DOE/ NASA/1059-78/1
NASA TM-73767

LARGE WIND TURBINE GENERATORS

Ronald L. Thomas and Richard M. Donovon
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Work performed for
DEPARTMENT OF ENERGY
Division of Solar Energy
Federal Wind Energy Program
Under Interagency Agreement E(49-26)-1059

TECHNICAL PAPER to be presented at the
5th Energy Technology Conference and Exposition
Washington, D.C., February 27 - March 1, 1978

NOTICE

LARGE WIND TURBINE GENERATORS

by Ronald L. Thomas and Richard M. Donovon

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-9553

INTRODUCTION

The Federal Wind Program was initiated in 1973 as a part of the nation's solar energy program. The first wind energy workshop was held in 1973 (Ref. 1) to review past work in wind energy and to assess the potential of wind power. From this workshop it became evident that it was desirable to test a representative large wind turbine as quickly as possible to provide engineering data for use as a base for the entire wind energy program. During FY 1974 a 5-year wind energy program plan was developed as part of the Solar Energy Plan of the Project Independence Blueprint (Ref. 2). This wind energy program included the 1973 workshop recommendation to proceed with the design, building and testing of a nominal 100 kW, 125-foot-diameter rotor wind turbine; this wind turbine was designated Mod-O.

The NASA-Lewis Research Center (LeRC) was delegated the responsibility for designing, building and testing the Mod-O wind turbine as part of the wind energy program being managed by the National Science Foundation. The Mod-O became operational in September 1975. In January 1975 the responsibility for managing the wind energy program was transferred to the Energy Research and Development Administration (ERDA) and then the recently formed Department of Energy (DOE). NASA-LeRC has continued to manage the Mod-O project and several other large wind turbine projects. These other projects include three 200 kW wind turbines similar to Mod-O and designated Mod-OA, one 200-foot-diameter 2000 kW wind turbine designated Mod-1, and several 300-foot-diameter 2500 kW wind turbines designated Mod-2. This paper contains a description of these wind turbine systems, their programmatic status, and a summary of their potential costs.

MOD-O (100 kW) TEST-BED PROJECT

Description

The Mod-O wind turbine has been described in several earlier reports (Refs. 3 to 9). Figure 1 is a photograph of the wind turbine in operation at the NASA-Plum Brook site near Sandusky, Ohio. The wind turbine has a two-bladed constant 40 rpm 125-foot-diameter rotor located downwind of the tower. The rotor drives a 100 kW synchronous alternator through a step-up gear box. The drive train and rotor are located in a nacelle with a centerline 100 feet above ground. The nacelle sits on top of a four-legged steel truss tower. Wind direction is sensed by a wind vane on top of the nacelle and is used as a signal for the yaw control for keeping the wind turbine alined in the direction of the wind. Details of the drive train system and the yaw system are shown in Figure 2.

The operation of the Mod-O wind turbine consists primarily of startup, normal operations connected to the utility network, shutdown, and standby. Figure 3 shows the several different modes that Mod-O can be operated in at Plum Brook. In addition to connection to the Ohio Edison utility system, Mod-O can be connected to: (1) a load bank; (2) a diesel generator of approximately 160 kW; and (3) the Plum Brook network. The Plum Brook network can be disconnected from Ohio Edison to provide a good simulation of a small utility network with several small generators and real load characteristics. The basic wind turbine controls are shown in Figure 4; these are: (1) the yaw control for alining the wind turbine with the wind direction; and (2) the blade pitch control used for startup, shutdown, and power control. All normal operation functions are programmed into a microprocessor which provides the supervisory control for the wind turbine. A safety shutdown system is wired into the Mod-O controls to automatically and safety shut the wind turbine down in the event any key parameters are out-of-tolerance. In addition to the on-site microprocessor and safety systems, a remote control and monitoring system is designed to allow the Wind Energy Project Office (or a local utility dispatcher in the case of follow-on wind turbines) to monitor and control the wind turbine operation.

When the wind turbine is shutdown the blades are feathered and are free to slowly rotate. The normal wind turbine operation for cut-in, rated and cut-out wind speeds is shown in Figure 5. Gilbert describes the normal startup, shutdown, and overspeed conditions in Reference 7. For wind speed at cut-in (7 mph) or greater, the yaw control is activated and the wind turbine alined with the wind. The blades are then pitched at a programmed rate and the rotor speed is brought to about 41 rpm. At this time the automatic syncrhonizer is activated and the wind turbine is synchronized with the utility network. Synchronization analyses for the Mod-O are reported in Reference 10.

