF of 61 days. It is felt that this figure is excessively low, and it is expected that the MTBF will approach at least 9 months as the system's configuration becomes better defined. As has been documented, improvements to the WECS's hardware are being continuously made. An example of

this is the use of the isolation transformer between the grid and the inverter. This modification has corrected the problem of power backflow into the inverter and other system electrical components. Since the transformer's incorporation into the line in early December 1980, there have been no further inverter failures. The WECS technology is still in the early stages of development. Many improvements in the system design are certainly forthcoming, which undoubtedly will lead to an increased system MTBF.

RECOMMENDATIONS

1. A more reliable means of controlling feathering of WECS rotor blades, needs to be developed. The ECU's located atop the system's tower have proven to be neither reliable nor of simple design. ECU's repair requires the use of specialized equipment and personnel. Maintainability can be significantly improved by locating the ECU at ground level.

2. If an ECU is employed in a WECS, at least one spare unit must be available at the site at all times.

3. If an ECU is used to control feathering of the roter blades, it must be protected against water intrusion.

4. Future tests of the WECS located at MCAS, Kaneohe Bay must focus on collecting reliability, maintainability, and availability (RMA) data.

5. Since many remote Naval installations are located in wind regimes where wind energy could be economically feasible, WECS designs requiring minimal specialized maintenance equipment and personnel for their installation, repair, and maintenance are needed. One such concept could employ a WECS mounted on a tower hinged at its base, which can be raised or lowered by a winch-operated hoist.

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Table 1. Cost of Four Power Conditioning Systems Suitable for the 20-kW WECS[a]

System Type	Cost per kW ($/kW)	Remarks
1. An alternator driven by a constant speed DC motor	500	High maintenance, easily available.
2. A solid state inverter	800	Low maintenance, high reliability, easily available.
3. A line-commutated synchronous inverter	400	Operates with an existing grid only, easily available.
4. Field modulated alternator	150[b]	System not available

[a] In 1980 dollars.

[b] Cost is in addition to the regular cost of the alternator.

Table 2. Harmonic Decomposition of Line Current Synchronous Inverter Supplied by Filtered DC Power Supply with 10 mH Output Inductance (Ref 7)

[Line Current = 29.2 to 37.8 Amperes (rms)]

Harmonic	Average Harmonic (rms) (%)
1st	98.97
2nd	2.24
3rd	11.54
4th	0.51
5th	5.56
6th	0.27
7th	3.45
8th	0.55
9th	2.43
10th	0.47
11th	1.64
12th	0.75
13th	1.24
Average	99.94

Table 3. Power Coefficient as a Function of Wind-Speed for the 20-kW Wind Turbine Generator

Windspeed (u)	Power Coefficient ($C_p(u)$)	Output (kW)
8	0.000	0.00
10	0.403	---
12	0.341	1.46
14	0.319	2.17
16	0.312	3.17
18	0.312	4.52
20	0.314	6.23
22	0.317	8.39
24	0.321	11.01
25	0.323	12.52
26	0.324	14.13
27	0.326	15.91
28	0.328	17.85
29	0.330	20.00
30	0.298	20.00
34	0.205	20.00
38	0.147	20.00
40	0.126	20.00
46	0.083	20.00
50	0.0645	20.00
52	0.000	0.00

Table 4. Overall System Voltage Accuracy, All Ranges (full-scale 100mV, 1V or 10 V)

Input Voltage (percent of full-scale)	Error (percent of full-scale) Standard Resolution
0	±0.02
33	±0.02
67	±0.02
100	±0.02
120	±0.03

Table 5. Specifications for the Three Wattmeters Used in the WECS Evaluation

Item	DC Wattmeter	AC Wattmeter	AC Bi-directional Wattmeter
Model	WH-7 Series 34 Ohio Semi-tronics	WH-3 Series 65 Ohio Semi-tronics	WH-3 Series 704 Semi-tronics
Input			
Current, normal	200 A maximum, 2 x rating	100 A maximum, 2 x rating	100 A maximum, 2 x rating
Voltage, normal	120 volts maximum, 1.25 x rating	240 volts maximum, 1.25 x rating	240 volts maximum 1.25 x rating
Phase, wire	DC, 2 wire	3-phase, 4 wire	3-phase, 4 wire
Outputs (signal)			
Power	8 volts DC = 25 kW	7.5 volts DC = 80 kW	7.5 volts DC = 75 kW
WH pulses	819.2/W-hr	204.8/W-hr	409.6/W-hr
Electromechanical	10 W-hr/count	10 W-hr/count	10 W-hr/count

Table 6. WECS Sample Performance Data[a]

Date	Time	Wind-Speed (mph)	Power Available in the Wind (kW)	WECS Output (DC)	Load Demand (AC)	Supplied to Utility by WECS (AC)	Supplied to Load by Utility (AC)	Overall System Efficiency (%)
1/22/79	1637	21.89	26.01	8.878	7.10	2.306	1.368	30.9
	1657	20.93	22.74	7.112	5.10	1.83	0.487	28.3
	1717	22.10	26.77	8.753	4.54	3.412	0	29.7
	1737	22.2	27.13	8.6125	5.08	2.915	0.206	28.7
	1757	21.8	25.69	7.953	6.33	1.481	0.609	28.0
	1817	21.27	23.86	7.618	4.53	2.68	0.309	28.9
	1837	21.5	24.65	7.912	3.91	3.328	0.084	29.0
	1857	22.5	28.25	8.975	3.91	4.293	0.075	28.8
	1917	23.2	30.97	9.987	3.99	5.090	0.037	29.2
	1937	21.6	24.99	7.956	4.05	3.309	0.150	28.8
	1957	22.3	27.50	8.618	4.01	3.843	0.056	28.3
	2017	20.2	20.44	6.73	3.59	2.596	0.103	29.8
	2037	21.9	26.05	8.58	3.93	3.965	0.112	29.9
1/23/79	0925	14.87	8.15	2.556	8.71	0	6.38	28.6
	0945	18.71	16.24	5.221	9.27	0	4.490	29.4
	1005	17.58	13.47	4.328	9.36	0	5.400	29.4
	1025	17.67	13.68	4.222	10.49	0	6.6	28.4
	1045	18.78	16.43	5.709	12.06	0	6.8	32.0
	1105	18.50	15.70	5.453	12.79	0	7.76	32.0
	1125	16.10	10.35	3.634	11.85	0	8.494	32.4
	1145	17.05	12.29	4.209	11.08	0	7.228	31.3
	1205	18.53	15.78	5.703	10.71	0	5.137	35.3
	1225	17.56	13.43	4.116	10.91	0	7.125	28.2
	1245	19.00	17.01	5.741	11.94	0	6.656	31.1
	1305	20.17	20.35	6.784	12.80	0	6.562	30.7
	1325	18.76	16.37	5.525	13.21	0	8.100	31.2

[a] All readings taken are averaged over a 20-minute interval.

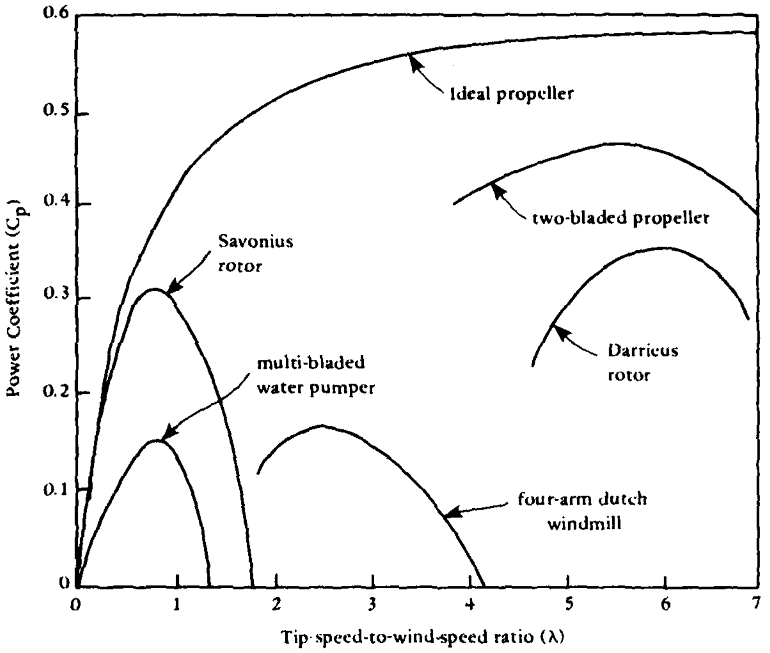

Figure 1. Characteristics of five wind turbine designs (Ref 4).

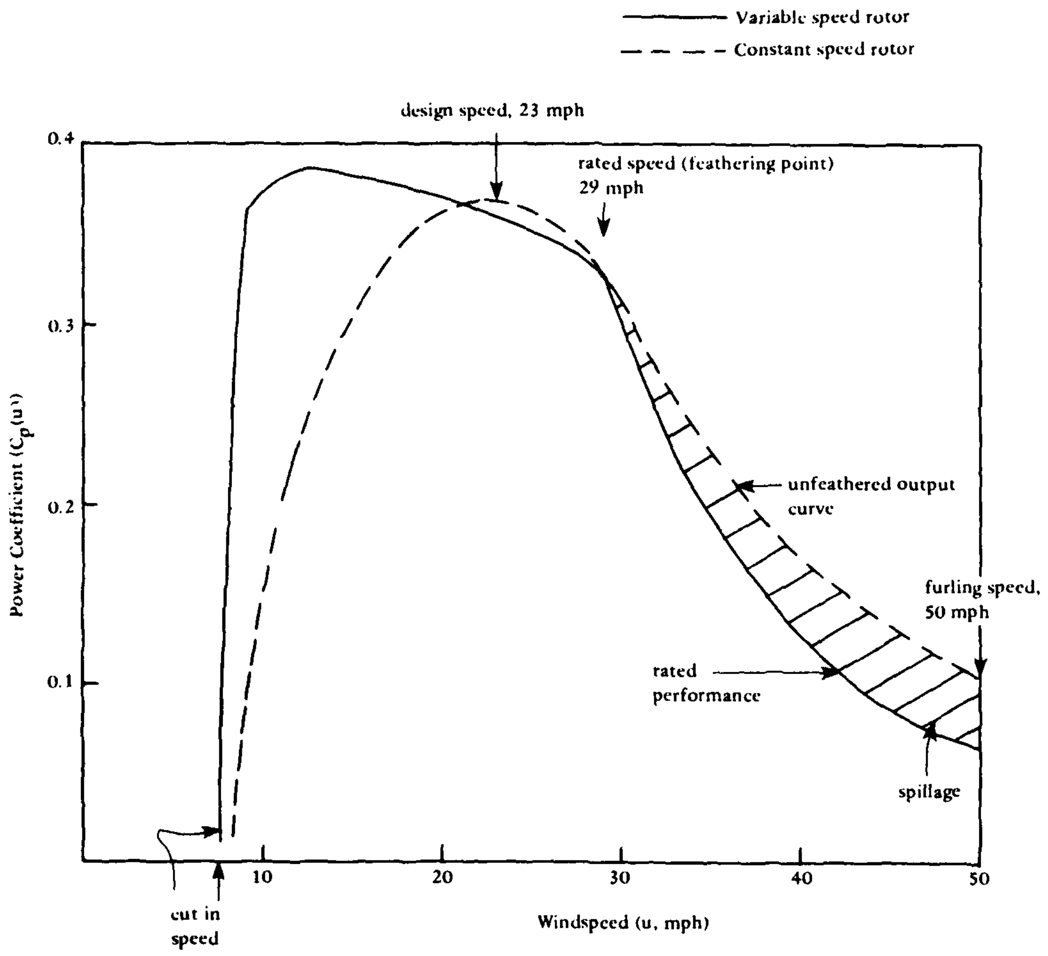

Figure 2. Output characteristics of a propeller WECS.

