TEST STATUS AND EXPERIENCE WITH THE 7.5 MEGAWATT MOD-2 WIND TURBINE CLUSTER

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ABSTRACT

On May 29, 1981, a ceremony was held to dedicate the 7.5 megawatt MOD-2 Wind Turbine Cluster located at Goodnoe Hills, near Goldendale, Washington. This paper presents a description of the development of that cluster, including site preparation and construction activities, preliminary test results and current status and future plans for the facility.

MOD-2 SYSTEM DESCRIPTION

MOD-2 Program Profile

The MOD-2 is a 91 meter (300 foot) diameter, 2.5 megawatt wind turbine system developed by Boeing Engineering and Construction Company (BEC) for the Department of Energy under direction of the NASA Lewis Research Center. The program started in August of 1977, first rotation occurred in November of 1980, and the first three units were completed by May of 1981. The basic objective was to design, fabricate, install, checkout, and deliver large megawatt-sized wind turbines which would be economically competitive with conventional power generating equipment operating in utility networks. The DOE-funded program is for four units of which three units have been installed as a cluster near Goldendale, Washington, and the fourth unit is being installed near Medicine Bow, Wyoming. The major milestones, as shown in Table 1, provide a chronology of program development.

The Goldendale Installation

The three-unit installation at the Goldendale (Goodnoe Hills) site overlooks the Columbia River in a location well suited for capturing the prevailing westerly winds. This site has been designated as a national wind turbine test facility and will serve as a test bed for evaluating cluster arrangement and operations as well as for individual machine performance optimization, product improvement, and maintenance program development.

The MOD-2 Machine

The MOD-2 program was initiated with several DOE/NASA specified ground rules which laid the framework for developing a new generation wind turbine suitable for commercial production and installation. The primary requirement was to provide a viable alternative to conventional power generation systems. The design optimization and economic evaluation conducted during these initial program phases resulted in the configuration shown in Figure 1.

Studies of various rotor configurations led to the selection of a steel, upwind-oriented rotor with movable tip sections for controlling rotor speed and power output. Upwind orientation with positive, hydraulic yaw control is employed to minimize tower shadowing effects, rotor fatigue and noise, and to maximize energy capture by accurately controlling nacelle heading. Rotor weight, cost and complexity are reduced significantly by controlling the pitch angle of the outer one-third of each rotor blade rather than employing full span control (see Figure 2). The pitch control system hydraulic elements are physically located on the rotating low speed shaft and in the mid-blade near the tip joint, thus eliminating hydraulic slip joints and increasing system reliability. The rotor hub incorporates elastomeric radial bearings which allow the rotor to teeter within a range of ±6 degrees. This feature significantly reduces fatigue loads thus permitting use of lighter, lower cost structure. The teetered hub arrangement is shown in Figure 3.

Unique aspects of the MOD-2 drive train include a "soft" quill shaft integral to the low speed shaft assembly, and an epicyclic planetary gearbox, which is notable for its compact size and maintainability features. The alloy steel quill shaft is configured with a torsional stiffness designed to dampen rotor torque fluctuations. The drive train arrangement is shown in Figure 4.

The wind turbine tower is a soft, monocoque shell structure. This configuration was selected because of its lower weight and cost factors, minimum wind blockage, and its capability to withstand the two-per-revolution bending loads induced by the rotor motion.

The electronic control system provides all functions necessary for fully automatic, unattended operation as well as continuous system monitoring and start-up/shutdown control from a remote terminal. Control and monitoring functions are performed by a single micro-processor controller located within the nacelle. Rotor tip pitch angles are controlled by the microprocessor through a closed loop electro-hydraulic servo system capable of driving the blade tips at a variable rate of up to 15 degrees/second. During operation the microprocessor integrates sensed power, RPM and collective pitch angle for pitch control processing and maintains 1) a nominal blade pitch angle during below-rated operation or 2) a constant power output level when operating at or above rated wind speeds. The microprocessor also monitors wind sensor outputs for start-up determination and to determine yaw error and initiate yaw correction.

SITE ACTIVATION AND TESTS

In October, 1979, the DOE/NASA selected the Bonneville Power Administration (BPA) to be operator of the first three machines. The BPA had proposed a site near Goldendale, Washington. The site selection enabled the detailed site activation planning to be completed and the initiation of site surveys. One of the first factors considered was the arrangement and positioning of the three units considering the terrain and the prevailing winds. Once the location of each of the machines was defined, borings were made to verify the suitability of the baseline tower foundation designed from the soil criteria of the contract statement of work. The data from these borings resulted in revision of the tower foundation from a spread foundation to use of foundation rock anchors.

