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INSTALLATION AND CHECKOUT OF THE DOE/NASA MOD-1 2000-kW WIND TURBINE GENERATOR

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Work performed for
U.S. DEPARTMENT OF ENERGY
Energy Technology
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Prepared for
Wind Energy Conference cosponsored by
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NOTICE

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Abstract

The Mod-1 wind turbine generator is the largest such machine ever built. It supplies up to 2000 kW of electricity to the Blue Ridge Electric Membership Corp. grid. The design and installation were performed by the General Electric Co. of Valley Forge, Pennsylvania, under contract to the NASA Lewis Research Center, who managed the program for the Department of Energy. The wind turbine consists of the turbine rotor, pitch-change mechanism, drive-train assembly, bedplate, yaw assembly, and tower. The turbine rotor operates at 35 rpm and generates 2000 kW of electricity in a 25.5-mph wind (at 30 ft). The entire system weighs 655,000 lb, 335,000 lb machine weight and 320,000 lb tower weight. The machine, without the blades, was assembled and tested at the General Electric Riverside facility in Philadelphia, Pennsylvania. After the system had been tested, the Mod-1 machine was then disassembled and sent to the site at Boone, North Carolina, for erection. The blades, fabricated by the Boeing Engineering and Construction Co., were sent directly to the site. After the machine had been erected, a series of checkout tests were conducted to evaluate its performance and loads. The results of these tests compared well with the design data and will contribute to the design of future low-cost wind turbines.

Introduction

Wind-energy systems have been used for centuries as a source of energy for man. The applications have ranged from pumping water and grinding grain to generating electricity. At times considerable interest existed in both the United States and Europe in developing large wind-driven generating systems as a source of electric power. However, interest in such systems ultimately declined because they were not cost competitive with the fossil fuel systems of that era. Also, these efforts were generally privately financed and thus suffered from the lack of a sustained research and development effort.

The continuing increase in energy requirements, increases in fuel costs, depletion of our fuel reserves, and dependence on foreign sources have made it necessary to investigate and develop alternative energy sources. Wind energy, being a clean, nondepletable source of energy, could be a viable alternative source. Thus a Federal Wind Energy Program was established to encourage research and development on the many concepts of wind-energy systems.

One phase of the Federal Wind Energy Program is to develop the technology necessary for the successful design, fabrication, and operation of large, horizontal-axis wind turbine systems. This phase of the program is being managed by the National Aeronautics and Space Administration's Lewis Research Center for the Department of Energy. To date, Lewis has erected an experimental wind turbine at Sandusky, Ohio, and has installed three 200-kW wind turbines - one at Clayton, New Mexico; one at Culebra, Puerto Rico; and one at Block Island, Rhode Island. Most recently Lewis has erected the Mod-1 2000-kW wind turbine at Boone, North Carolina.

The Mod-1 wind turbine generator is the largest such machine ever built. It supplies up to 2000 kW of electricity to the Blue Ridge Electric Membership Corp. grid and will provide the electricity for as many as 500 homes. The overall objective of this project is to obtain early operation and performance data while gaining initial experience in the operation of large, horizontal-axis wind turbines in a utility environment.

The design and construction of the Mod-1 wind turbine generator were performed by the General Electric Co. of Valley Forge, Pennsylvania, under contract to Lewis, who managed the program for the Department of Energy. Major components such as the gearbox and blades were subcontracted by GE, the gearbox to Philadelphia Gear and the blades to Boeing Engineering and Construction Co. The machine, without the blades and tower, was assembled in Philadelphia, where tests were conducted before shipment to the site. The blades were delivered directly to the site for final assembly of the machine on top of the tower. After final assembly a system integration test was conducted.

This paper describes the wind turbine, the assembly and testing at Philadelphia, and the installation at Boone, North Carolina. The report concludes with performance data taken during the initial tests conducted on the machine.

Description of the Mod-1 Wind Turbine Generator

The Mod-1 2000-kW wind turbine generator is mounted on top of a truss tower with its rotor axis 140 feet high. Its two blades are 200 feet in diameter (fig. 1) and located downwind of the tower. The nacelle/bedplate, which supports and encloses all equipment mounted on top of the tower, is driven through a yaw-bearing assembly that rotates about the vertical axis of the tower in response to changes in the wind direction. The tower is 12 feet square at the top and 48 feet square at the bottom and is anchored to reinforced concrete footings at each leg. Figure 2 shows the machine installed on Howard's Knob, at Boone, North Carolina. The elevation at the site is approximately 4500 feet. The design specifications are presented in table I.

The wind turbine assembly consists of the rotor assembly, the drive-train/bedplate assembly, the yaw assembly, and the tower (fig. 3). The turbine rotor operates at 35 rpm and generates 2000 kW of electric power in a 25.5-mph wind (at

30 ft). The hub and blades are connected to a low-speed shaft (35 rpm) that drives a gearbox. In the gearbox the shaft speed is increased from 35 rpm to 1800 rpm. A high-speed shaft connects the gearbox to the 2000-kW alternator. The entire system weighs 655,000 lb, 335,000 lb machine weight and 320,000 lb tower weight. Table 11 presents a weight breakdown of the machine. The major components are described in the following subsections.

Rotor Assembly

The rotor assembly consists of three major subassemblies, the blades, the hub assembly, and the pitch-change mechanism. Each blade is attached to the hub through a three-row, cylindrical roller bearing that permits the full pitch of the blade from the power position (0°) to the feather position (90°). Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades at an average rate of 8 degrees per second.

The blades are constructed of a monocoque, welded-steel leading-edge spar and an aerodynamically contoured, polyurethane foam afterbody with bonded 301 stainless-steel skins (fig. 4). Measuring 100.8 feet long with a tapered planform and thickness, the blade uses an NACA 44XX series airfoil with a thickness ratio varying from 10 percent at the tip to 33 percent at the root. The blades, which weigh approximately 21,500 lb each, are assembled in six main sections. Spar welds are located at five stations, as are the trailing-edge-section splices. A transition piece is welded to the spar to provide the blade continuity to the interface with the hub. A longitudinal stiffner and chordwise webs are welded in the spar to provide buckling strength. Ballast weights are used at each blade tip for static and dynamic balance.

The hub assembly consists of a hub barrel and a hub tailshaft (fig. 5). The hub barrel houses the pitch-change bearing and supports the blades at a 9° cone angle. The tailshaft joins the barrel with a 120° saddle flange and a transition to the circular main-bearing seat and flange. The main rotor bearing is shrink fitted to the hub tailshaft and bolted to the bedplate adapter to form the rotor-bedplate interface.

The pitch-change mechanism positions the blades in response to commands from the control system. It consists of hydraulic actuators, swing links, a thrust ring and bearing, and two blade pitch rods (fig. 6). The stationary hydraulic actuators translate fore and aft motion to the rotating (35 rpm) pitch assembly through a thrust ring. This assembly is supported by stationary arms to maintain clearance from the low-speed shaft and thus allow the fore and aft motion to change the pitch of the blade through the pitch rods.

Drive Train/Bedplate Assembly

The drive-train assembly consists of a low-speed shaft and couplings, a three-stage gearbox, and a high-speed shaft that drives the alternator (fig. 7). The high-speed shaft incorporates a dry-disk slip clutch for protection against torque overloads and a disk brake that stops the rotor and holds it in the parked position. The entire assembly is supported on a bedplate and enclosed in an aluminum nacelle for protection.

Yaw Drive Assembly

Yaw rotation of the machine to aline with the wind is provided by the yaw drive, which consists of upper and lower structures, a cross roller bearing, dual hydraulic drive motors, and six hydraulic brakes (fig. 8). Each yaw motor drives a pinion meshing with a ring gear on the inner race of the yaw bearing. The yaw brakes dampen dynamic excitations in yaw motions while the nacelle is being driven. These components are housed in a yaw structure that interfaces between the machine and the pintle structure of the tower.