For wind speeds between cut-in and rated (14.5 mph) the blade pitch angle is held constant at 0^{o} (at 3/4 of the blade radius). For wind speeds above rated the blade pitch angle is automatically controlled to limit the wind turbine power to 100 kW. For winds above cut-out (34 mph), the blades are feathered and the wind turbine is shutdown. All of these wind speeds are measured at a 30-foot-elevation.

Dynamic Loads

The Mod-O first achieved rated speed and power in December 1975. At this time, the machine performed as predicted except for larger than expected blade bending moments (Ref. 11).

These blade loads were higher than expected for both the flatwise (out-of-plane) and edgewise (in-plane) moment loads. These high loads did not damage the blades, but continuous operation at these load levels would have resulted in early fatigue failure of the blades. Figure 6 shows the predicted blade loads, both flatwise and edgewise, and the December 1975 data as reported by Spera (Ref. 12). The predicted loads were obtained using the MOSTAB rotor analysis code (Ref. 13). The cyclic moments plotted in Figure 6 are at station 40 in the blade shank (40 in. from the rotor axis) and are plotted versus nominal wind speed. Cyclic moment is equal to one-half the difference between the maximum and minimum values of moment during one revolution of the rotor. The data is represented by mean values with the bars representing $\pm 1\ \sigma$ (± 34 percent of the data about the mean). The variations about the mean are caused by such things as variations in wind direction and velocity and control changes.

As a result of the high blade loads, an intensive study was undertaken to analyze the loads data and to (1) determine the causes of the high loads and (2) to reommend modifications to reduce the loads. This study clearly showed that the flatwise bending moments were primarily caused by the impulse applied to the blade each time it passed through the wake of the tower. It was concluded that the tower was blocking the airflow much more than had been expected. The higher blockage was confirmed by site wind measurements (Ref. 14) and wind tunnel tower model tests (Ref. 15). To reduce the tower blockage and increase the airflow through the tower it was decided to remove the stairways from the tower. Figure 7 shows the tower with and without stairs. This modification reduced the tower blockage from 0.64 to 0.35 (a blockage of 1.0 meaning that the airflow through the tower is zero).

The study of the edgewise blade loads, particularly their harmonic content, led to the conclusion that these high loads were caused by excessive nacelle yawing motion. To reduce these loads it was recommended that the single yaw drive be replaced by a dual yaw drive. This dual yaw drive was expected to help by (1) changing the torsional frequency of the system and moving it away from the 2P (two cycles per rotor revolution) resonance; and (2) eliminating the free-play present in the single yaw drive. Figure 8(a) shows the dual yaw drive that was implemented on Mod-O. In addition to the dual yaw it was also decided to add three brakes to the yaw system to provide additional stiffness (Fig. 8(b)). The result of these modifications on the blade moments is shown in Figure 9. Both flatwise and edgewise bending moments were reduced below the values predicted by MOSTAB.

It should be noted that tower shadow and yaw stiffness are excellent examples of why the Mod-O project was initiated. The early higher than expected loads led to extensive re-evaluation of the analytical tools and subsequent redesign of the wind turbine. This information has been extremely important in the design of the large follow-on wind turbines.

Operations Summary

The Mod-O operations to date have shown that the wind turbine controls for speed, power and yaw work very satisfactorily. Synchronization to the utility network has been demonstrated routinely. The normal wind turbine operations for startup, utility operation, shutdown and standby have all been demonstrated and performance is quite satisfactory. the Mod-O has also been used to check out remote operation as is planned for the Mod-OA and Mod-1 wind turbines. In summary, the Mod-O has exhibited quite satisfactory operation and no operations problems are apparent at this time.

Major Tests Planned

Several major tests are being planned for the Mod-O. These are primarily tests of various concepts that appear to offer ways of reducing system weight, loads and complexity and thereby reducing the costs of large wind turbines. The tests presently planned include:

Passive yaw. - Decoupling of the yaw drive on the Mod-O to determine the effects on stability, performance and dynamic loads. Lower yaw stiffness could result in lighter weight towers, bed plate structure and lower cost yaw controls.

Upwind rotor. - Analysis has indicated that blade cyclic loads are reduced with the rotor in the upwind direction. The Mod-O will be modified to allow upwind testing.

Blade tip control. - It appears that rotor power can be controlled effectively by only controlling a small portion of the blade (~15 percent). Such control should result in simpler and less-expensive hub and pitch control systems. Tests with tip controlled blades are planned for Mod-O.