In early 1980, BOECON, the construction subsidiary of Boeing Engineering and Construction, moved an office to Goldendale and began preparatory work to set up the construction site. Actual site activities started in March, 1980 and included excavations, forms, embedments, and pouring of concrete for all foundations.

Completion of the tower foundation was accomplished with a pour of 400 cubic yards of concrete in an octagonal underground pad. The 72 installed anchor bolts extend 8.8 meters (29 feet) below the base of the concrete foundation into solid rock. The four tower base sections were bolted to the buried foundation and welded together along field splices. The remainder of the tower was then erected by vertically stacking each of the tower sections and welding it to the lower tower section along field splices.

Site electrical installations installed at ground level for each machine included switchgear, transformer, and a grounding grid. Electrical power panels were installed inside the tower bases and power and signal wiring were connected from the tower base and up the raceway to the yaw slip rings at the top of the tower in preparation for installation of the nacelle on top of the tower. Site nacelle assembly operations included installing the gearbox, generator, lube module, and roof-mounted equipment. Each nacelle was then subjected to an integration test at ground level to verify proper operation of all significant functions before committing it to installation at the 61 meter (200 foot) elevation. The assembly and erection flow and the transition to the testing sequence are shown in Figure 5.

Integration testing of each nacelle included 1) continuity testing of all of the electrical wiring, 2) control system tests to subject the nacelle control unit (NCU) and associated sensors to operational and failure mode scenarios, and 3) operational tests of the gearbox, lubrication system, pitch system, and the yaw system. After completion of the nacelle integration test, each nacelle was installed on its respective tower using a gin pole.

The gin pole used for the MOD-2 cluster is a 73 meter (240 foot) truss boom with 90,000 kg (100 ton) capacity, secured and manipulated by steel cables. The gin pole itself was first load tested prior to lifting the nacelle. Recertification of the gin pole by load testing was accomplished after reassembly at each of the other two wind turbine sites. Use of the gin pole at the MOD-2 cluster has been a cost-effective way of accomplishing the installation requirements of the site (versus the higher cost of renting a ringer crane for the extended period required).

After assembly, each rotor was also integration tested prior to installation on the nacelle. Tests conducted include electrical wiring continuity, operation and setting of the pitch system blade position potentiometers, tests of the ice detector and part of the crack detector system, operation of the pitch system actuators and hydraulic system, and verification of all of the engineering instrumentation system sensors and wiring. After successful completion of the rotor integration test, each rotor was installed on its nacelle using the gin pole. Figure 6 shows a rotor lift, and Figure 7 shows the completed wind turbine.

Pre-rotation activities included drive train alignments (possible only after the weight of the rotor is installed on the nacelle) and rotor strain gage calibrations. Integration testing of the completed machine was then accomplished. This test series included some of the same tests run on the ground, but with a complete system and all of the operational sensors installed. End-to-end testing of the engineering instrumentation system from the transducers through to the NASA Mobile Data System (MDS) was also accomplished. A final pre-rotation confidence test was then run prior to committing the machine to wind-powered tests.

Wind-powered tests are comprised of checkout and acceptance tests. On WTS 1, a series of qualification tests was also run to satisfy those system qualification test requirements which could only be accomplished during wind-powered tests. After wind-powered operation was verified during the checkout test, acceptance tests were run to demonstrate that the machine is fully operable and ready for acceptance. Included in these tests were wind-powered operation for 100 hours, operation through various operating regimes, specified numbers of start/stop cycles, demonstration of fail safe system operations, and operability demonstrations of all WTS systems.

As of June 1, 1981, all three machines had completed system checkout, WTS 1 and WTS 2 had completed acceptance test requirements, and WTS 3 had completed 50% of acceptance test requirements.

CURRENT SITE STATUS

Figure 8 shows how the MOD-2 cluster is configured. The spacings between the three wind turbines are approximately 5, 7 and 10-rotor diameters. These spacings enable evaluation of wake effect of one of the turbines on a downwind turbine. The prevailing wind at Goodnoe Hills is from the west, and relatively common wind conditions result in test conditions enabling data on wake effects over 7 and 10-rotor diameters. Somewhat fewer but adequate opportunities are available for testing at 5-rotor diameters. The location of the two met towers was optimized to assure that at least one, and usually both, of the met towers receive unperturbed wind during required test conditions.