Tower

The steel tubular truss tower (fig. 1) is made of seven vertical bays with the bracing designed for bolted field assembly. Tubular members were used to reduce "tower shadow" loads on the blades as they pass the tower. The tower was designed to provide stiffness in the lateral and torsional modes. The bending frequency is 2.8 times the rotor operating frequency, and the torsion frequency is 6.5 times the rotor operating frequency. The maximum design wind load is 150 mph. All the members of the tower were fabricated from A333 steel, which provides a low-temperature fracture toughness.

The tower is supported by separate foundations for each of its four legs. Because of the dead weight of the wind turbine, relatively small tension loads are developed in the foundation. Each leg is secured by eight 1.5-inch-diameter anchor bolts, hooked at a depth of 30 inches into the foundation. Tower baseplate shear loads react through a nonshrink grout to a lip on the foundation that is tied into reinforcing bars in the foundation.

Control System

The control system for the Mod-1 machine includes a PDP 11/34 computer located in the ground enclosure at the base of the tower. The PDP 11/34 interfaces with two PDP 11/04 computers. One PDP 11/04 is located in the control enclosure, and the other in the nacelle. The control system provides unattended safe and reliable operation of the wind turbine. It must automatically start, operate, and stop the machine, aline it with the wind, and provide dispatcher control through a telephone link. Figure 9 presents a simplified control schematic. References 1 to 4 provide a detailed description and a summary of the design calculations, including an analysis of failure modes and effects.

Assembly and Installation

Procurement of Major Components

Many of the components that make up the Mod-1 wind turbine were subcontracted by General Electric and procured under their specifications. The policy established early in the program was to use catalog components wherever possible. All the fastening hardware met this requirement. Larger components such as the gearbox, generator, yaw hydraulic drive motors, blade bearings, and mainshaft bearings are also examples of purchased components that were listed in a catalog.

Of the noncatalog items that were procured by GE, the blades were the largest contract. Specifications were written by GE that defined the blade loads, the maximum weight and the weight distribution, and the blade's bending and torsional natural frequencies. Boeing Engineering and Construction Co. was responsible for designing the blades to meet these requirements. Periodic design reviews were held between Boeing, GE, and Lewis to monitor the progress of the contract. Other major components that are noncatalog items are the hub assembly, the tower, and the bedplate.

Assembly and Test

As the various components were delivered to the General Electric Riverside facility in Philadelphia, they were prepared for assembly. The first major component necessary for assembly was the tower pintle (fig. 1). This component was used as a fixture for the assembly of the machine. After the pintle, the yaw assembly, bedplate, drive train, generator, blade pitch-change mechanism, and hub were assembled. The bedplate structure was delivered to Riverside without plumbing for the hydraulic system and without wiring for the electrical controls, instrumentation, power, and auxiliary power. The plumbing and wiring were installed at Riverside.

The hydraulic systems for the pitch-change assembly and the yaw system were delivered from the vendors as a complete power package. The data acquisition and control systems for the machine were also delivered as a package. The data acquisition and control systems had received a prior acceptance test at the Valley Forge facility. An auxiliary 200-hp motor was mounted on the nacelle structure above the low-speed shaft to rotate the drive train and rotor for testing (fig. 10).

The factory test program conducted on the system consisted of a checkout of the gearbox and main-bearing lubrication system and operation of the yaw drive and pitch-change mechanism with the drive shaft driven by the auxiliary motor at 35 rpm. A small electrical load (100 kW) was applied to the alternator while the entire system was operated for 20 hours at rated rpm. The tower was sent directly to the site for assembly and erection.

The blades, after being fabricated, were subjected to an acceptance test. This test included determining the elastic axis, calibrating the strain gages, performing a modal survey to determine the natural frequencies of the blade both in bending and torsion, and conducting a bond verification test. The test setup is shown in figure 11. The bond verification test applied a load both flapwise and chordwise to determine possible face wrinkling failures or disbonding in the upper and lower trailing-edge skin surfaces.

Disassembly and Shipment of Components to Boone

The Mod-1 machine was then disassembled into nine subassemblies and shipped from Philadelphia to the site. Shipment by truck was elected to avoid the long schedule delays inherent in rail shipment. All the components were shipped by truck except the rotor pitch-change mechanism. The weight of this assembly exceeded that which would be permitted for transit through some states by truck. Shipment by rail took approximately 2 weeks, and a site work-around schedule was established. Table III lists the weights and sizes of the nine subassemblies that were shipped. The rotor pitch-change mechanism weighed 96,000 lb.

Initially the blades were also to be shipped by rail. Upon receiving the rail schedules and evaluating the loads that could be expected on the blades during rail shipment, Boeing elected to ship the blades by truck. This was accomplished by loading each blade root on a separate semi-trailer-tractor and supporting the tip of the blade by a steerable dolly at the 0.75 station (fig. 12). Both blades were transported from Seattle, Washington, to Boone, North Carolina, without incidence. The trip up to Howard's Knob was also made with little trouble. The ease of shipping such a large structure over that distance and often around tight corners (as was experienced going up to Howard's Knob) can be attributed directly to the use of the steerable dolley.

Installation at Howard's Knob

The tower was erected in three sections by using a Manitowoc 4100N crane with a boom height of 230 feet and a lift capacity of 55 tons. The machine installation followed later and consisted of a series of lifts. A one-lift installation was considered, but it would have required a large crane that was more costly and difficult to schedule because of the limited availability of cranes with 200-ton lift capacity. The installation sequence and weight of each subassembly are shown in table IV.

Some typical views of the wind turbine installation are shown in figures 13 to 17. Figure 13 shows the installation of the pintle and yaw assembly on the tower. The pintle part of the tower was used during testing at Philadelphia. Figures 14 to 16 show the bedplate assembly, the hub and pitch-change mechanism installation, and the assembly of the completed machine on top of the tower.

The blade was attached to the machine by two cranes with 20-ton lift capacity (fig. 17). One crane was used for lifting and installation, and the second crane was used for holding the first blade horizontal during installation of the second blade.

Initial Checkout

After the Mod-1 wind turbine was installed at the Boone site, a series of checkout tests were conducted to evaluate the performance of the system and to make any corrective changes necessary. During these tests such engineering data as blade loads, rotor rpm, generator power, voltage, wind speed, and blade angle were recorded. The following are the results of three of these tests: the emergency feather test, the power generation test, and the power performance test.

Emergency Feather Test

This test consisted of the first rotation of the machine in incremental steps from 5 rpm to 38 rpm in a speed feedback control mode and the initiation of an emergency feather. The normal turbine operating speed is 35 rpm. In the event of a sudden loss of load, such as a disconnect from the utility grid the turbine can overspeed to 38 rpm (110 percent) before the feathering of the blades will begin to reduce the rotor speed. Figure 18 presents the flapwise and chordwise loads recorded on the blades during the 110-percent overspeed as the machine executed an emergency feather shutdown at an average of 8 degrees per second with no electrical load. The solid lines are the loads predicted by General Electric from their dynamic computer codes, and the data points are the actual loads recorded. The actual loads compare quite favorably with the calculated loads and are generally lower.

Power Generation Test

The power generation test consisted of a checkout, adjustment, and demonstration of the Mod-1 electrical and electronic control system. It also consisted of the demonstration of the machine's performance when operating in a completely automatic control mode under local and remote dispatcher supervision.

During this test over 92 channels of both engineering and operational data were recorded on tape. Some of these data were displayed on a CRT, and some were traced on two 8-channel Brush recorders. The data included generator power, nacelle wind speed, blade pitch angle, blade flapwise and chordwise moments, and rotor speed.

Figure 19 shows typical traces of 7 of the 16 channels available on the two brush recorders. In this power generation test the rotor was operating at 35 rpm, was synchronized to the grid, and generated approximately 1000 kW of electricity. The wind speed average was between 20 and 25 mph at 30 feet. The blade angle was near the maximum power setting (0° - 5°) since the wind speed was still below rated velocity (25.5 mph at 30 ft). Chordwise and flapwise cyclic bending moments are shown at the 0.1 station, and flapwise bending moments are shown at the 0.4 station. These loads compare well with the design loads presented in reference 2.