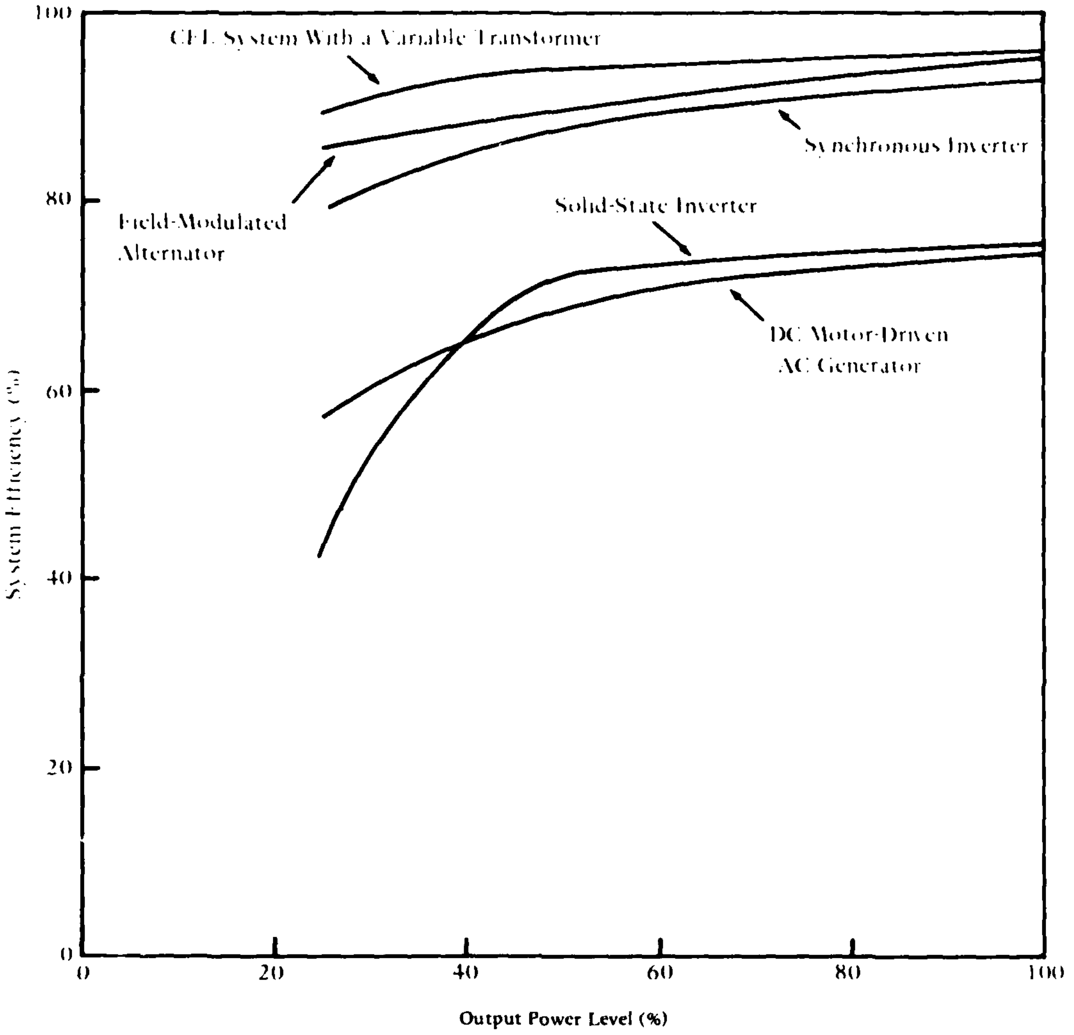

Figure 3. Efficiency versus load characteristics of four power conditioning systems suitable for a 20-kW WECS.

Figure 4. WECS wind turbine generator at MCAS, Kaneohe Bay, Hawaii.

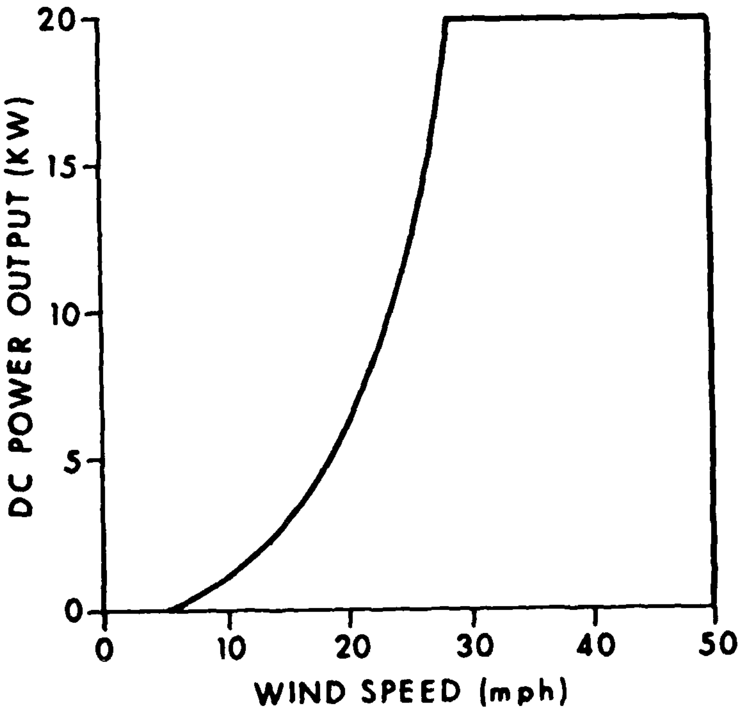

Figure 5. Power output of the 20-kW WECS installed at MCAS, Kaneohe Bay, Hawaii.

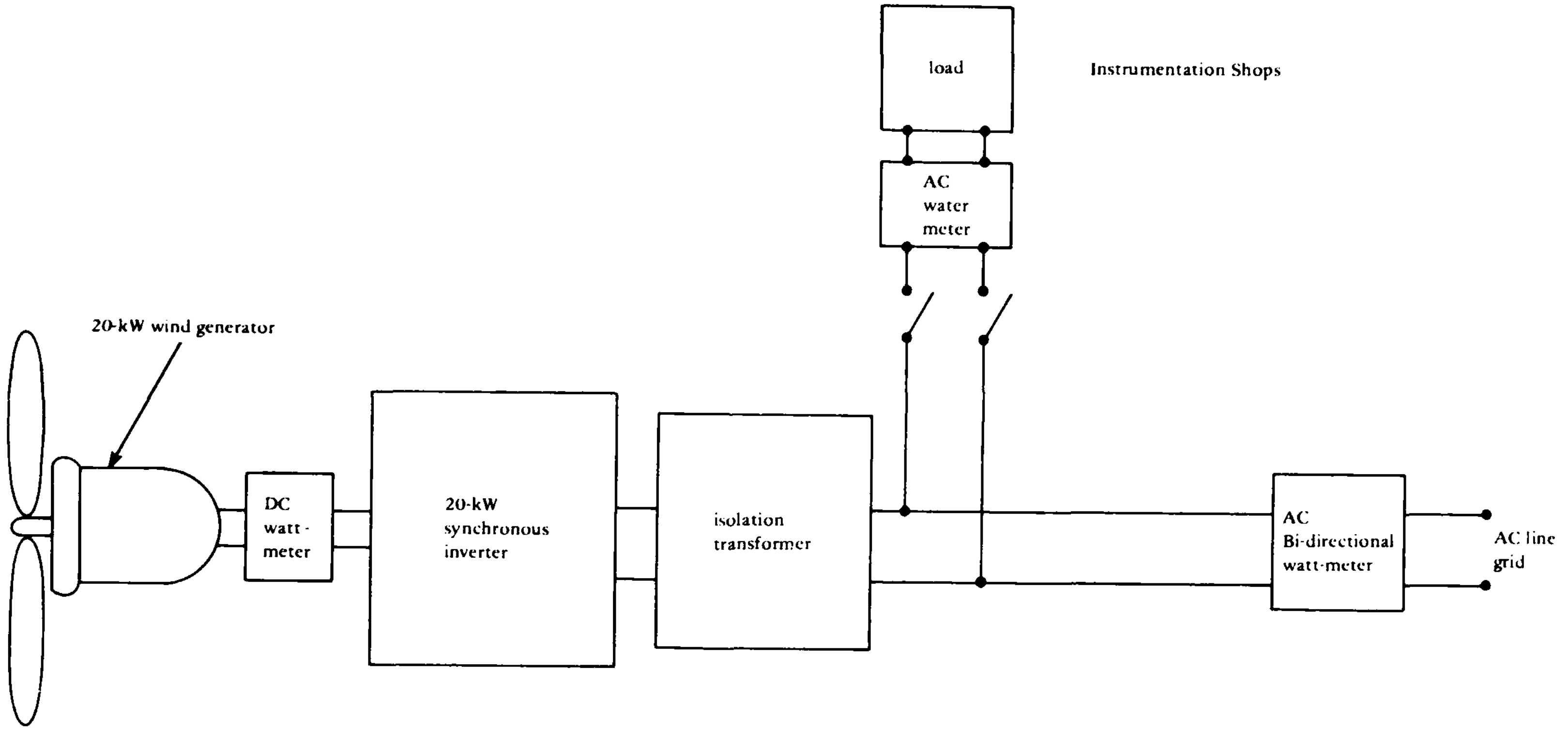

Figure 6. Schematic of the 20-kW wind plant setup for MCAS, Kaneohe Bay, Hawaii.