Multiple operation of all three machines was first accomplished in May, 1981, initiating MOD-2 cluster operation. Both of the met towers and the BPA substation had been installed and checked out earlier and were operational. Construction equipment had been removed and the gin pole disassembled and stored on site.

The nature of the testing of the MOD-2 cluster, including aerodynamic wake effects of multiple wind turbines, requires simultaneous recording of instrumentation on all three machines as well as met tower data. The MOD-2 intersite data system was designed, installed and checked out to accomplish this objective. The data collection center for this system is housed in a 3 by 4.5 meter (10 by 15 foot) building adjacent to WTS 2. Operation of the data center was initiated in April, 1981, and the capability is provided to record and display data from the three wind turbines and the two met towers. In addition to recording analog tapes for data analysis, the data center also houses two computers for formating data to be sent to BPA and the Battelle Northwest Laboratory. Strip chart recorders, a line printer, and a CRT present real time data displays to enable test control. A patch panel is included to permit data access to organizations requesting test data. To facility post-test processing, all of the data is recorded on a single tape recorder with a common time base.

Engineering data is collected on each wind turbine using the Engineering Instrumentation System (EIS) designed and installed as part of the NASA data system used on all NASA large wind turbines. This system employs one rotating FM multiplexer mounted on the low speed shaft and one FM multiplexer mounted on the nacelle wall to multiplex a total of 64 channels at any one time. A total of 80 transducers are available on each machine and up to 40 may be selected for cluster tests. During qualification, checkout testing, and acceptance testing of the individual wind turbines, the NASA-provided Mobile Data System (MDS) was used for data recording and display. Having substantially completed these activities, the MDS has been released for other NASA programs.

Met data are also transmitted from the two met towers to the data center. Transmission of all of the data to the data center is accomplished using fiber optics to preclude the possibility of electrical interference from the adjacent buried power output cables which are located a few inches from the FM (analog) data cables (see Figure 8 for approximate cable routing).

PRELIMINARY TEST RESULTS

Table 2 summarizes operation of the three wind turbines to date. During the majority of the checkout and acceptance testing period of each wind turbine, the MDS as well as most of test team, was required for testing. One hundred hours of operating time are required for completion of the test requirements for each machine. As of June 1, 1981, the hundred-hour requirements had been met for WTS 1 and 2, and test emphasis was shifted to WTS 3.

Substantial early wind power testing was accomplished on WTS 1 prior to attempting to synchronize with the utility. A lesser period of presynchronization test time was accomplished on WTS 2. Satisfaction of the presync test requirements during testing on WTS 1 and WTS 2 has resulted in relatively short periods of nonsync operation on WTS 3.

During normal automatic operations, synchronization with the utility is usually accomplished in less than two minutes after reaching rated speed. Power generated has averaged between 1000 kw and 2000 kw during testing, although all three machines have operated over the power spectrum from 100 kw to above rated (2500 kw). In late May, 1981, all three machines were simultaneously operated on-line with no problems.

Test data obtained on all three machines have been used to verify the MOD-2 design, satisfy checkout and most of the acceptance test requirements for the cluster, and make suitable adjustments to subsystems to optimize the operation of each machine. Noteworthy are the control system improvements that have resulted in significantly improving power quality (assuring that power output is relatively insensitive to wind gusts) and significantly reducing tower and rotor loads by use of a notch filter and optimizing the gain setting.

Preliminary test data on power output versus wind speed is shown in Figure 9. The data points are relatively well grouped showing consistent data over several days of operation. The data is shifted to the right compared to the design curve, but optimization of power output versus wind speed (controlled blade position versus wind speed) has not yet been accomplished. Detailed analysis must yet be accomplished to verify the preliminary data.

FUTURE PLANS/ACTIVITY

Continuing activities at the Goldendale site will include completion of acceptance test requirements on WTS 3 and formal NASA acceptance of all three wind turbines. These actions will be accomplished in concert with BPA assumption of normal operation and maintenance functions, and commencement of a two-year test and evaluation program. This two-year program will be conducted as a joint government/industry team effort with specific activities planned and controlled by a working group chaired by NASA LeRC and comprised of BPA, NASA, BEC and Battelle representatives. The scope of effort under this program will encompass special tests (noise, TV interference, aerodynamic wake effects, utility interface); hardware product improvements; performance optimization and improvements; system availability and maintainability evaluation; implementation of performance, maintenance, and reliability data collection systems; refinements/ improvements to operating and maintenance procedures; and development of a cost-effective supply support program.