Power Performance Test

The performance of the Mod-1 wind turbine, in terms of power output versus wind speed, is shown in figure 20 (ref. 5). The system is designed to generate power at wind speeds above 11 mph (at 30 ft). Rated power of 2000 kW is produced at wind speeds above 25.5 mph (at 30 ft). When the wind exceeds 35 mph (at 30 ft), the machine is shut down to avoid overstressing the blades. At the site elevation of 4500 ft the standard air density is 14 percent less than at sea level, and this effect is included in the design performance curve (ref. 2).

The test data shown in figure 20 represent approximately 1 hour of operation. Continuous records of electric power and free-stream wind speed were analyzed statistically to obtain the data points in this figure. As figure 20 indicates, median measured power output is very close to the design output.

Concluding Remarks

The successful installation and initial operation of the Mod-1 wind turbine generator has had the following results:

1. Megawatt-size wind turbines can be operated satisfactorily on utility grids.

2. The structural loads can be predicted by existing codes.

3. Assembly of the machine on top of the tower in components presents no basic problem.

4. Large blades of 100 ft in length can be transported long distances and over mountain roads.

5. Operating experience and performance data from the Mod-1 program will contribute substantially to the design of future low-cost wind turbines.

References

1. "Executive Summary: Mod-1 Wind Turbine Generator Analysis and Design Report," General Electric Co., Philadelphia, Pa., Mar. 1979. (DOE/NASA/0058-79/3; NASA CR-159497)

2. "Mod-1 Wind Turbine Generator Analysis and Design Report," General Electric Co., Philadelphia, Pa., May 1979. (DOE/NASA/0058-79/2-Vol. I; NASA CR-159495)

3. "Appendix: Mod-1 Wind Turbine Generator Analysis and Design Report," General Electric Co., Philadelphia, Pa., May 1979. (DOE/NASA/0058-79/2-Vol. II; NASA CR-159496)

4. "Mod-1 Wind Turbine Generator Failure Modes and Effects Analysis," General Electric Co., Philadephia, Pa., May 1979. (DOE/NASA/0058-79-1; NASA CR-159494)

5. Spera, D. A., Viterna, L. A., Richards, T. R., and Neustadter, H. E., "Preliminary Analysis of Performance and Loads Data from the 2 MW Mod-1 Wind Turbine Generator," NASA TM-81408, 1979.

TABLE I. - DESIGN SPECIFICATIONS FOR MOD-1 WIND TURBINE GENERATOR

Rotor	
Number of blades	2
Diameter, ft	200
Speed, rpm	35
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable pitch
Cone angle, deg	9
Tilt angle, deg	0
Blade	
Length, ft	100
Material	Steel spar/ foam trailing edge
Weight, lb/blade	21,500
Airfoil	NACA 44XX
Twist, deg	11
Tip chord, ft	2.8
Root chord, ft	12
Chord taper	Linear
Tower	
Type	Pipe truss
Height, ft	131
Ground clearance, ft	40
Hub height, ft	140
Access	Hoist
Transmission	
Type	Three-stage conventional
Ratio	51
Rating, hp	2209
Generator	
Type	Synchronous ac
Rating, kVA	2225
Power factor	0.8
Voltage, V	4160 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive	
Type	Ring gear
Yaw rate, deg/sec	25
Yaw drive	Hydraulic
Control system	
Supervisory	Computer
Pitch actuator	Hydraulic
Performance	
Rated power, kW	2 000
Wind speed at 30 ft, mph:	
Cut-in	11
Rated	25.5
Cut-out	35
Maximum design	125

TABLE II. - WEIGHT BREAKDOWN OF MOD-1
WIND TURBINE GENERATOR

	Weight, lb
Rotor assembly	
Hub	15,000
Blades	41,000
Bearings and structure	29,000
Pitch-change mechanism	11,000
Pitch-control hydraulics	12,000
	108,000
Nacelle assembly	
Bedplate	68,000
Fairing	5,000
Generator and exciter	14,000
Power generator equipment	1,000
Shafts, couplings, and clutch	18,000
Gearbox	58,000
Lubrication and hydraulic systems	4,000
Data acquisition system	1,000
Cables, lights, etc.	2,000
	171,000
Yaw assembly	
Bearing supports	47,000
Yaw brake	1,000
Yaw drive	8,000
	56,000
Tower assembly	
Structure	313,000
Elevator and miscellaneous	1,000
Cabling and conduit	6,000
	320,000
Total (excluding ground equipment)	655,000

TABLE III. - SHIPMENT SUBASSEMBLIES

Subassembly	Weight, lb	Size, ft		
		Length	Width	Height
Pintle (top section of tower)	41,000	16	10	11
Yaw drive	50,000	15	14	8
Bedplate (with hydraulic systems)	90,000	33	13	10
Gearbox	63,000	10	8	10
Synchronous generator and miscellaneous electrical equipment	13,000	9	5	6
Rotor pitch-change mechanism	96,000	23	8	11
Nacelle electronics	1,500	5	3	8
Fairing	6,500	33	13	11
Control enclosure	34,000	28	11	11

TABLE IV. - INSTALLATION SEQUENCE AND WEIGHT OF LIFT

Subassembly	Weight, lb
Tower (multiple sections)	(a)
Transformer	12,000
Pintle (top section of tower)	41,000
Lift (personnel)	1,000
Yaw drive	50,000
Bedplate (with hydraulic systems)	90,000
Gearbox	63,000
Synchronous generator	13,000
Rotor pitch-change mechanism	96,000
Nacelle electronics	1,500
Fairing	6,500
Control enclosure	34,000

[a]Multiple lifts.

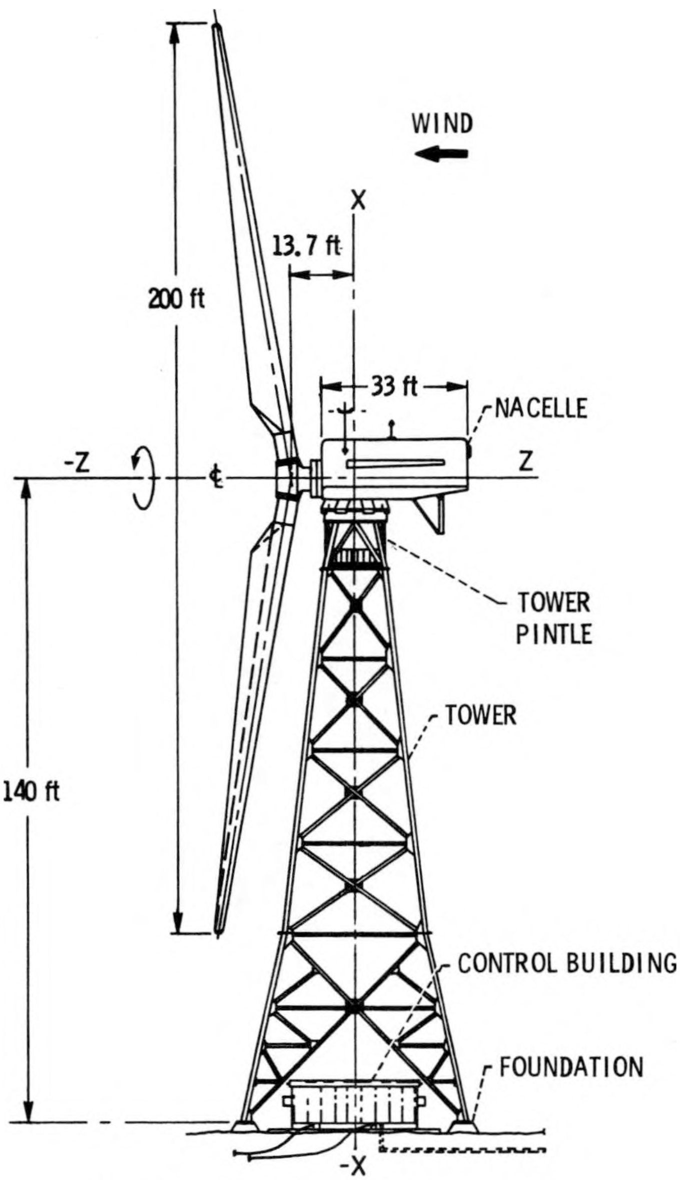


Figure 1. - Mod-1 2000-kilowatt wind turbine.