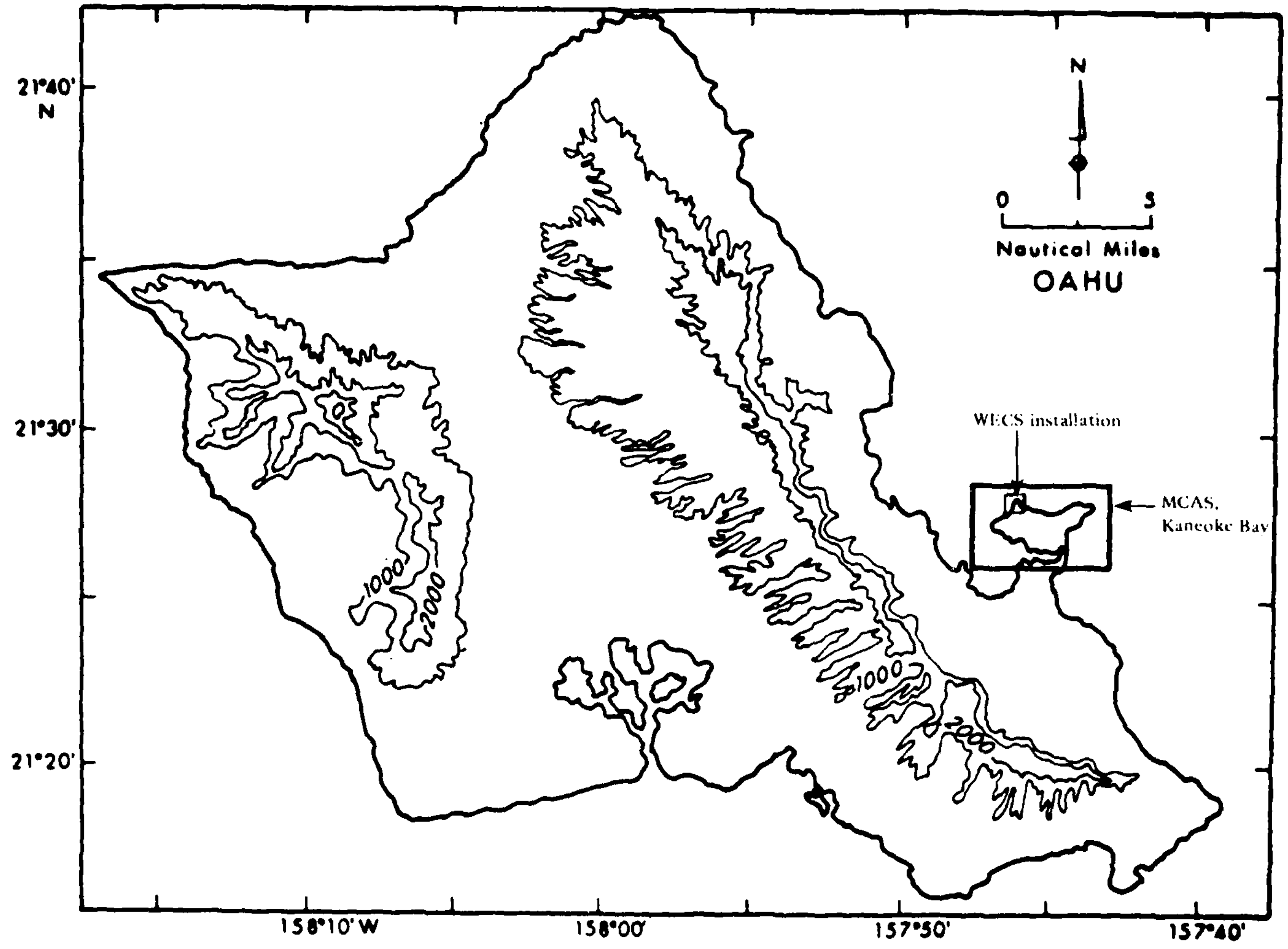

Figure 7. Island of Oahu, showing location of WECS installation.

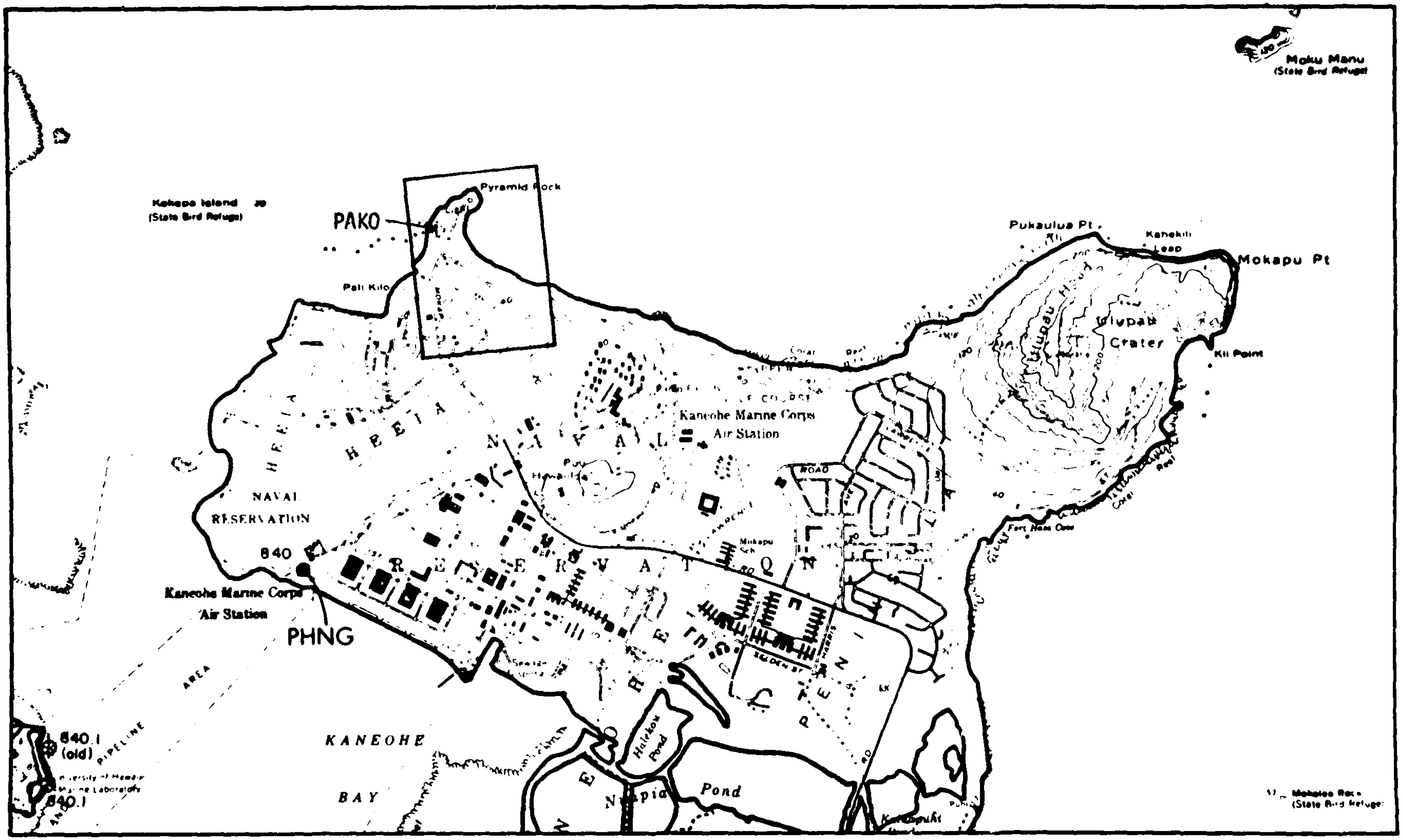

Figure 8. U.S. geological survey quadrangle map of MCAS, Kaneohe Bay, Hawaii.

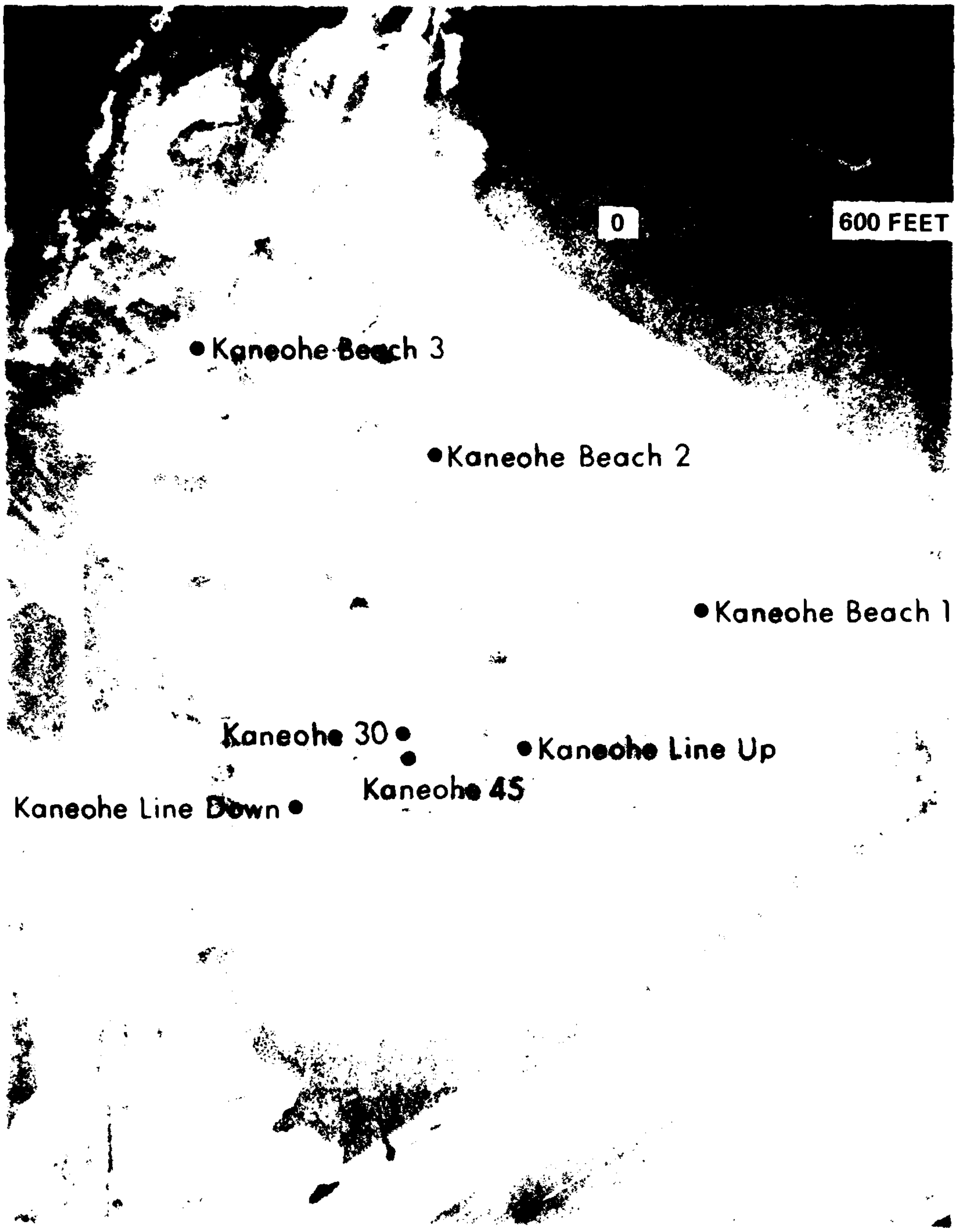

Figure 9. Aerial photograph of the survey area with monitoring sites.