The ultimate goal is to achieve maximum commercial viability of the MOD-2 wind turbine through knowledge and experience gained from the Goldendale installation.

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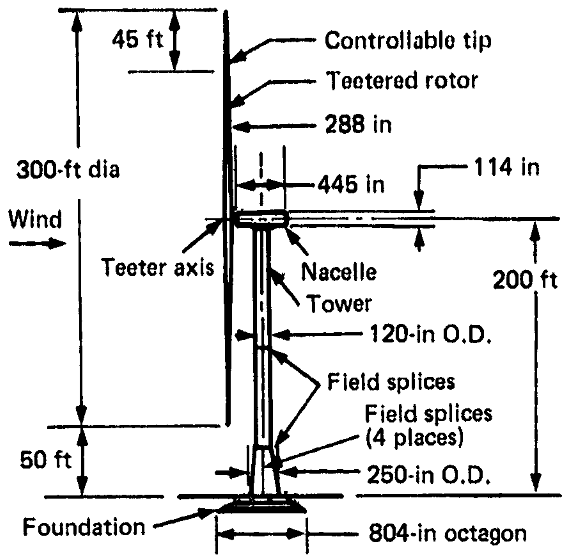
TABLE 1. PROGRAM MILESTONES

• Go-ahead	August 1977
• Conceptual design complete	July 1978
• Preliminary design complete	November 1978
• Detail design complete	May 1979
• Fabrication start	June 1979
• Site selection for first three units	October 1979
• First unit	
• Start site preparation	March 1980
• Site performance complete	June 1980
• Component fabrication complete	July 1980
• Tower installation complete	August 1980
• Nacelle integration and tests complete	August 1980
• Installation complete	October 1980
• Initial rotation	November 1980
• Synchronized power production	December 1980
• Second unit	
• Installation complete	March 1981
• Third unit	
• Installation complete	May 1981
• Fourth unit	
• Medicine Bow site selected	April 1981
• Installation complete	December 1981

TABLE 2. MOD-2 OPERATIONS SUMMARY

	Operating time (hours)	Time On-Line (hours)	Power Generated (KWH)
WTS No.1	107	84	99,400
WTS No.2	122	112	138,000
WTS No.3	19	18	24,000
Total	248	214	261,400



Rated power	2,500 kW
Rotor diameter	91.4m (300 ft)
Rotor type	Teetered - tip control
Rotor orientation	Upwind
Rotor airfoil	NACA 230XX
Rated wind @ hub	12.2 m/s (27.5 mph)
Cut-off wind speed @ hub	
Goldendale units	20.1 m/s (45 mph)
Medicine Bow unit	26.8 m/s (60 mph)
Rotor tip speed	83.8 m/s (275 ft/sec)
Rotor rpm	17.5
Generator rpm	1,800
Generator type	Synchronous
Gearbox	Compact planetary gear
Hub height	61m (200 ft)
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor