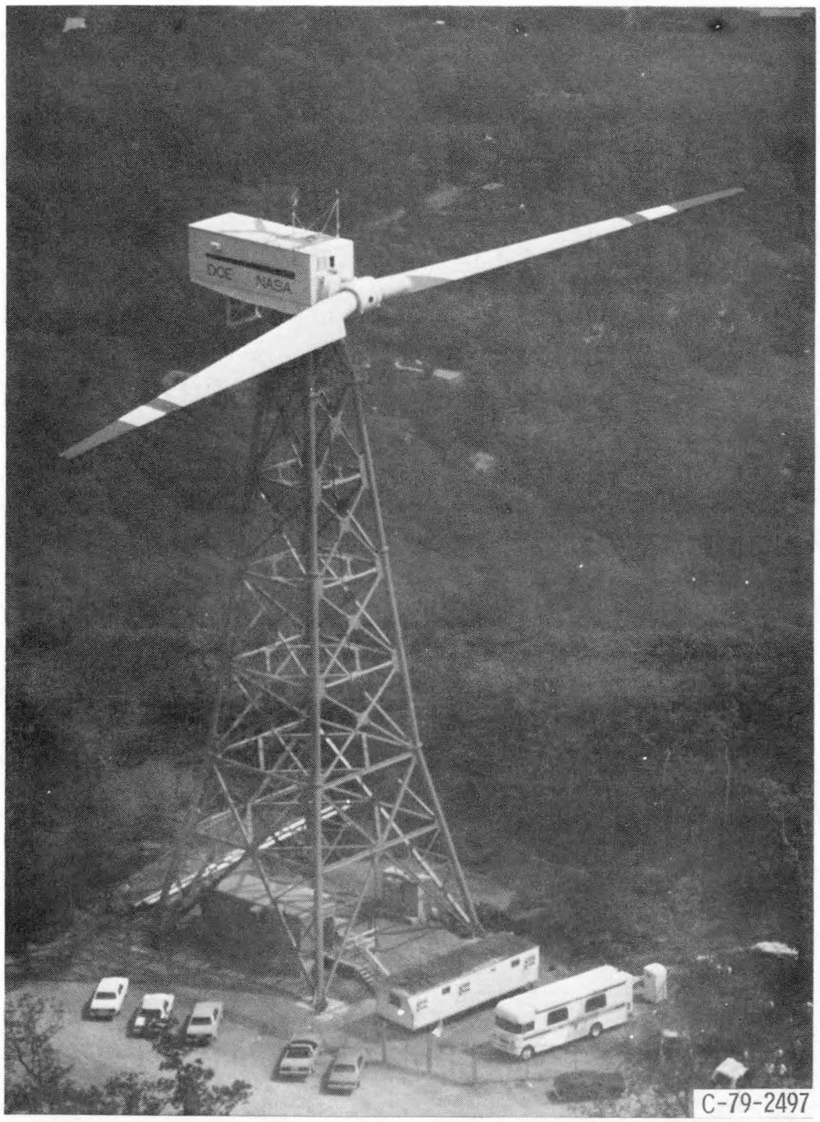


Figure 2. - DOE/NASA 2000-kW experimental wind turbine. Howard's Knob, Boone, North Carolina.

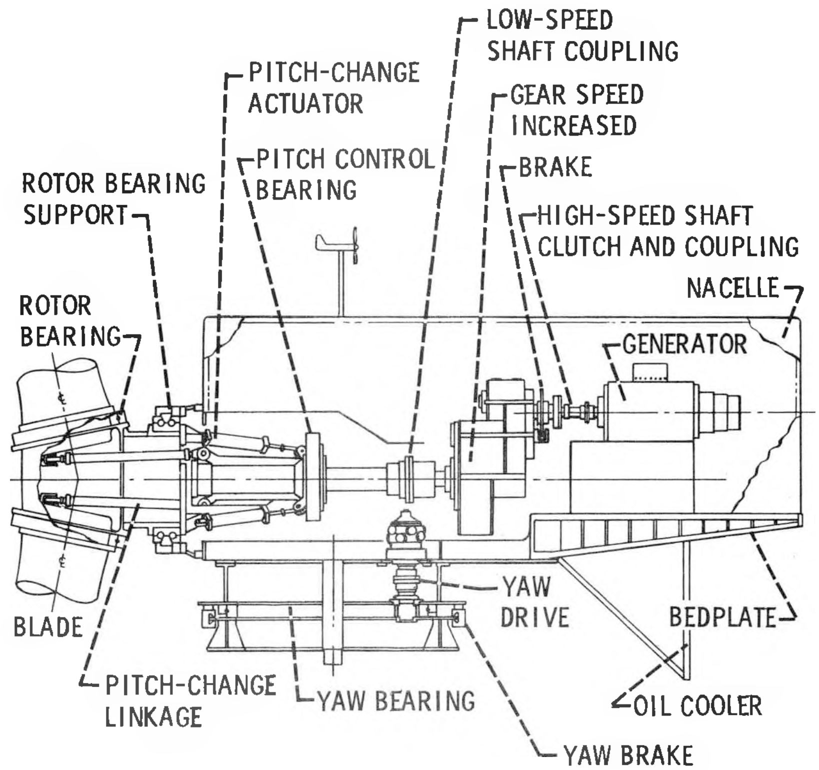
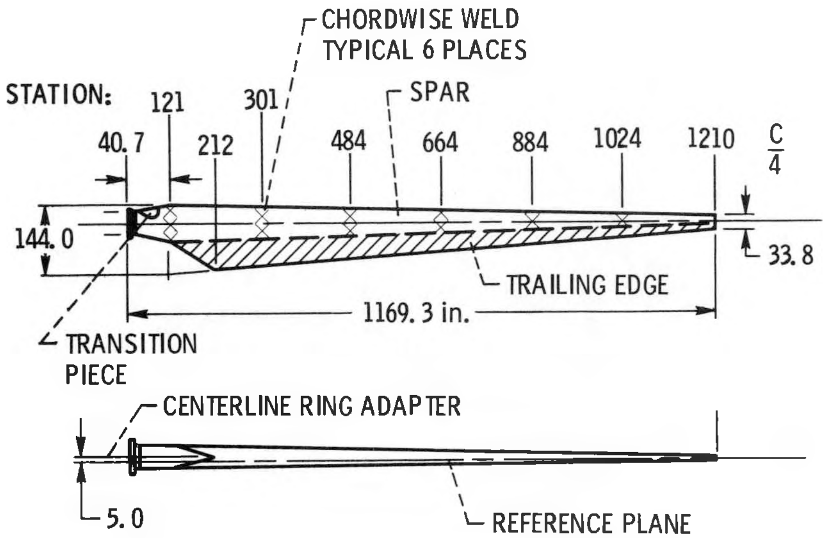
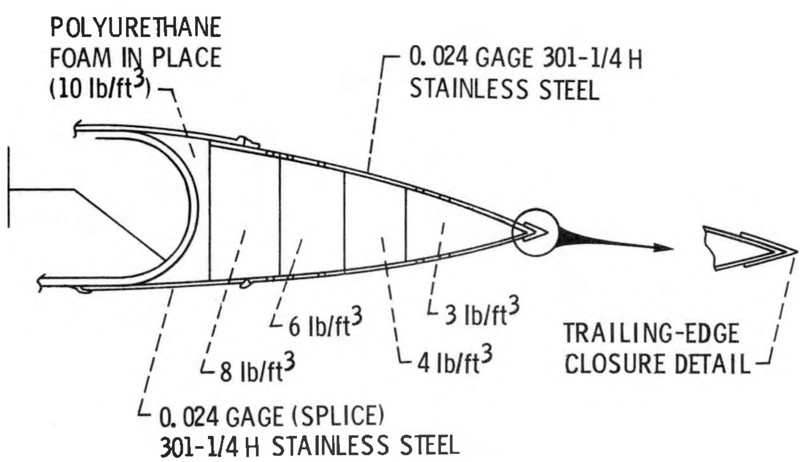


Figure 3. - Schematic diagram of the Mod-1 wind turbine assembly.