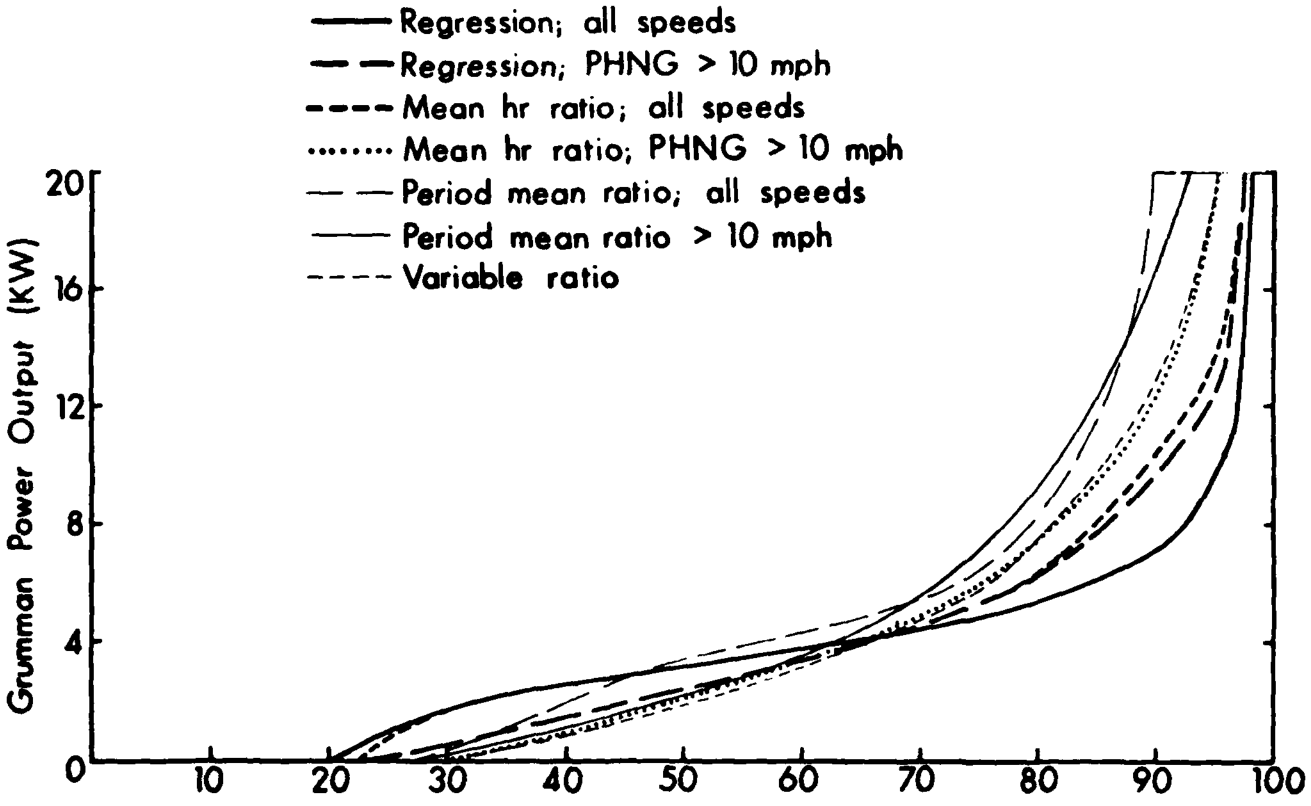

Figure 10. Estimated annual cumulative power output for the 20-kW WECS based on the seven statistical relationships between Kaneohe 45 and *PHNG*.

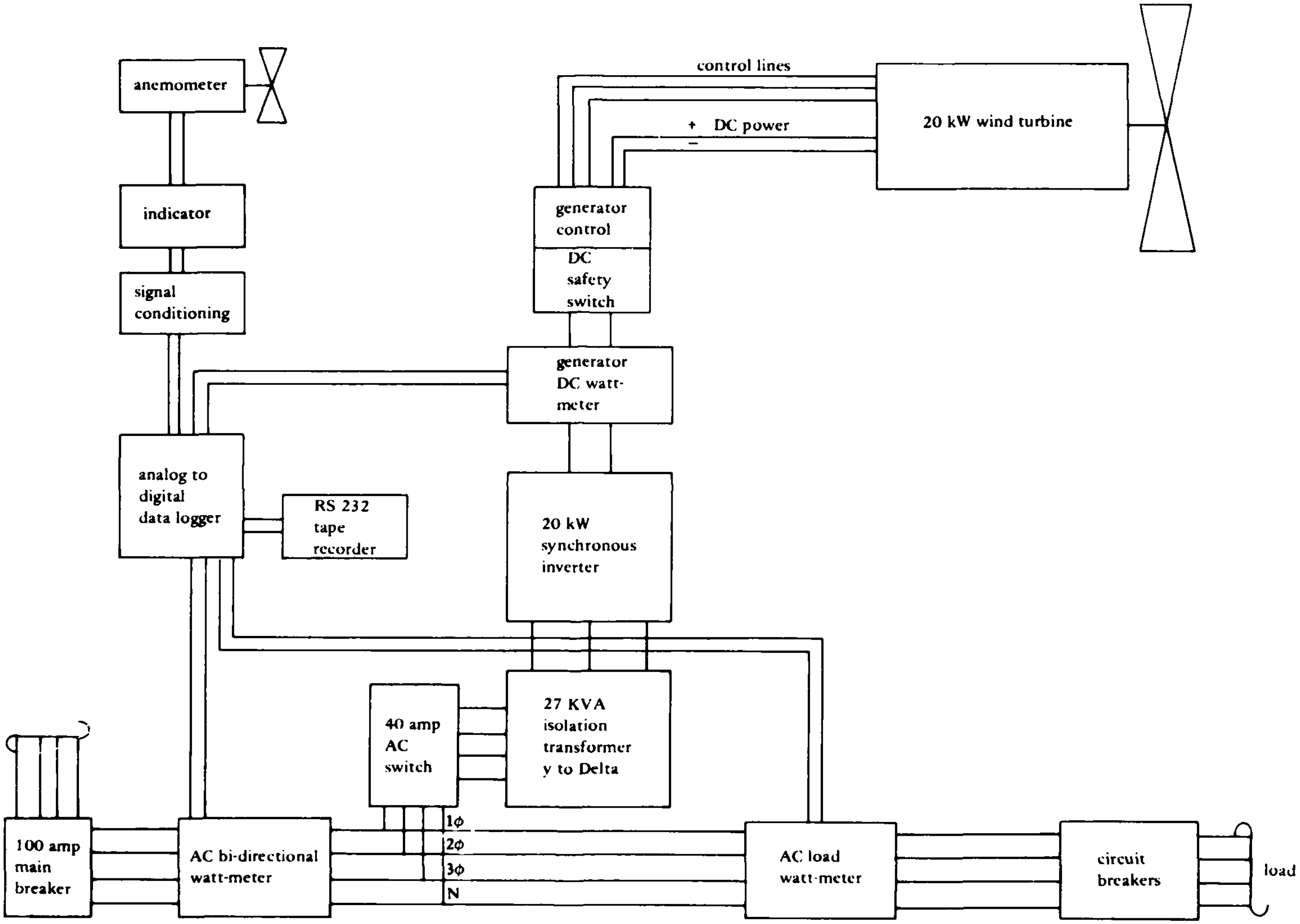

Figure 11. Schematic of instrumentation setup for the field evaluation at MCAS, Kaneohe Bay, Hawaii.

Figure 12. Aerovane Wind Transmitter, Model 120.

Figure 13. Bendix Aerovane Indicator, Model 135.