FIGURE 1. MOD-2 CONFIGURATION FEATURES AND CHARACTERISTICS

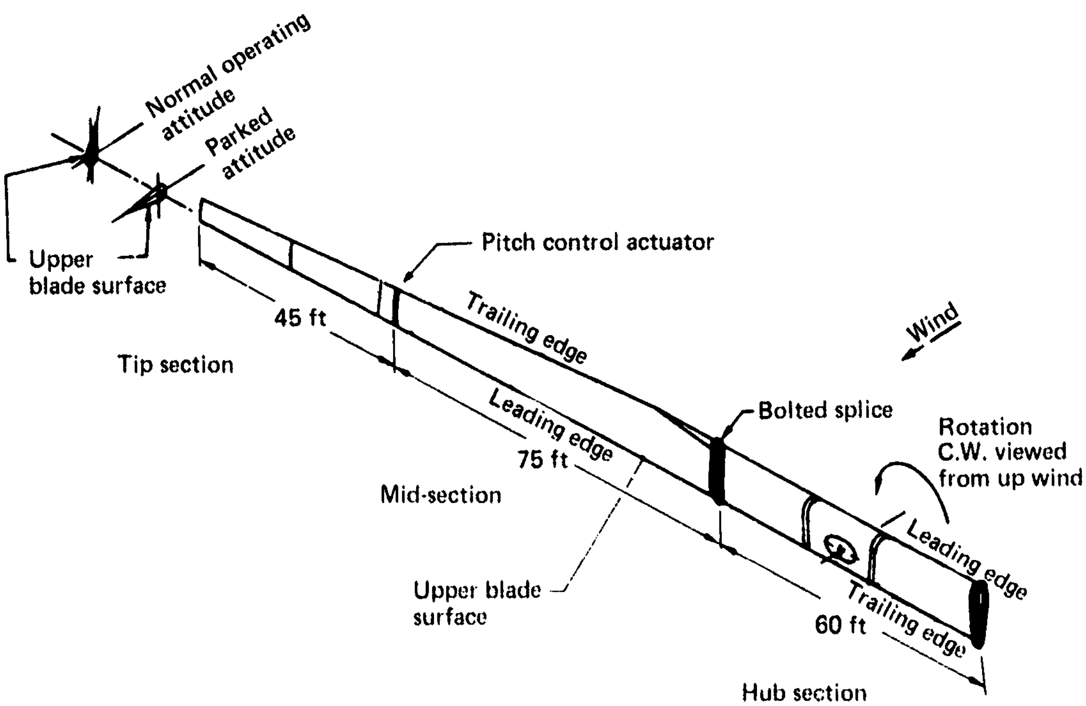


FIGURE 2. ROTOR BLADE CONFIGURATION

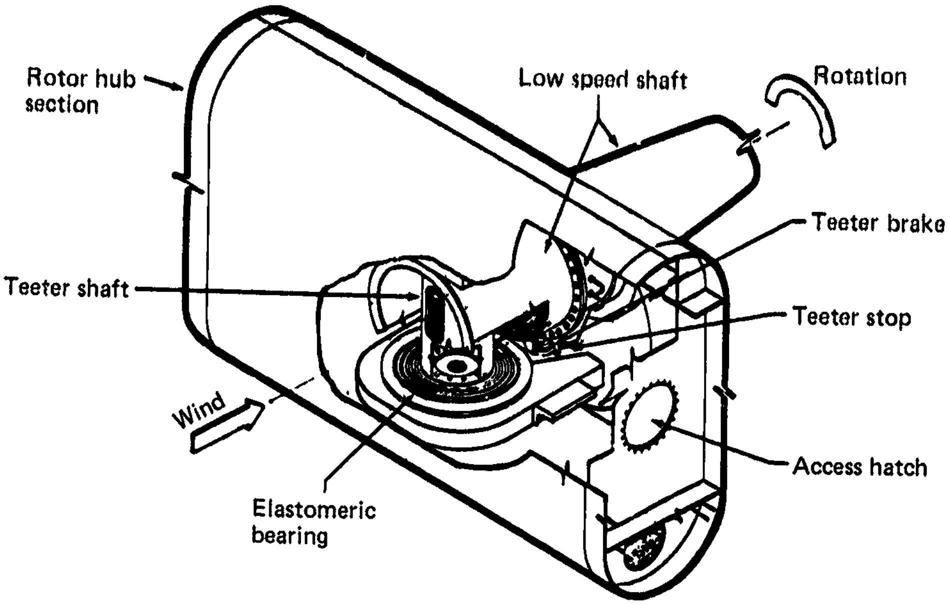