Teetered hub. - Analysis has shown that the use of a teetered hub reduces the blade flapwise loads and the yaw loads. A teetered hub test is planned for Mod-O to experimentally verify these analysis results.

Nonrigid tower. - Analysis has indicated that stable operation can be obtained with nonrigid towers. Such towers will be lighter in weight and lower in cost. Tests are planned for the Mod-O to simulate less-rigid towers to obtain data to verify the analysis.

LARGE EXPERIMENTAL WIND TURBINES FOR ELECTRIC UTILITY APPLICATIONS

As a part of the Federal Wind Program, it is planned to test several large experimental wind turbines at selected electric utility sites. These large experimental wind turbines include three of the Mod-OA (200 kW) type, one Mod-1 (2000 kW) and possibly several of the Mod-2 (2500 kW) designs.

Electric Utility Sites

The selection of utility company sites for experimental wind turbines was made on the basis of proposals submitted by the utility companies. Over 64 utility companies submitted detailed information about their company and the site they proposed for installation of a wind turbine. These proposed sites were evaluated on the basis of available wind energy, need for supplemental power, interest in supplying personnel for the program, and variations in climatic and topographical conditions. The 17 sites selected for more detailed evaluation are shown and listed in Figure 10 along with the participating utility company. Identical meteorological towers and wind instrumentation were installed at each site so that the wind potential of the sites could be evaluated on a common basis.

Mod-OA Project

The Mod-OA project was initiated in 1975 for the purpose of obtaining early experience with large wind turbines operating on utility networks. A description of this project is made by Robbins in Reference 16.

The Mod-OA wind turbine is very similar to the Mod-O. The major difference is that the gear box and generator have been increased in size and capacity to provide a power output of 200 kW instead of 100 kW. The 200 kilowatts is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. The rated wind speed is defined as the lowest wind speed at which full power is achieved. The power output as a function of wind speed, shown in Figure 11, is regulated by varying the pitch angle of the blades. At wind speeds below cut-in and above cut-out the rotor blades are placed in a feathered position and no power is produced. The cut-in wind speed, defined as the lowest wind speed at which power can be generated, is 7.0 mph. The cut-out wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade stress, is 34.2 mph. All of these wind speeds are measured at a 30-foot-elevation.

Three utility sites selected for installation of Mod-OA wind turbines are: Clayton, New Mexico, Island of Culebra, Puerto Rico, and Block Island. All three sites currently use diesel or natural gas fueled reciprocating engines to drive their generators. The peak power demand for each of these utilities is in the 1500- to 2500-kilowatt range. An overall view of the Clayton site is shown in Figure 12. The wind turbine at Clayton is currently undergoing checkout operations, having achieved first rotation on November 30, 1977. The wind turbines at Culebra and at Block Island are scheduled to become operational in June and December of 1978, respectively.

Mod-1 (2000-kW Project)

The objective of the Mod-1 wind turbine project is to develop a megawatt size wind turbine which has the potential for generating electrical power on utility systems at costs competitive with alternative energy sources. General Electric's Space Division was awarded a contract in July 1976 to design and build a megawatt sized wind turbine optimized for a site with a mean wind speed of 18 mph. Details of this design were presented by Barchet in Reference 17. Figure 13 is an artist's sketch of the WT. In summary, the resulting design is rated at 2000 kW and has a 200-foot-diameter, two-bladed down-wind rotor driving a conventional gearbox and synchronous generator. The rotor and drive train are mounted on a large bearing at the top of a truss tower. The Mod-1 is a much larger machine than the Mod-OA, but in concept it is very similar to the Mod-O/-OA designs. Figure 14 is a comparison of the Mod-1 and Mod-OA operating characteristics.

At this time the design has been completed and fabrication of the system is in process. The Blue Ridge Electrical Membership Corporation has been selected by DOE as the utility to receive the Mod-1. The site selected is in Howard's Knob in Boone, North Carolina. The Mod-1 is scheduled to first rotate in November 1978.

During the Mod-1 design the costs and weight of the wind turbine grew to approximately twice what was originally proposed. This growth was primarily the result of an increase in the expected loads. At the beginning of the program the analysis codes for estimating loads had not yet been verified and resulted in low loads prediction.

At the completion of the Mod-1 design, General Electric was requested by NASA to do an additional design study with the objective of meeting the proposed costs and weights.

Mod-1A Design Study

The objective of this design study was to design a 2000 kW wind turbine with an estimated second unit cost of two million dollars and with a system weight of less than 400 000 pounds. The wind turbine was to meet the same application and environmental requirements as Mod-1, but could incorporate design ideas for reducing loads and weight that have emerged during the past several years.