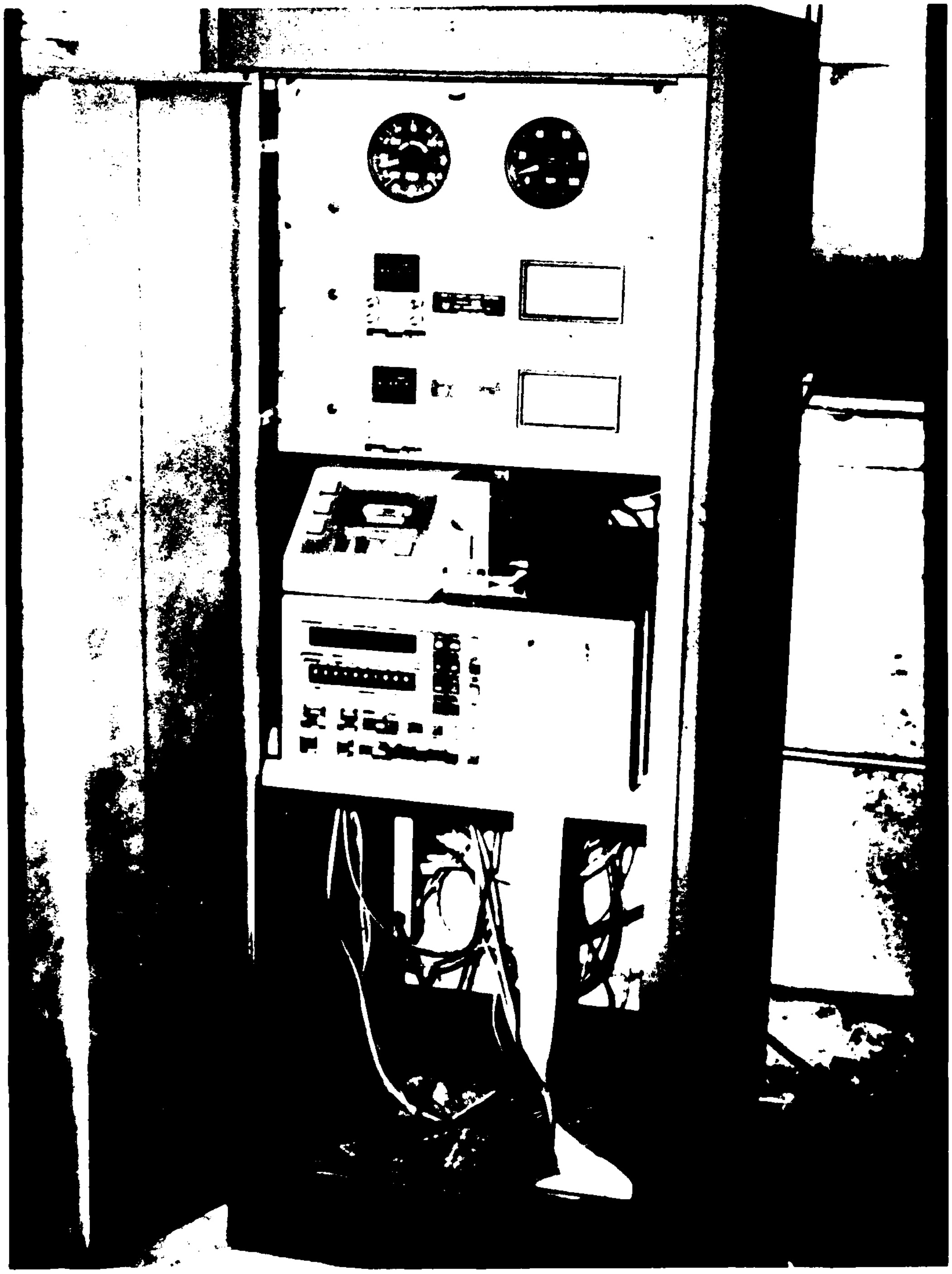

Figure 14. WECS instrument panel.

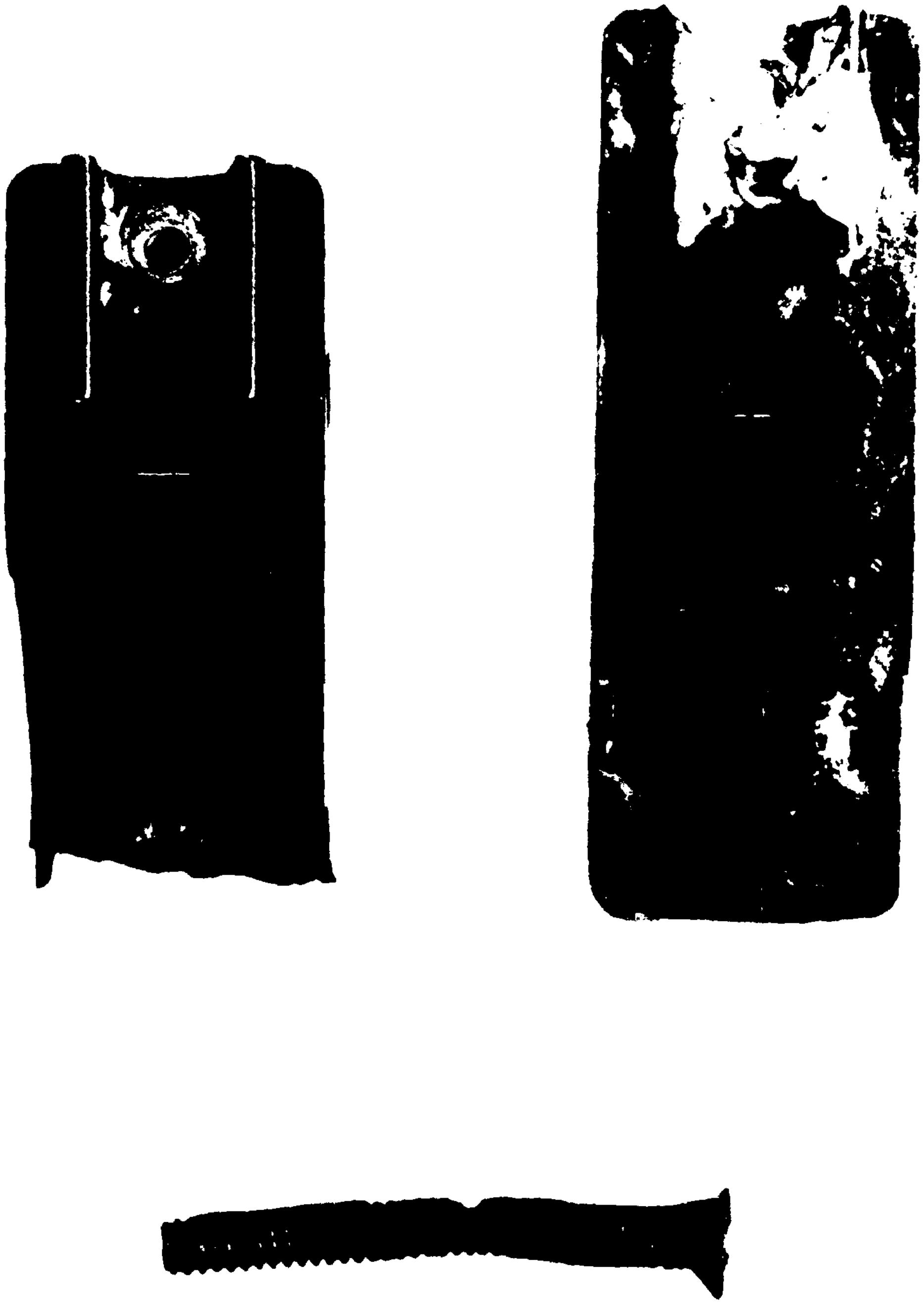

Figure 15. Corroded limit switches in the WECS.

Figure 16. Corroded steel tubing of the wind pressure switch.

Figure 17. Corroded steel guy wire end.

Figure 18. Loose control motor housing at the hub end.

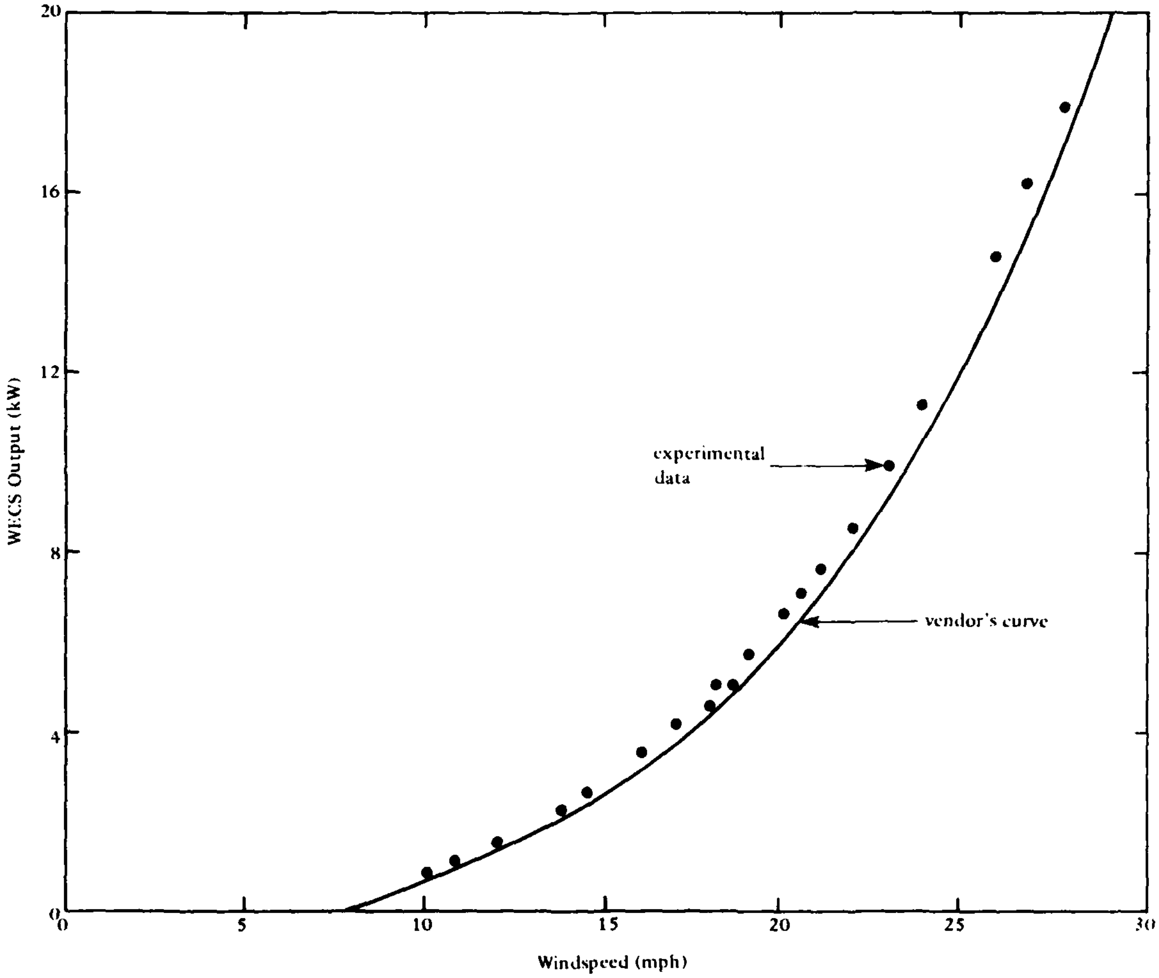

Figure 19. Measured performance curve for the 20-kW WECS. (Data points are averaged over 20-minute intervals.)