FIGURE 3. ROTOR HUB CONFIGURATION

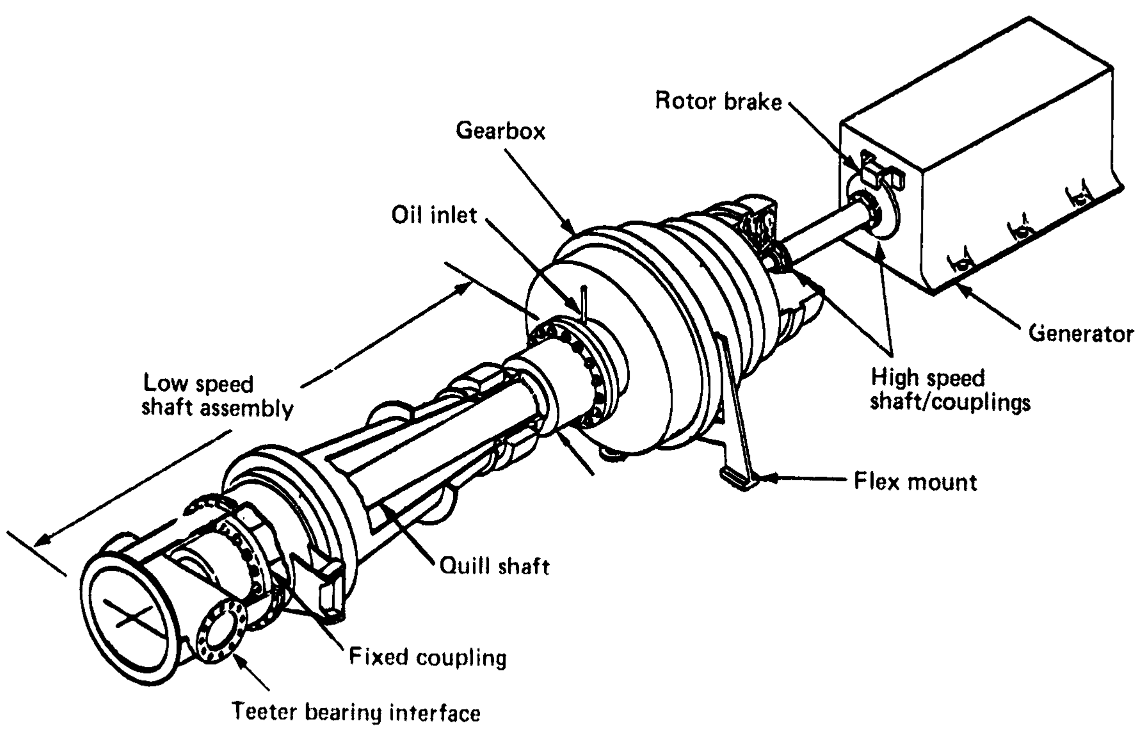


FIGURE 4. DRIVE TRAIN ARRANGEMENT

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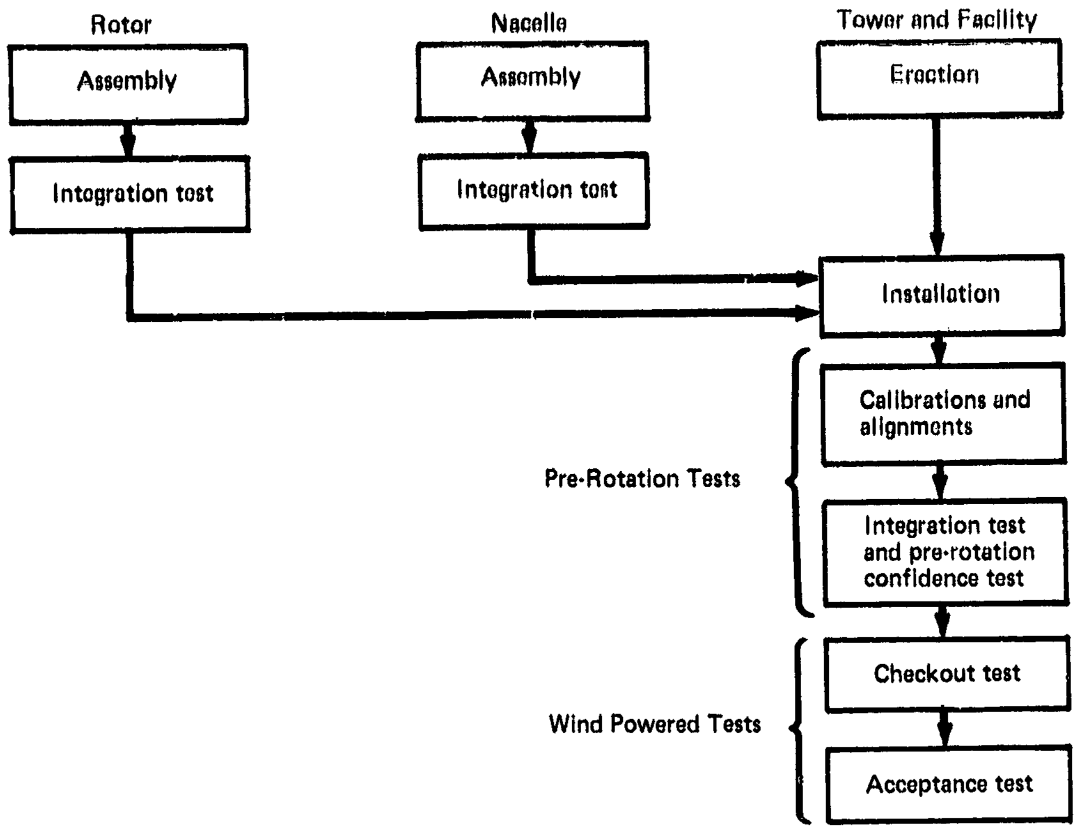