(a) BLADE GEOMETRY.



(b) TRAILING EDGE.

Figure 4. - Blade and trailing-edge geometry.

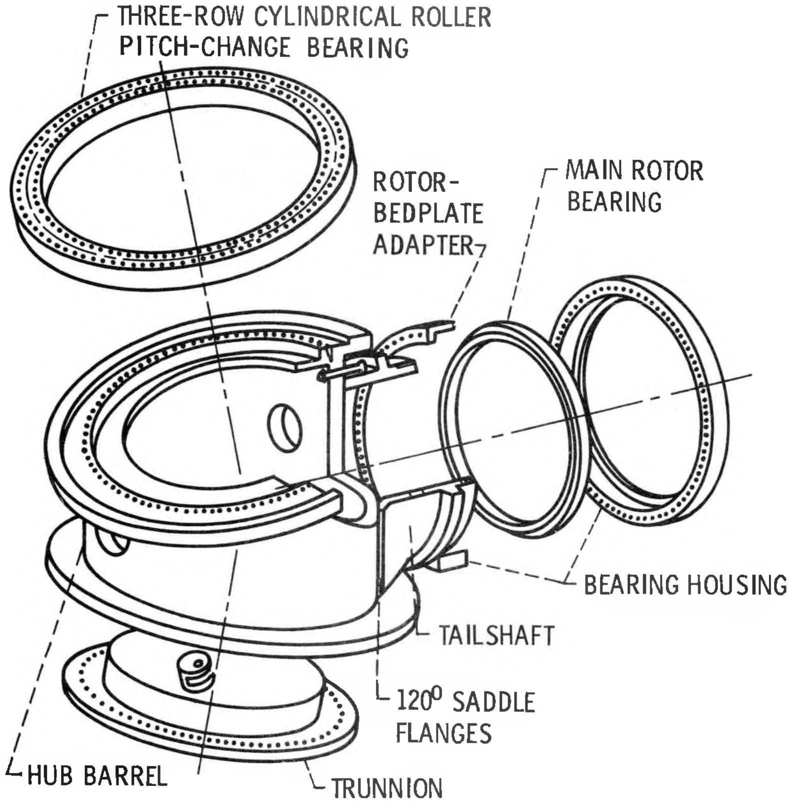


Figure 5. - Hub assembly.

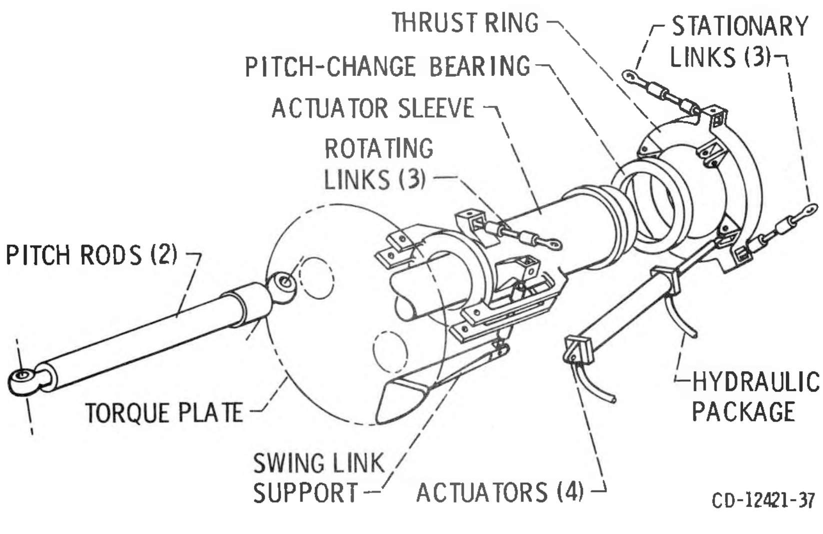


Figure 6. - Pitch-change mechanism.

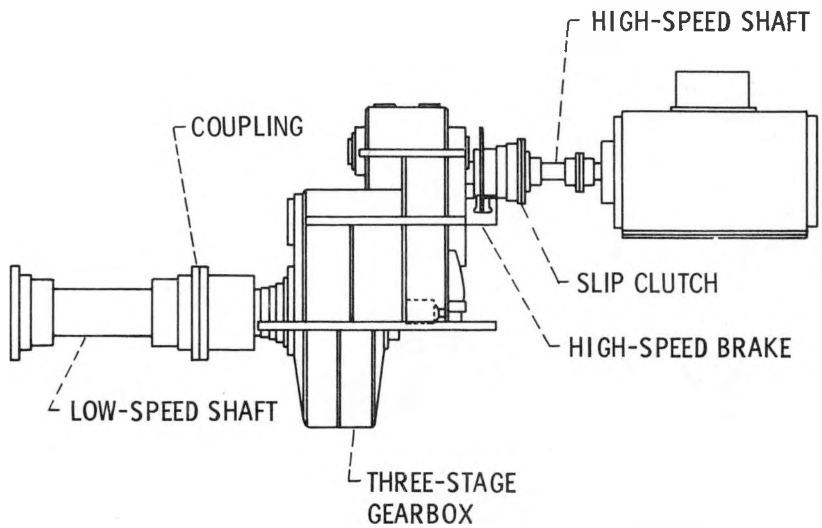


Figure 7. - Drive-train assembly.

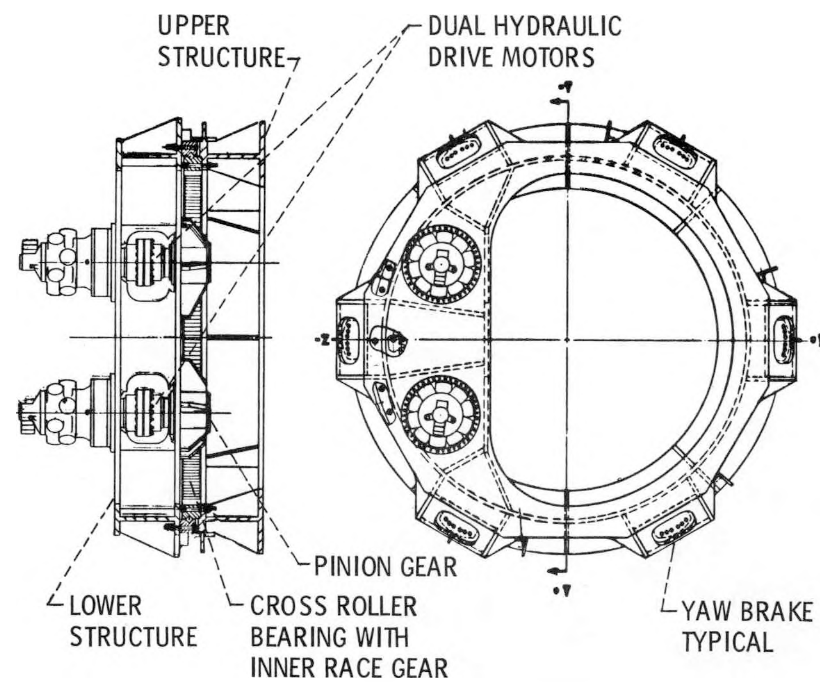


Figure 8. - Yaw drive assembly.