The results of the design study concluded that a 2000 kW machine could be designed to meet the Mod-1 requirements and that the weight could be reduced from 698 000 to 320 000 pounds and the cost for the second unit reduced from $3.2 to $2.0 M. Figure 15 shows a sketch of the resulting Mod-1A wind turbine. A discussion of the potential energy costs for a Mod-1A is presented in the last section of this paper.

Mod-2 (2500 kW) Project

The objective of the Mod-2 project is to determine the potential cost-effectiveness of megawatt-sized wind turbines, with rotors of 300-feet in diameter or more, when located at sites with moderate (14 mph mean) winds.

A contract for the design, fabrication and assembly of three wind turbines was awarded to the Boeing Engineering and Construction in August 1977. Boeing proposed a two-bladed downwind wind turbine rated at 2500 kW (Fig. 16). The estimated power outputs of the Mod-2 as a function of wind speed is compared with the Mod-1 and Mod-OA in Figure 17. This machine has a conventional gearbox and generator but the whole assembly is mounted on a more flexible tower than the Mod-OA/ Mod-1 designs.

Boeing has been evaluating several primary trade-offs during the initial part of the program. These trades include: upwind and down-wind rotors, two or three bladed rotors, teetered and rigid hubs, soft and rigid towers and a number of different drive train and power generation configurations.

The wind turbine proposed by Boeing utilizes conventional welded steel construction for the blades and towers and is estimated to weigh a total of 625 000 pounds. The first Mod-2 is scheduled to start operation in November 1979. The sites for the Mod-2 wind turbines will be selected this year by DOE.

SCHEDULE

The schedule for the first operation of the large experimental wind turbines at utility sites is shown in Figure 18. The first Mod-OA (200 kW) wind turbine became operational at Clayton, New Mexico, in November 1977. The Mod-OA machinery for Culebra, Puerto Rico, has been assembled by Westinghouse and the site preparation is now in process. First operation is planned for May 1978. The third Mod-OA is scheduled for operation at Block Island, Rhode Island, for December 1978. The Mod-1 (2000 kW) wind turbine is being assembled by General Electric and site work at Boone, North Carolina, has been initiated. First operation of the Mod-1 is scheduled for November 1978. The first Mod-2 (2500 kW) is scheduled for operation in November 1979, but the site for wind turbine will not be selected until late this year by DOE. Additional Mod-2 wind turbines may be built but they will not be scheduled until later in the program.

ENERGY AND COST COMPARISON

Energy

The annular energy output of the large wind turbines is shown in Figure 19 of a range of site mean wind speeds from 12 to 18 mph. The energy output was calculated assuming a 90 percent machine availability of the wind turbine; it was assumed that the wind turbine would be shutdown for maintenance 10 percent of the time that the winds are in the range for generating power. Figure 19 shows the large increase in annual energy that is available as the rotor diameters are increased from 125 to 200 to 300 feet and shows that a Mod-2 at a site with a mean wind speed of 15 mph should produce 10 400 MWh a year. This amount of annual energy is enough to provide the electrical requirements of approximately 1400 households assuming an average household requires 600 kWh per month. A Mod-1 and a Mod-OA wind turbine at the same site could generate enough electricity for 640 and 120 households, respectively.

Cost of Electricity

The cost-of-electricity (COE) provided by a wind turbine is calculated using the following equation:

$$\text{COE } (¢/\text{kWh}) = \frac{(\text{Capital cost})\ (\text{Annual charge rate})}{\text{Annual energy}}$$

The annual charge rate is assumed to be equal to 0.18 and includes the following: (1) capital recovery; (2) state and federal taxes; and (3) operations and maintenance.

Second unit costs. - Table I gives the estimated captial costs for the second Mod-OA, -1, -1A, and -2 wind turbines and the annual energy output at two different mean wind speed sites. Using these capital costs, annual energy outputs and the above equation, the cost-of-electricity for each of these machines was calculated (Fig. 20). Figure 20 shows that the cost-of-electricity for these large machines at sites with mean wind speeds of 18 to 15 mph varies from 5 to 7 cents per kWh for the Mod-2, from 5 to 8 cents per kWh for Mod-1A and from 20 to 25 cents per kWh for the Mod-OA.