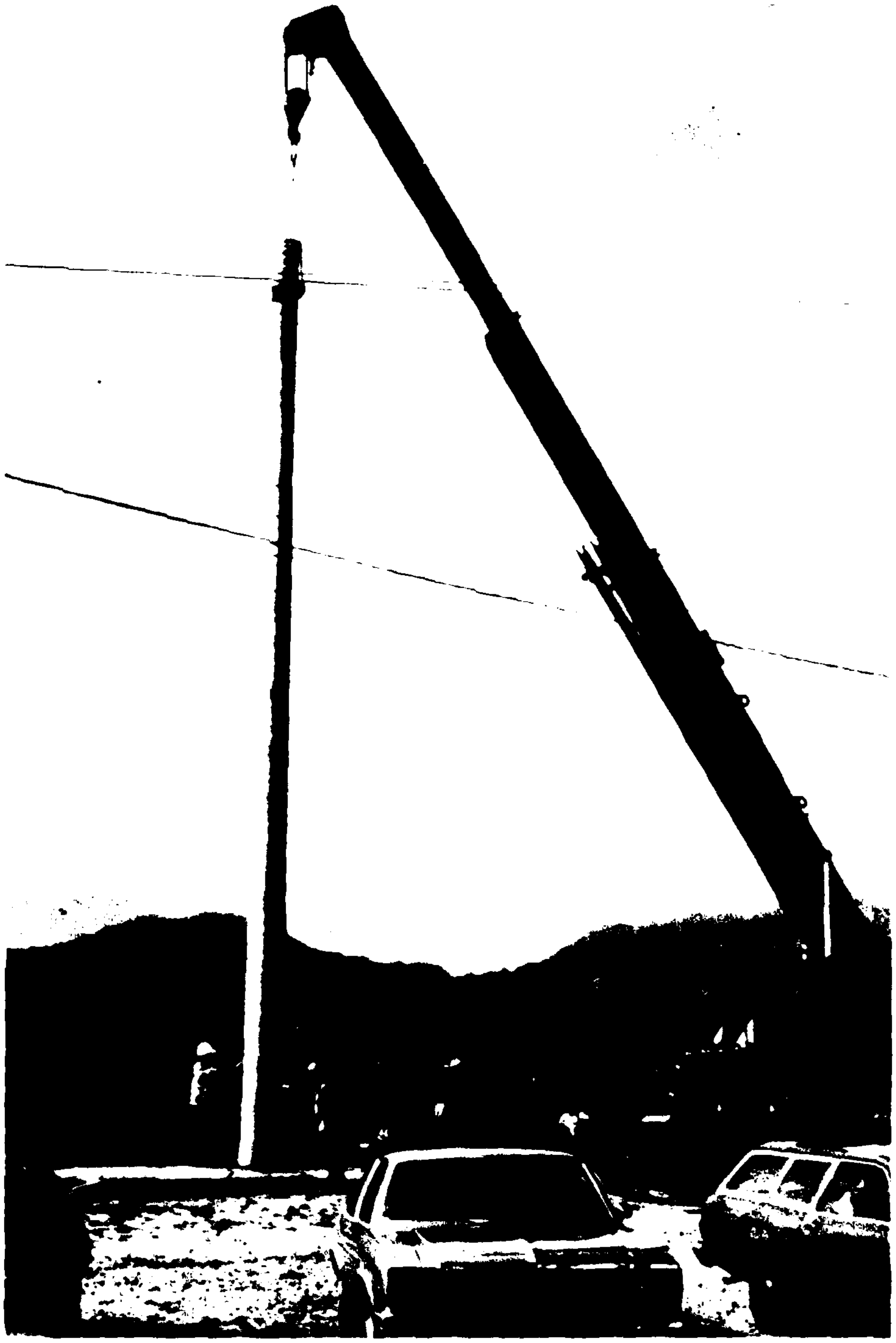

Figure 20. The WECS tower being installed using a crane.

Figure 21. Grouting of the tower in the foundation

Figure 22   The hub and blade assembly being worked on before its installation on the tower

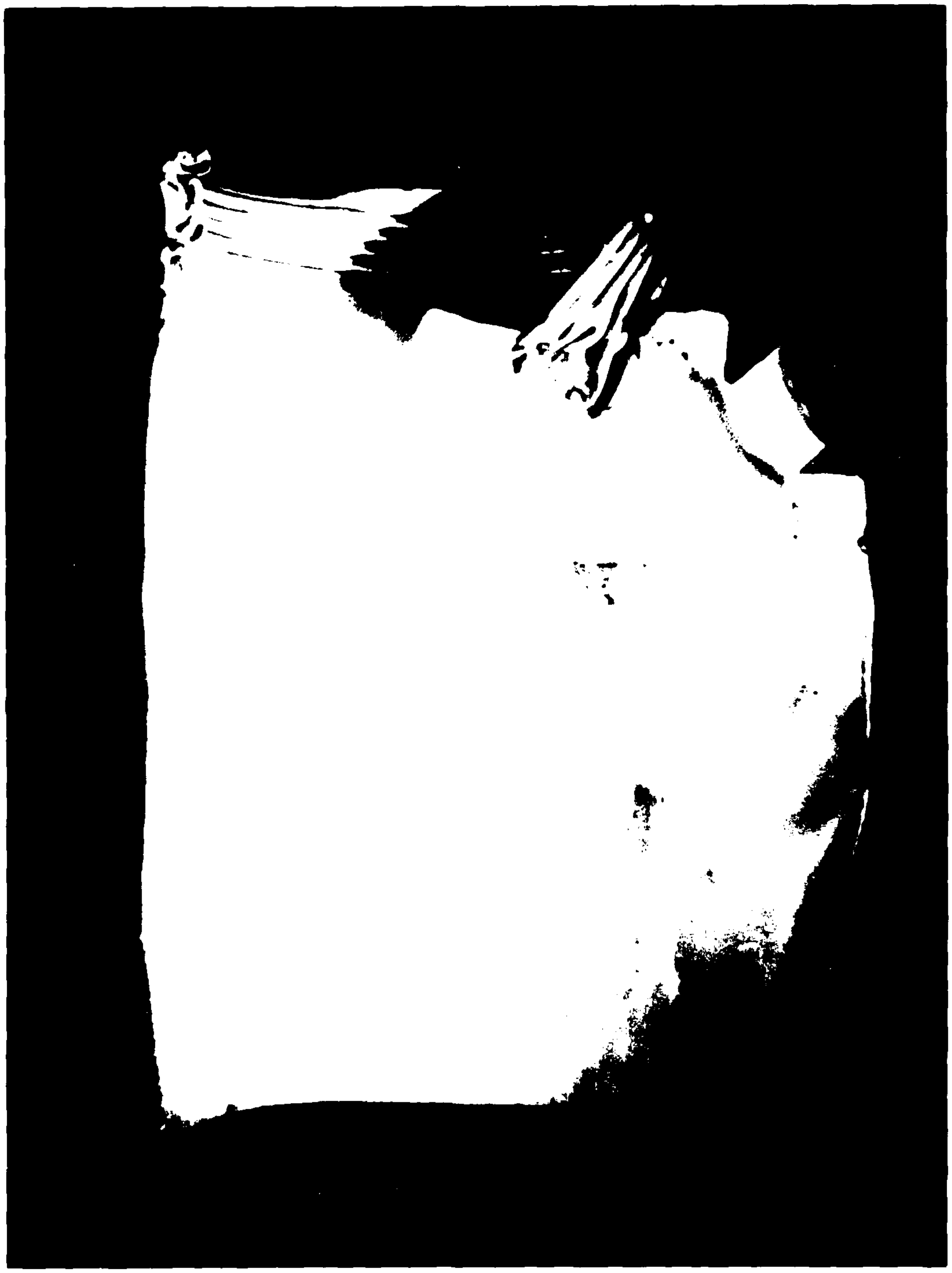

Figure 23. Sleeve fitting damaged during installation.

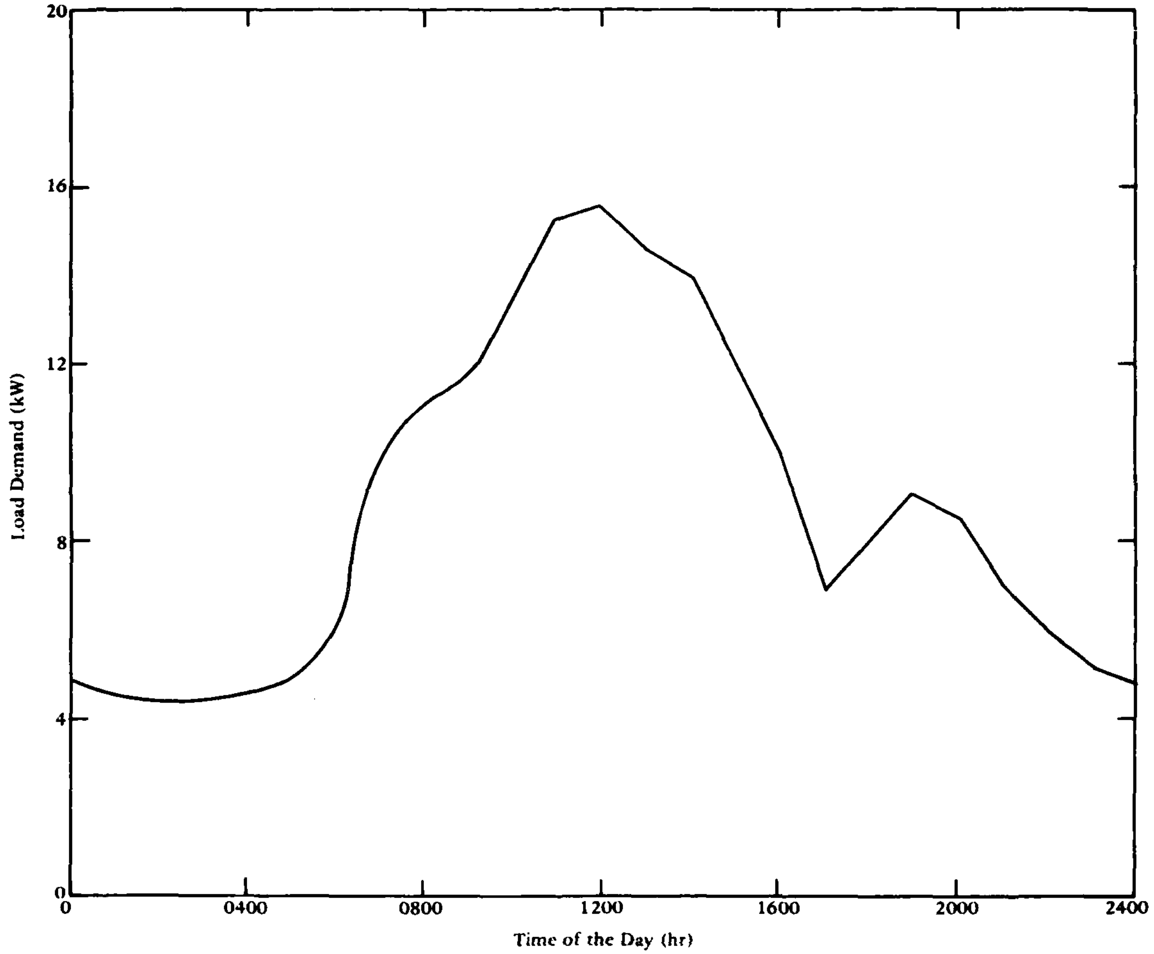

Figure 24. Diurnal load characteristics measured on 17 August 1979 at MCAS, Kaneohe Bay, Hawaii.

Appendix A

LINE-COMMUTATED SYNCHRONOUS INVERSION OF DC POWER

For simplicity, consider a single-phase AC line connected to a source of DC power through a system of thyristors arranged in a bridge arrangement as shown in Figure A-1. The source of DC power in Figure A-1 is the output of a wind turbine-driven DC generator or an alternator with its output rectified. Next, Figures A-2(a) and A-2(b) show alternative paths for current flow from the DC source to the AC line depending upon the polarity of the AC line voltage.