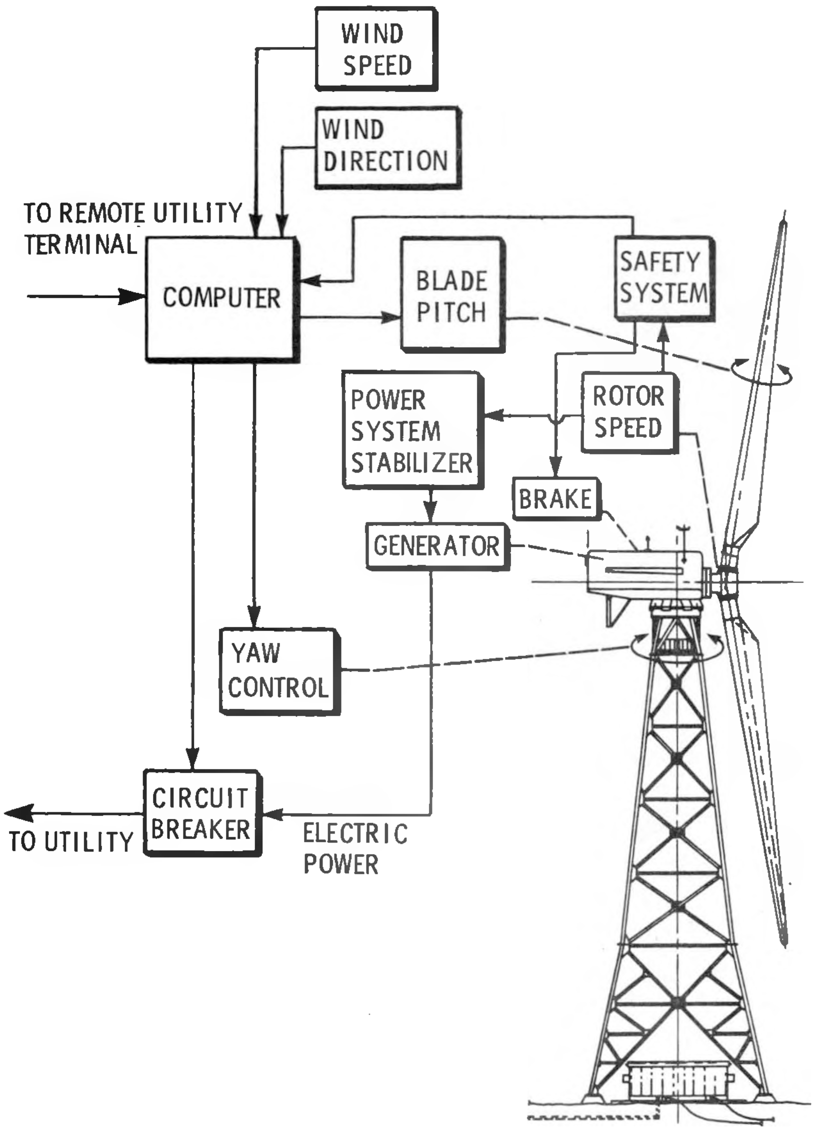


Figure 9. - Simplified Mod-1 control schematic.

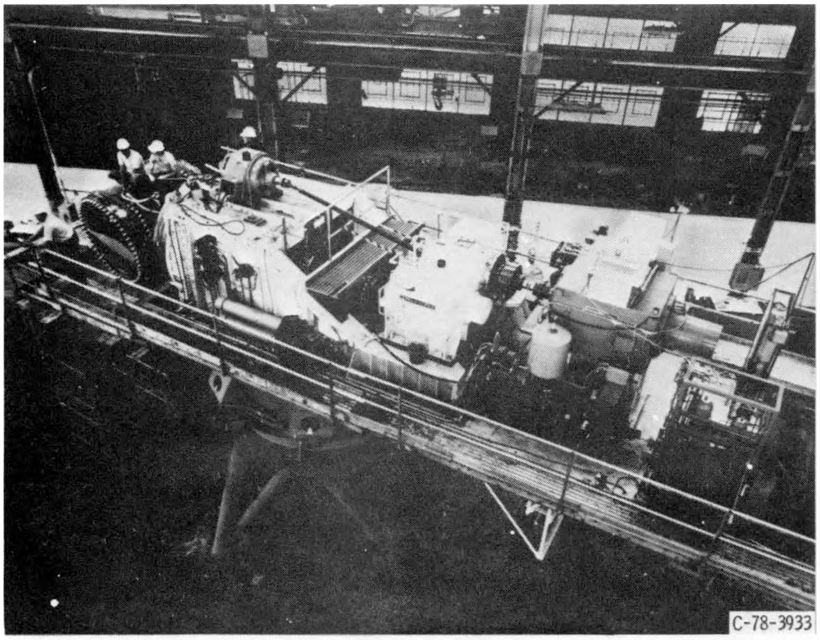


Figure 10. - Factory testing.

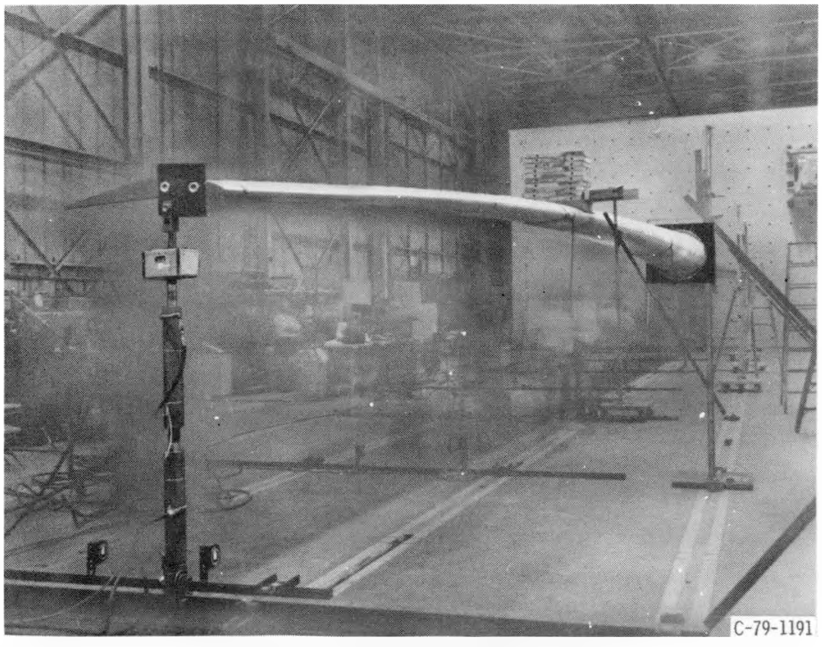
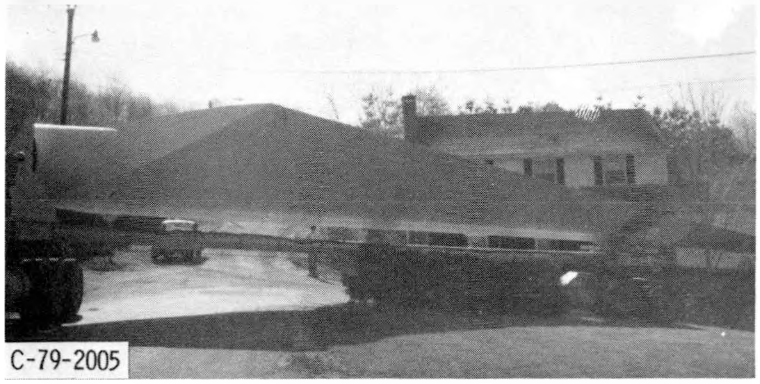
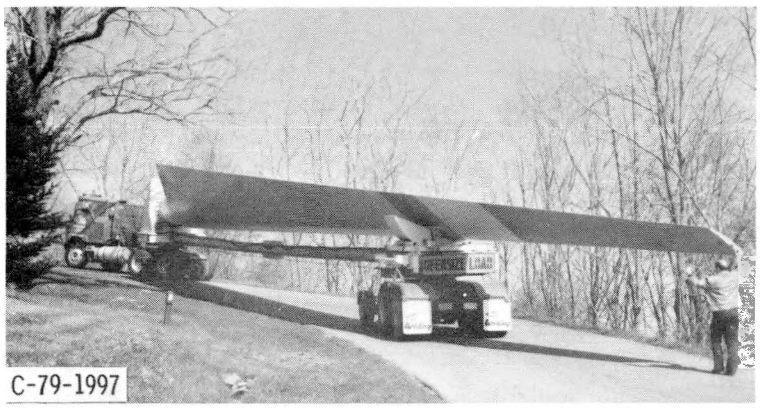


Figure 11. - Blade acceptance test.