FIGURE 5. MOD-2 WTS SYSTEM TEST FLOW

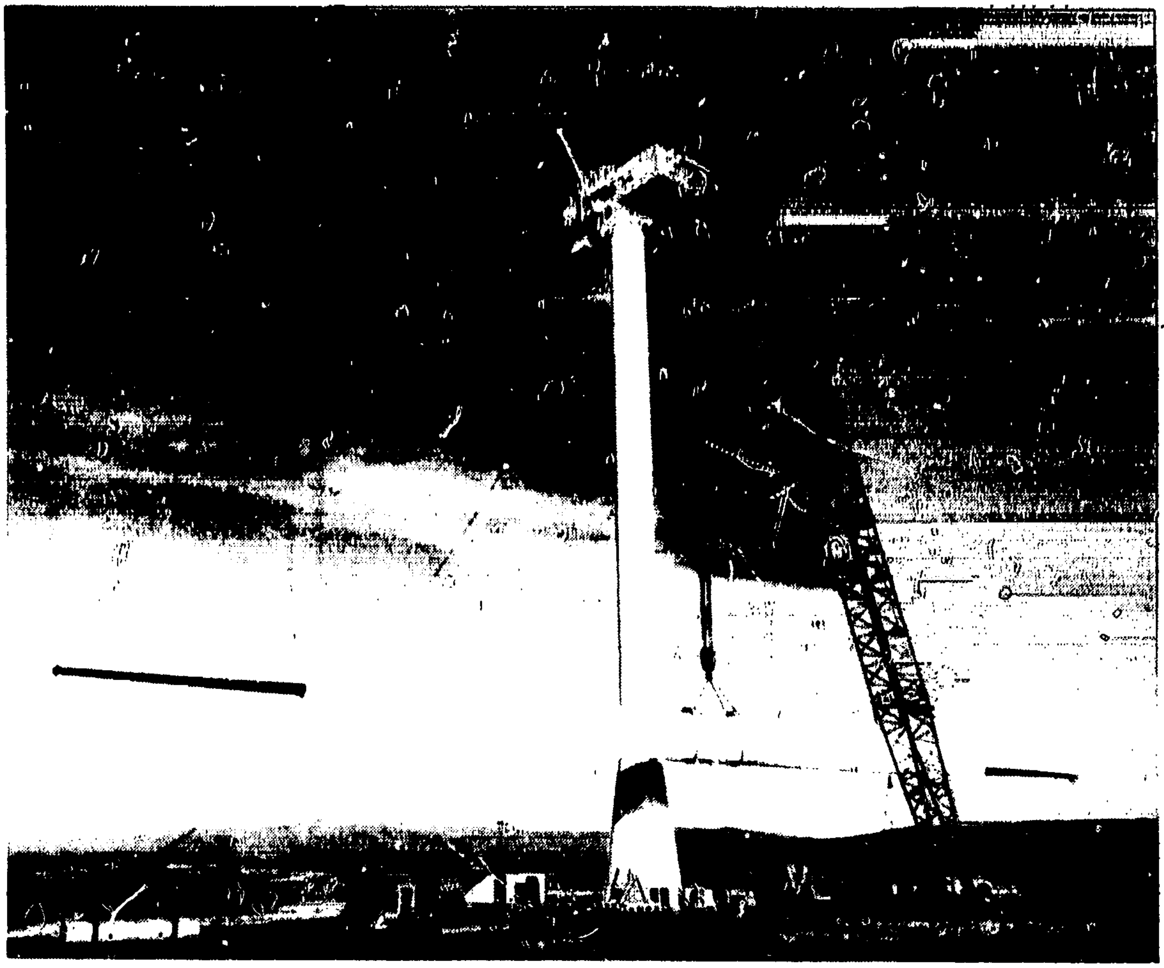

FIGURE 6. MOD-2 INSTALLATION

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FIGURE 7. MOD-2 WIND TURBINE