Further, the relative voltage and the wave form of the AC line and the DC source for the first path of power flow (Figure A-2(a)) is shown in Figure A-3 schematically. While Figure A-3 shows an arbitrary value of DC voltage, the actual magnitude can be any value from zero to the peak of the AC line. During the positive half cycle there are two distinct intervals, 1 and 2, where the DC source voltage is instantaneously more positive than the AC line voltage. Hence, current flows from the DC source to the line; thus, power flows to the line. During the negative half cycle of the AC line voltage, the current does not oppose the line voltage, and power flow is in the opposite direction, (i.e., from the AC line to the DC source).

The time intervals 1 and 2 have one significant difference. During interval 1, the difference between the AC and DC voltages is initially high and decreases to zero. This condition is useful when thyristors are employed as power switches because it automatically reduces the current in the thyristors to zero, thus making it commutate naturally. In interval 2 the reverse occurs, that is, the voltage differential is zero initially and increases with time until it attains a large value at the end of the inverval. For a thyristor to function properly during this interval, an independent or external means of commutating is generally required to switch it to the off state. For thyristors, the commutating circuitry can be complex, and for this reason the conversion period is generally limited to interval 1 and the inverter is called a line-commutated inverter.

The circuitry of Figure A-2(a) and the DC power waveform depicted in Figure A-3 provide line current of a single polarity and the power thus transferred to the AC line is DC. Hence, a circuitry of Figure A-2(b) is also needed for proper inversion of DC power from the wind generator. Figure A-4 shows the DC voltage and AC line waveform for a synchronous inverter technique based upon schematics of Figure A-2. The current flowing from the DC power source is truly AC and has the wave form given in Figure A-5. This discussion applies to single-phase inverters, the same principles can be extended to multiphase circuits.

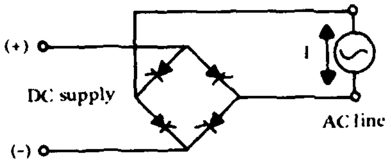

Figure A-1. Schematic of a synchronous inversion circuit.

(a) (b)

Figure A-2. Two paths of power flow from a wind-generated DC source to AC lines.

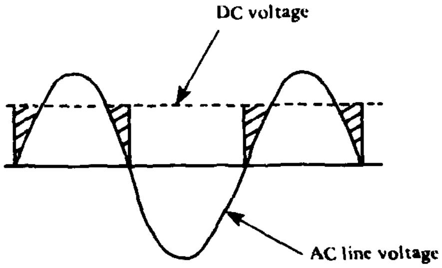

Figure A-3. A graphical description of DC source and AC line voltages.

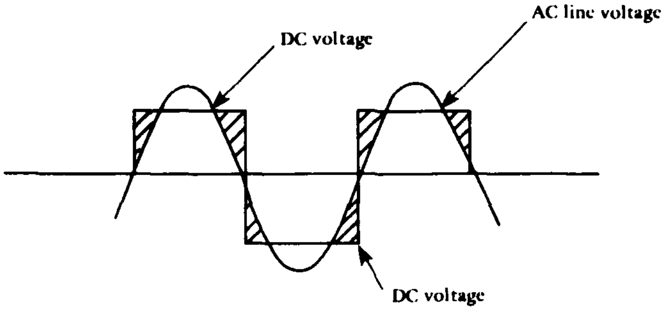

Figure A-4. A graphical description of synchronous inverter integration with the AC line.

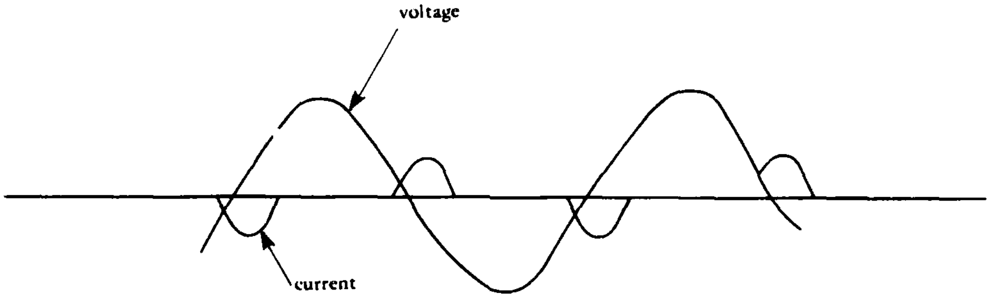

Figure A-5. Current and voltage profiles for the synchronous inversion method.

Appendix B

CONSTRUCTION PROCEDURES FOR INSTALLATION OF THE FOUNDATION FOR THE 20 kW WIND TURBINE

EXCAVATION AND INSTALLATION

1. Remove soil from excavation site to the dimensions and depths indicated on drawings.

2. Excavation site shall be shored sufficiently to prevent injury to persons working during backfilling and compaction processes.

3. Compact bottom of excavation to 95% of maximum density as specified by ASTM designation D-1557-70 method B, and measured by ASTM designation D-1556-64 (74).

4. Backfill excavation site with select base course to a depth of 15 inches deposited in layers not more than 3 inches in depth and each layer shall be properly moistened to within 2% below or above optimum moisture prior to compaction. Select base course shall be compacted to 100% of maximum density as determined by ASTM D-1577-70 method D, and measured by ASTM designation D-1556-64 (74).

5. Place the galvanized 16-gage multiplate pipe (10 feet in diameter and 12 feet long) in center of excavation as indicated on plan and adjust to proper elevation and plumb (see Figure B-1.)

6. Place the concrete pad (4-foot by 4-foot by 3-inches) in center of multiplate pipe.

7. Place the concrete pipe (2 feet in diameter and 4-feet long) in vertical position and center on concrete pad. Brace and shore as necessary to ensure that the 4-ft long concrete pipe does not move during placement of concrete into the forms and remains plumb and concentric with the 10-ft-diam pipe.

8. Install welded wire mesh 3 inches below surface of concrete. NOTE: Ensure 2-ft-diam pipe remains plumb and level.

9. Fill annulus to top of 10-ft-diam multiplate pipe with 3,000-psi minimum concrete, vibrated in place, finished to grade, and allowed to cure.

EARTHWORK

Scope

The work includes furnishing all labor, equipment, and materials, and performing all operations pertaining to excavation, trenching, filling, backfilling, and preparation of subgrade for all structures.

REQUIREMENTS

General

The work shall be based upon the following:

a. That the surfaces are as indicated on the drawings.

b. No pipes or other artificial obstructions, except those shown on the drawings of the area, will be encountered.

Protection of Existing Improvements and Utilities that are indicated on the plans or at locations made known by the Resident Officer in Charge of Construction (ROICC) or the utility representative, prior to excavation, shall be protected from damage during earthwork operations and if damaged, shall be repaired by the ROICC MCAS Kaneohe Bay, Hawaii. Any existing utilities that are now shown or the location of which has not been made known in sufficient time to avoid damage shall be repaired as directed by the ROICC.

Topsoil. Material from the excavation suitable for topsoil shall be deposited in piles separate from other excavated material. Piles of topsoil shall be located so that the material can be readily used for the finished surface grading and shall be protected and maintained until needed. When used for finished surface grading, topsoil shall be spread uniformly over the areas designated to receive it.

EARTHWORK FOR STRUCTURES

Excavations

The SITE shall be excavated to the dimensions and depths shown on the plans for the foundation. Excavations shall extend a sufficient distance from the footings to permit placing and removal of forms and inspection. Excavations carried below the depths specified shall be refilled to the proper grade with fill that shall be thoroughly compacted to the specified degree.

Filling and Backfilling

Backfilling against concrete structures shall be done only after the concrete has obtained a 7-day strength as specified, and has been inspected and approved for backfilling by the ROICC. All fill and backfill shall be free from vegetable matter and refuse, shall be deposited in layers not more than 6 inches in depth, and each layer shall be properly moistened to within 2% of optimum moisture prior to compaction. Filling and backfilling shall be brought to the lines and grades indicated, and shall be graded to drain water away from buildings and structures.

Hand Tampers

Areas inaccessible to wheeled rollers shall be compacted with hand tampers weighing at least 48.5 pounds with a face area not larger than ft^2.

Shoring and Sheeting

Excavations shall be shored and sheeted with members of sufficient size and arrangement to prevent injury to persons, damage to structures, injurious caving in, and erosion. Shoring, sheeting, and bracing shall be removed as the excavations are backfilled. Care shall be exercised to prevent injurious caving in during the removal of the shoring or sheeting.

Compaction

Compaction shall be not less than 90% (for cohesive) and 95% (for cohesionless material) of maximum density as determined by ASTM designation D-1557-70 and measured by ASTM designation D-1556-64 (74).

Test

Any tests required to determine maximum density (optimum moisture relationship), in-place field density and moistures, gradations, and other physical properties of the wind turbine facility foundation will be performed by and at the expense of the ROICC MCAS, Kaneohe Bay, Hawaii.

Appendix C

A CATALOGUE OF FIELD DATA FOR THE WECS

A complete listing of field data for the WECS demonstration at Kaneohe Bay is available from the Naval Civil Engineering Laboratory, Port Hueneme, California, 93043. For details contact the author at (805) 982-4207.