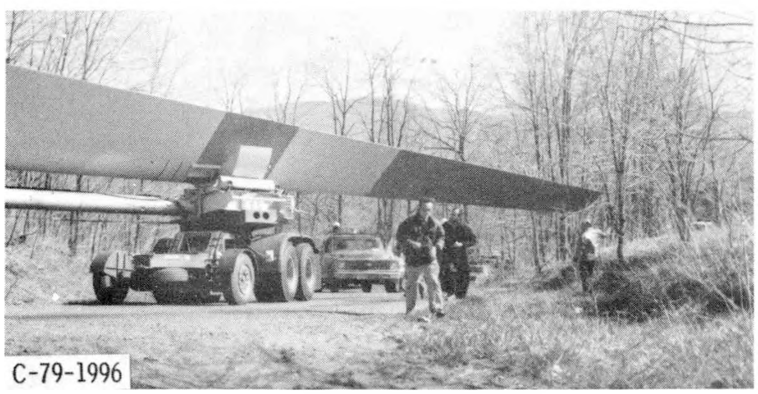


Figure 12. - Mod-1 blade in transit.

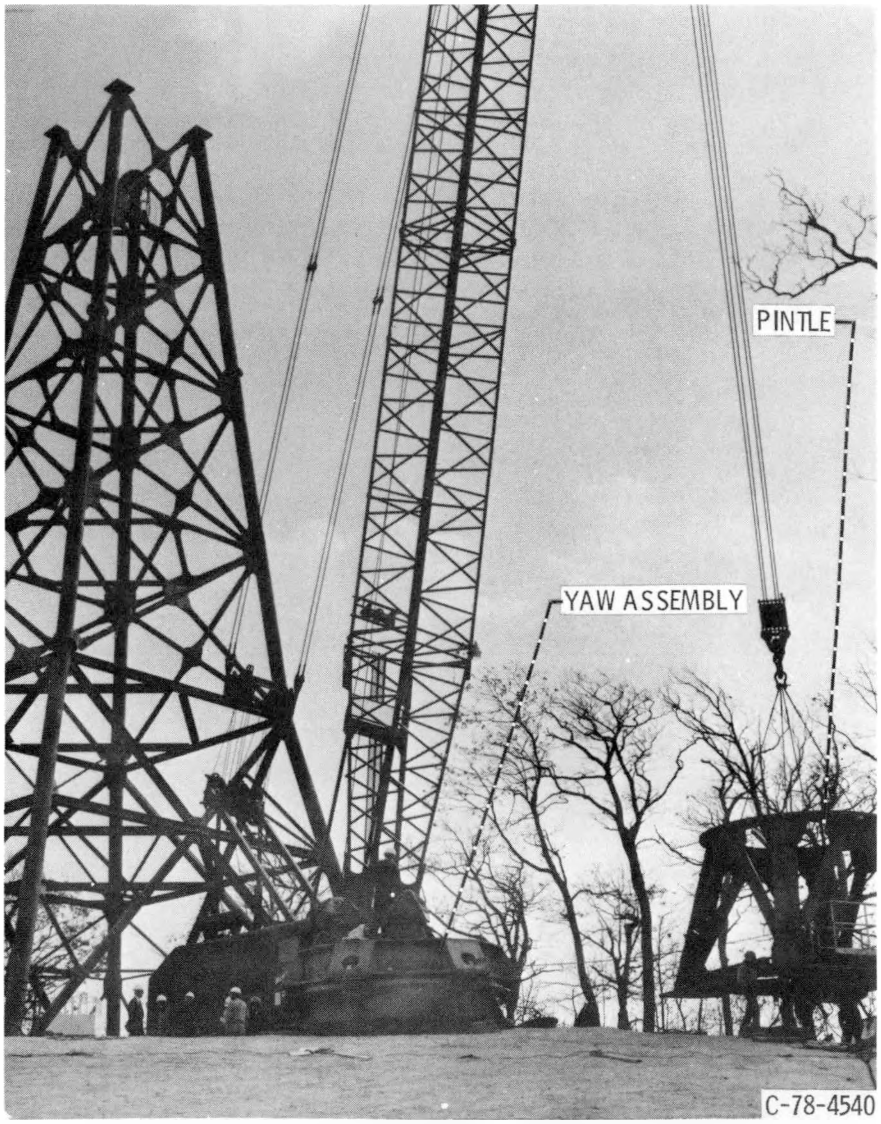


Figure 13. - Pintle installation.

Figure 14. - Bedplate assembly.

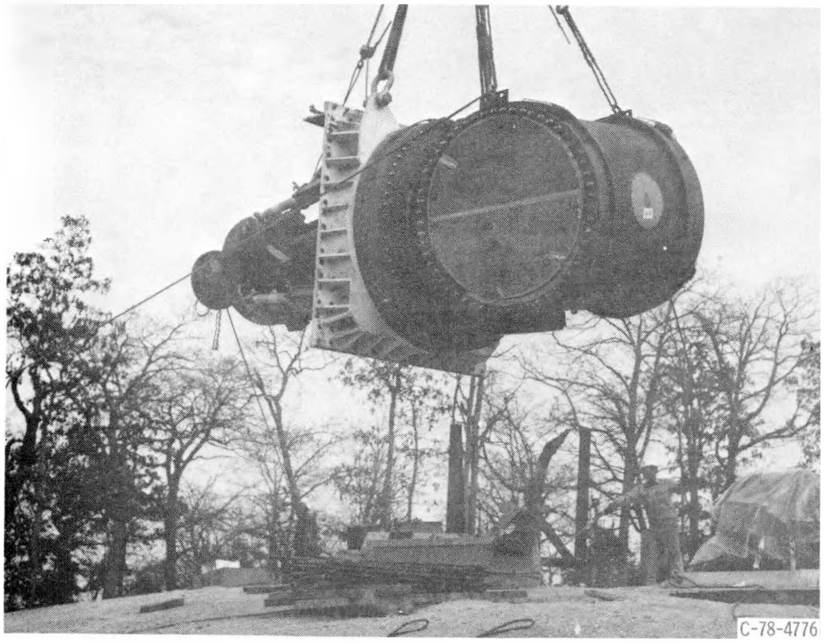


Figure 15. - Hub and pitch-change mechanism installation.

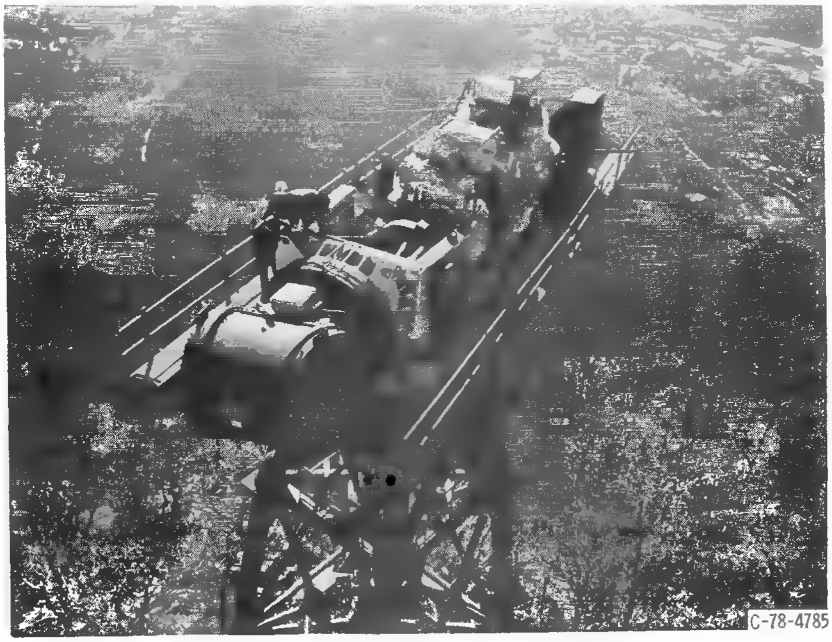


Figure 16. - Final assembly on top of tower.