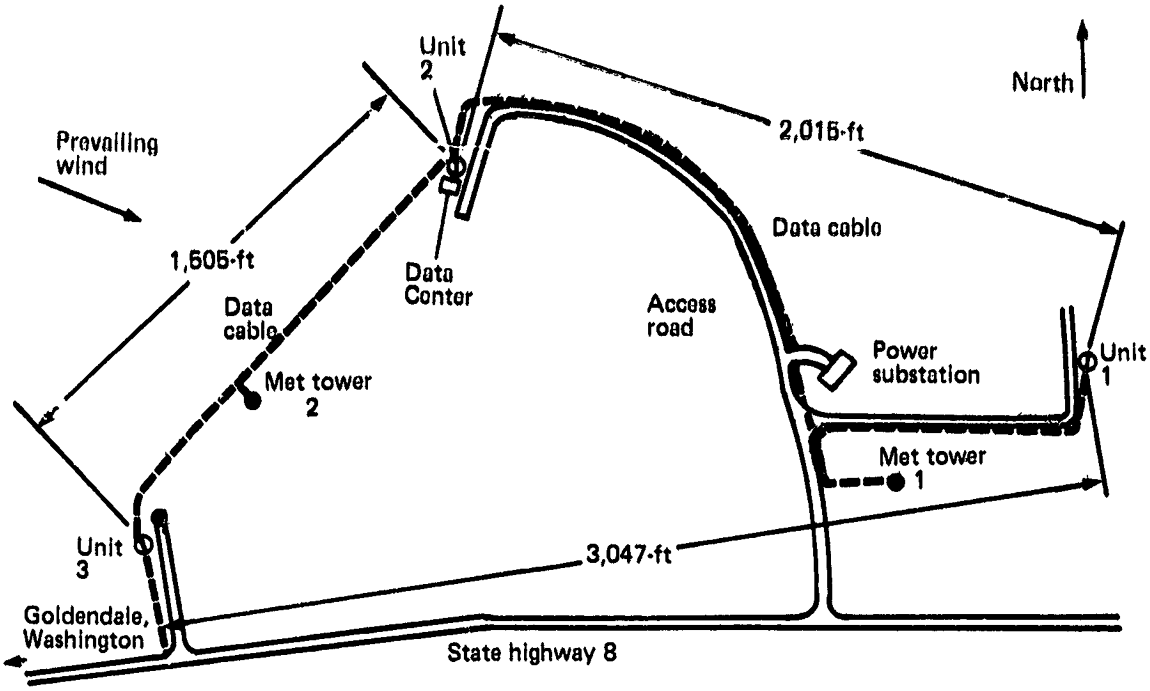

FIGURE 8. SITE PLAN (INCLUDING DATA ACQUISITION SYSTEM)

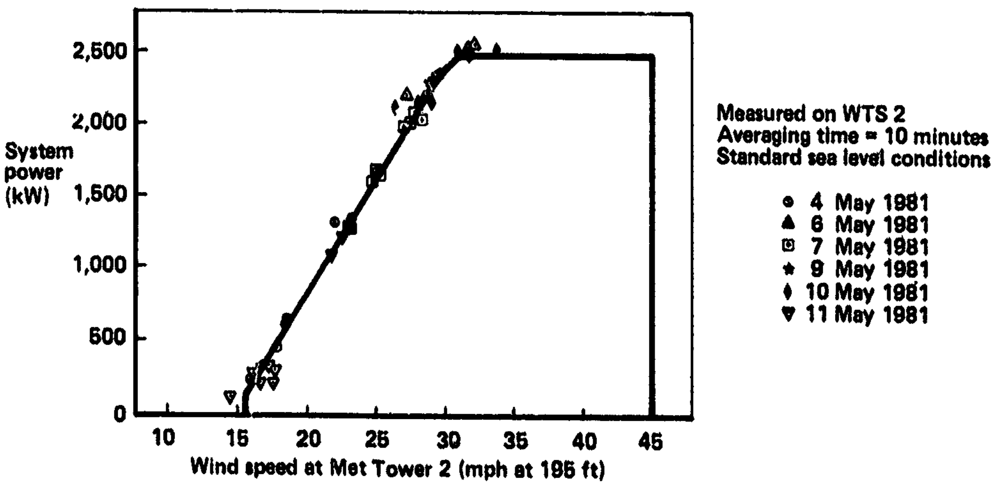

FIGURE 9. VARIATION OF MOD-2 POWER OUTPUT WITH WIND SPEED