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CNO Code NOP-964, Washington DC; Code OP 987 Washington DC; Code OP-413 Wash, DC; Code OPNAV 09B24 (H); OP-098, Washington, DC; OP987J, Washington, DC
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NARF Code 100, Cherry Point, NC; Code 612, Jax, FL; Code 640, Pensacola FL
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NAVFACENGCOM - NORTH DIV. Code 04 Philadelphia, PA; Code 09P Philadelphia PA; Code 1028, RDT&ELO, Philadelphia PA; Code 111 Philadelphia, PA; Code 4012/AB (A. Bianchi) Philadelphia, PA; Library, Philadelphia, PA; ROICC, Contracts, Crane IN
NAVFACENGCOM - PAC DIV. (Kyi) Code 101, Pearl Harbor, HI; CODE 09P PEARL HARBOR HI; Code 04 Pearl Harbor HI; Code 11 Pearl Harbor HI; Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI; Library, Pearl Harbor, HI
NAVFACENGCOM - SOUTH DIV. Code 04, Charleston, SC; Code 11, Charleston, SC; Code 403, Gaddy, Charleston, SC; Code 90, RDT&ELO, Charleston SC; Library, Charleston, SC
NAVFACENGCOM - WEST DIV. AROICC, Contracts, Twentynine Palms CA; Code 04, San Bruno, CA; Code 04B San Bruno, CA
NAVFACENGCOM CONTRACTS Contracts, AROICC, Lemoore CA
NAVFACENGCOM - WEST DIV. Library, San Bruno, CA; O9P/20 San Bruno, CA; RDT&ELO Code 2011 San Bruno, CA
NAVFACENGCOM CONTRACTS AROICC, NAVSTA Brooklyn, NY; AROICC, Quantico, VA; Dir, Eng. Div., Exmouth, Australia; Eng Div dir, Southwest Pac, Manila, PI; OICC, Southwest Pac, Manila, PI; OICC-ROICC, NAS Oceana, Virginia Beach, VA; OICC/ROICC, Balboa Panama Canal; ROICC AF Guam; ROICC, Keflavik, Iceland; ROICC, NAS, Corpus Christi, TX; ROICC, Pacific, San Bruno CA; ROICC-OICC-SPA, Norfolk, VA
NAVHOSP PWD - Engr Div, Beaufort, SC
NAVMAG PWD - Engr Div, Guam; SCE, Subic Bay, R.P.
NAVOCEANSYSCEN Code 4473 Bayside Library, San Diego, CA; Code 4473B (Tech Lib) San Diego, CA; Code 523 (Hurley), San Diego, CA; Code 6700, San Diego, CA; Code 811 San Diego, CA
NAVORDMISTESTFAC PWD - Engr Dir, White Sands, NM
NAVORDSTA PWO, Louisville KY
NAVPETOFF Code 30, Alexandria VA
NAVPETRES Director, Washington DC
NAVPHIBASE CO, ACB 2 Norfolk, VA; Code S3T, Norfolk VA
NAVFACENGCOM CONTRACTS OICC/ROICC, Norfolk, VA
NAVPHIBASE SCE Coronado, SD,CA
NAVREGMEDCEN Code 3041, Memphis, Millington TN; PWD - Engr Div, Camp Lejeune, NC; PWO, Camp Lejeune, NC; SCE, Newport, RI
NAVREGMEDCEN PWO, Okinawa, Japan
NAVREGMEDCEN SCE; SCE San Diego, CA; SCE, Camp Pendleton CA; SCE, Guam; SCE, Oakland CA

NAVREGMEDCEN SCE, Yokosuka, Japan
NAVSCOLCECOFF C35 Port Hueneme, CA
NAVSCSOL PWO, Athens GA
NAVSEASYSCOM Code 0325, Program Mgr, Washington, DC; Code PMS 395 A 3, Washington, DC; SEA 04E (L Kess) Washington, DC
NAVSECGRUACT PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa
NAVSHIPYD Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 400, Puget Sound; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 453 (Util. Supr), Vallejo CA; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth, VA; PWD (Code 450-HD) Portsmouth, VA; PWD (Code 453-HD) SHPO 03, Portsmouth, VA; PWO, Bremerton, WA; PWO, Mare Is.; PWO, Puget Sound; Tech Library, Vallejo, CA
NAVSTA Adak, AK; CO, Brooklyn NY; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Dir Engr Div, PWD, Mayport FL; Dir Mech Engr 37WC93 Norfolk, VA; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Panama Canal; PWD - Engr Dept, Adak, AK; PWD - Engr Div, Midway Is.; PWO, Keflavik Iceland; PWO, Mayport FL; SCE, Guam; SCE, Pearl Harbor HI; SCE, San Diego CA; Utilities Engr Off. Rota Spain
NAVSUPPACT CO, Naples, Italy; PWO Naples Italy
NAVSUPPFAC PWD - Maint. Control Div, Thurmont, MD
NAVSUPPO PWO, La Maddalena, Italy
NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD
NAVTECHTRACEN SCE, Pensacola FL
NAVTELCOMMCOM Code 53, Washington, DC
NAVWPNCEN Code 24 (Dir Safe & Sec) China Lake, CA; Code 2636 China Lake; Code 266, China Lake, CA; Code 26605 China Lake CA; Code 3803 China Lake, CA; Code 623 China Lake CA; PWO (Code 266) China Lake, CA; ROICC (Code 702), China Lake CA
NAVWPNEVALFAC Technical Library, Albuquerque NM
NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092A, Seal Beach, CA
NAVWPNSTA PW Office Yorktown, VA
NAVWPNSTA PWD - Maint. Control Div., Concord, CA; PWD - Supr Gen Engr, Seal Beach, CA; PWO, Charleston, SC; PWO, Seal Beach CA
NAVWPNSUPPCEN Code 09 Crane IN
NCTC Const. Elec. School, Port Hueneme, CA
NCBC Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 430 (PW Engrng) Gulfport, MS; Code 470.2, Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme, CA; PWO, Davisville RI; PWO, Gulfport, MS
NCR 20, Code R70
NMCB FIVE, Operations Dept; THREE, Operations Off.
NOAA (Dr. T. Mc Guinness) Rockville, MD; Library Rockville, MD
NRL Code 5800 Washington, DC
NSC Code 54.1 Norfolk, VA
NSD SCE, Subic Bay, R.P.
NSWSES Code 0150 Port Hueneme, CA
NUSC Code 131 New London, CT; Code 4111 (R B MacDonald) New London CT; Code EA123 (R.S. Munn), New London CT; Code SB 331 (Brown), Newport RI
OFFICE SECRETARY OF DEFENSE OASD (MRA&L) Dir. of Energy, Pentagon, Washington, DC
ONR Code 221, Arlington VA; Code 700F Arlington VA
PACMISRANFAC HI Area Bkg Sands, PWO Kekaha, Kauai, HI
PERRY OCEAN ENG R. Pellen, Riviera Beach, FL
PHIBCB 1 P&E, San Diego, CA
PMTC Code 3331 (S. Opatowsky) Point Mugu, CA; Pat. Counsel, Point Mugu CA
PWC ACE Office Norfolk, VA; CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; CO, Pearl Harbor HI; Code 10, Great Lakes, IL; Code 105 Oakland, CA; Code 110, Great Lakes, IL; Code 110, Oakland, CA; Code 120, Oakland CA; Library, Code 120C, San Diego, CA; Code 154 (Library), Great Lakes, IL; Code 200, Great Lakes IL; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 424, Norfolk, VA; Code 500 Norfolk, VA; Code 505A Oakland, CA; Code 600, Great Lakes, IL; Code 610, San Diego Ca; Code 700, Great Lakes, IL; Library, Guam; Library, Norfolk, VA; Library, Pearl Harbor, HI; Library, Oakland, CA; Library, Pensacola, FL; Library, Subic Bay, R.P.; Util Dept (R Pascua) Pearl Harbor, HI; Library, Yokosuka, JA
SPCC PWO (Code 120) Mechanicsburg PA
SUPANX PWO, Williamsburg VA
TVA Smelser, Knoxville, Tenn.; Solar Group, Arnold, Knoxville, TN
U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)
USAF REGIONAL HOSPITAL Fairchild AFB, WA
USCG (Smith), Washington, DC; G-DMT-3/54 (D Scribner) Washington DC; G-MMT-4/82 (J Spencer)

USCG R&D CENTER D. Motherway, Groton CT
USDA Forest Service Reg 3 (R. Brown) Albuquerque, NM; Forest Service, San Dimas, CA
USNA Ch. Mech. Engr. Dept Annapolis MD; ENGRNG Div, PWD, Annapolis MD; Energy-Environ Study Grp, Annapolis, MD; Environ. Prot. R&D Prog. (J. Williams), Annapolis MD; Mech. Engr. Dept. (C. Wu), Annapolis MD; USNA Sys Eng Dept, Annapolis, MD
USS FULTON WPNS Rep. Offr (W-3) New York, NY
ARIZONA Kroelinger Tempe, AZ; State Energy Programs Off., Phoenix AZ
AUBURN UNIV. Bldg Sci Dept, Lechner, Auburn, AL
BATTELLE PNW Labs (R Barchet) Richland WA
BERKELEY PW Engr Div, Harrison, Berkeley, CA
BONNEVILLE POWER ADMIN Portland OR (Energy Consrv. Off., D. Davey)
BROOKHAVEN NATL LAB M. Steinberg, Upton NY
CALIFORNIA STATE UNIVERSITY LONG BEACH, CA (CHELAPATI)
CORNELL UNIVERSITY Ithaca NY (Serials Dept, Engr Lib.)
DAMES & MOORE LIBRARY LOS ANGELES, CA
DRURY COLLEGE Physics Dept, Springfield, MO
FLORIDA ATLANTIC UNIVERSITY Boca Raton, FL (McAllister)
FOREST INST. FOR OCEAN & MOUNTAIN Carson City NV (Studies - Library)
GEORGIA INSTITUTE OF TECHNOLOGY (LT R. Johnson) Atlanta, GA; Col. Arch, Benton, Atlanta, GA
HARVARD UNIV. Dept. of Architecture, Dr. Kim, Cambridge, MA
HAWAII STATE DEPT OF PLAN. & ECON DEV. Honolulu HI (Tech Info Ctr)
IOWA STATE UNIVERSITY Dept. Arch, McKrown, Ames, IA
WOODS HOLE OCEANOGRAPHIC INST. Woods Hole MA (Winget)
KEENE STATE COLLEGE Keene NH (Cunningham)
LEHIGH UNIVERSITY BETHLEHEM, PA (MARINE GEOTECHNICAL LAB., RICHARDS); Bethlehem PA (Linderman Lib. No.30, Flecksteiner)
LOUISIANA DIV NATURAL RESOURCES & ENERGY Div Of R&D, Baton Rouge, LA
MAINE OFFICE OF ENERGY RESOURCES Augusta, ME
MISSOURI ENERGY AGENCY Jefferson City MO
MIT Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.); Cambridge, MA (Harleman)
MONTANA ENERGY OFFICE Anderson, Helena, MT
NATURAL ENERGY LAB Library, Honolulu, HI
NEW HAMPSHIRE Concord NH (Governor's Council on Energy)
NEW MEXICO SOLAR ENERGY INST. Dr. Zwibel Las Cruces NM
NY CITY COMMUNITY COLLEGE BROOKLYN, NY (LIBRARY)
NYS ENERGY OFFICE Library, Albany NY
PENNSYLVANIA STATE UNIVERSITY STATE COLLEGE, PA (SNYDER)
POLLUTION ABATEMENT ASSOC. Graham
PURDUE UNIVERSITY Lafayette, IN (CE Engr. Lib)
SCRIPPS INSTITUTE OF OCEANOGRAPHY LA JOLLA, CA (ADAMS)
SEATTLE U Prof Schwaegler Seattle WA
SOUTHWEST RSCH INST King, San Antonio, TX
SRI INTL Phillips, Chem Engr Lab, Menlo Park, CA
STATE UNIV. OF NEW YORK Fort Schuyler, NY (Longobardi)
STATE UNIV. OF NY AT BUFFALO School of Medicine, Buffalo, NY
TEXAS A&M UNIVERSITY W.B. Ledbetter College Station, TX
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