Figure 17. - Blade installation.

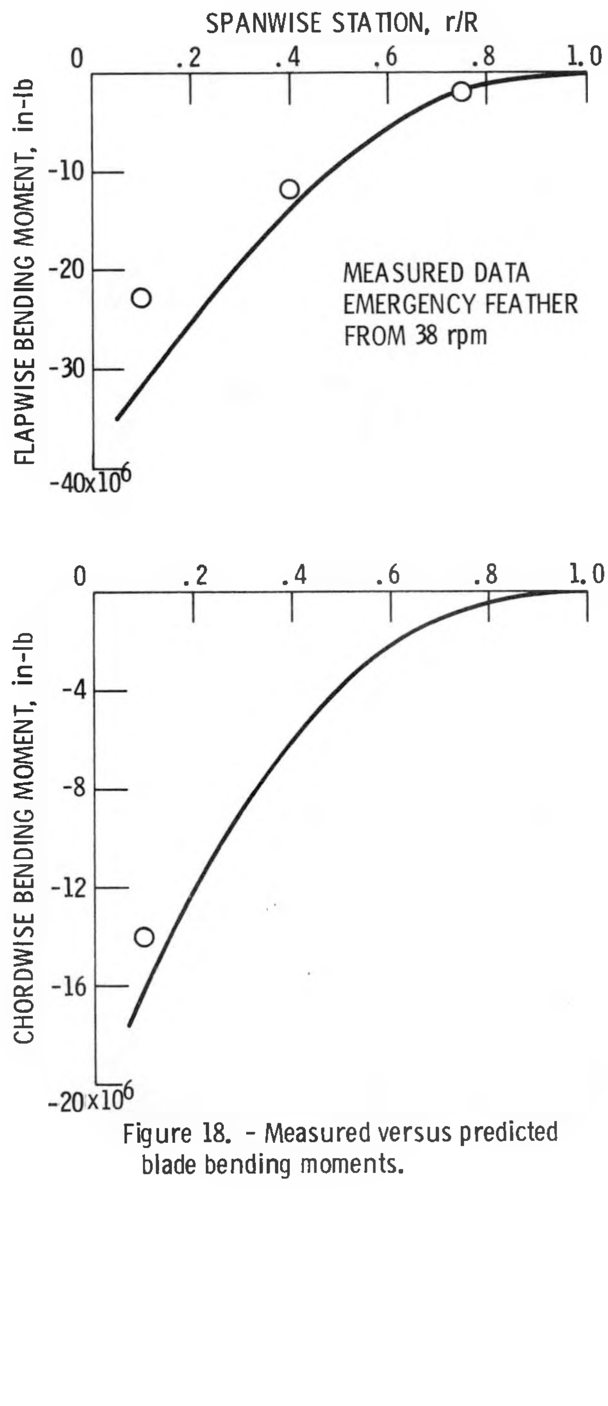


Figure 18. - Measured versus predicted blade bending moments.

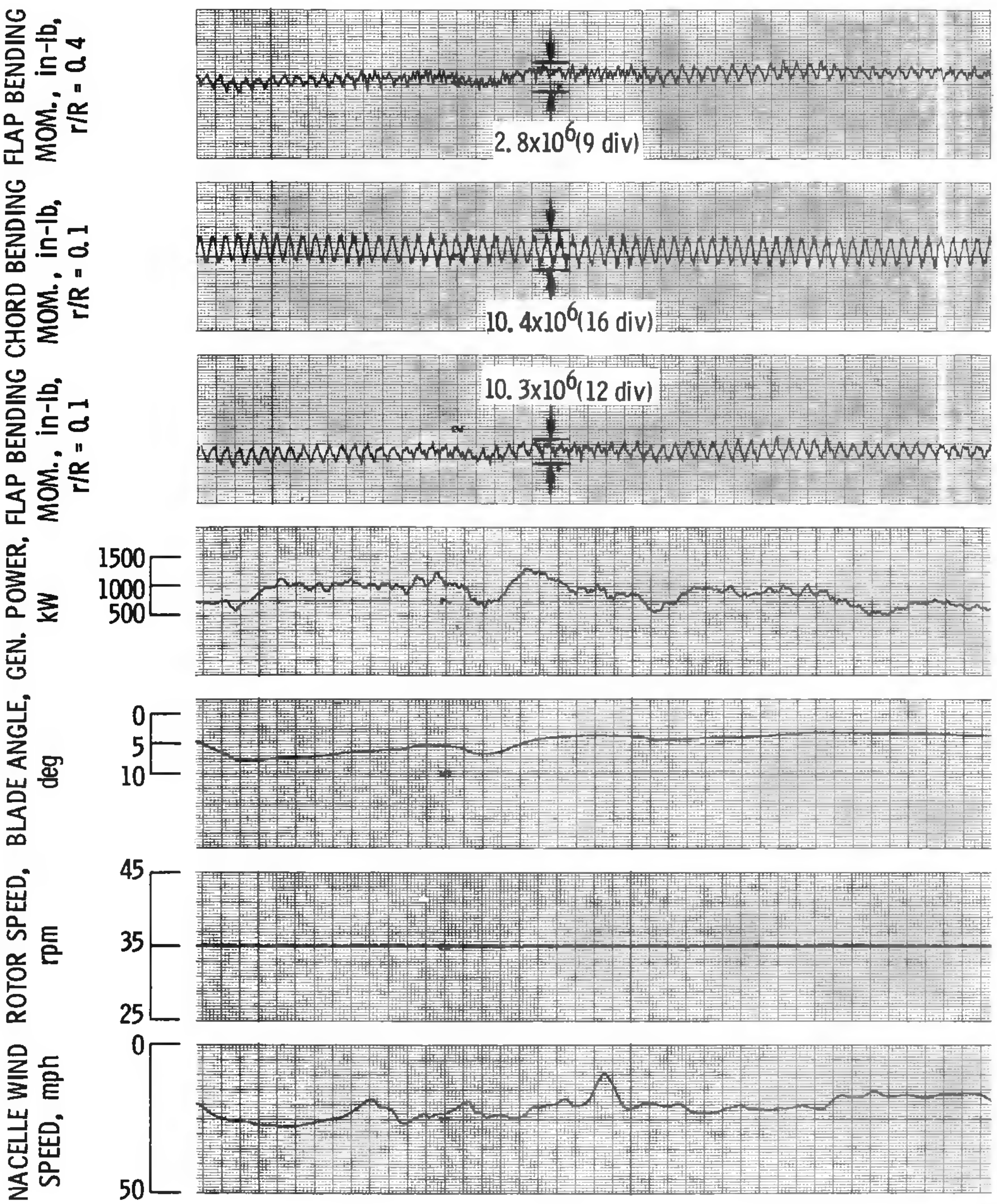


Figure 19. - Typical traces of power generation tests.

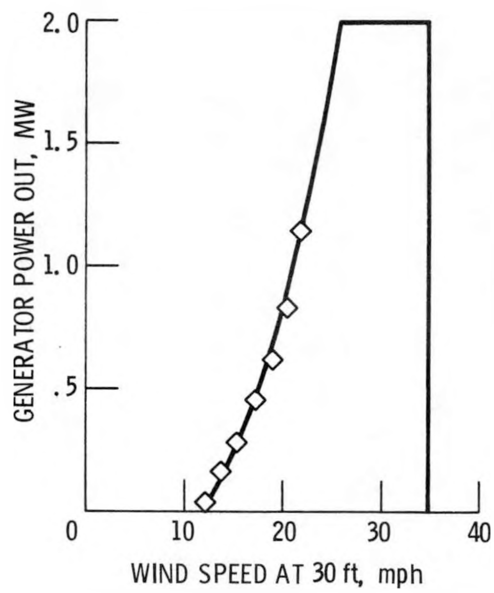


Figure 20. - Power performance test.