Mature product costs. - To estimate what the cost of a wind turbine might eventually be in production, it was assumed that wind turbines could be fabricated, assembled and installed for a cost of 2 to 3 dollars per pound. This is a rather simplistic way to estimate cost of a mature product, but data is available that shows that many machinery items such as large tractors, power shovels, steam turbines, etc., are fabricated, assembled, and distributed for 2 to 3 dollars per pound. An estimated captial cost range for the Mod-1A and Mod-2 wind turbines was made using the 2 to 3 dollars per pound and the weights given in Table I. The potential cost-of-electricity was then calculated using the estimated annual energy for the 12, 15, and 18 mph mean wind speed sites (Fig. 21).

Using this estimation method for obtaining the potential cost-of-electricity for these large wind turbines results in rather attractive results. Figure 21 shows that the Mod-2 and Mod-1A machines have the potential to generate electricity at 1.7 to 2.5 cents per kWh and 2.2 to 3.3 cents per kWh at 18 and 15 mph mean wind speed sites, respectively.

CONCLUDING REMARKS

The large wind turbine portion of the Federal Wind Energy Program consists of two major project efforts: (1) the Mod-O test bed project for supporting research technology, and (2) the large experimental wind turbines for electric utility applications. The Mod-O has successfully demonstrated startup, synchronization to utility network, blade pitch control for power control and shutdown. Also, fully automatic operation of the wind turbine similar to the operation planned for utility sites has been demonstrated. In summary, the Mod-O has met its primary objective of providing the entire wind energy program with early operations and performance data. Mod-O is continuing to be used as a test bed to evaluate wind turbine concepts that show promise for loads and weight reduction and consequently lower costs.

The large experimental wind turbines to be tested in utility applications include three of the Mod-OA (200 kW) type, one 2000 kW (Mod-1) and possibly several of the Mod-2 (2500 kW) designs. The first Mod-OA became operational at Clayton, New Mexico, in November 1977, and the other two are planned to be installed at Culebra, Puerto Rico and Block Island, Rhode Island, in 1978. The Mod-1 design is complete and fabrication is underway. The Mod-1 is to be installed at Boone, North Carolina, in November 1978, as a part of the Blue Ridge Electrical Membership Corporation. The Mod-2 contract was initiated in August 1977 and preliminary designs are underway. The first Mod-2 is scheduled to start operations in December 1979 at a site to be selected by DOE.

The energy costs for the first Mod-OA and Mod-1 wind turbines vary from 10 to 25 cents per kWh for sites with mean annual wind speeds of 18 to 15 mph. A recent redesign of the Mod-1 (Mod-1A) to incorporate design improvements show that second unit costs of 5 to 8 cents per kWh are possible for these large machines at the 18 to 15 mph sites. Also, the early results of the Mod-2 design studies indicate even slightly lower second unit costs for electricity. It has been estimated that these energy costs can be reduced to 1.5 to 3.5 cents per kWh assuming a mature product industry. For calculation purposes it was assumed that a mature product would result in the fabrication, assembly, and installation of a large machine at costs of 2 to 3 dollars per pound.

In summary, it appears that large wind turbines have the potential to be cost effective in many utility applications if the present designs materialize into mature product lines.

REFERENCES

1. Savino, J., ed.: Wind Energy Conversion Systems, Workshop Proceedings. NSF/RA/W-73-006, National Science Foundation, Dec. 1973. Also NASA TM X-69786, 1973.
2. Project Independence Report. Federal Energy Administration, Washington, D.C., Nov. 1974.
3. Ruthoff, R. L.; and Sirocky, P.: Status Report of 100 kW Experimental Wind Turbine Generator Project. NASA TM X-71758, 1975.
4. Puthoff, R. L.: Fabrication and Assembly of the ERDA/NASA 100-Kilowatt Experimental Wind Turbine. NASA TM X-3390, 1976.
5. Thomas, R. L.: Large Experimental Wind Turbines - Where We Are Now. NASA TM X-71890, 1976.
6. Linscott, B. S.; Shapton, W. R.; and Brown, D.: Tower and Rotor Blade Vibration Test Results for a 100-Kilowatt Wind Turbine. NASA TM X-3426, 1976.
7. Gilbert, L. J.: A 100 kW Experimental Wind Turbine: Simulation of Starting, Overspeed, and Shutdown Characteristics. NASA TM X-71864, 1976.
8. Donham, R. E.; Schmidt, J.; and Linscott, B. S.: 100 kW Hingeless Metal Wind Turbine Blade Design, Analysis and Fabrication. Presented at the 31st Annual National Forum of the American Helicopter Society, (Washington, D.C.), May 13-15, 1975.

9. Thomas, R. L.; and Richards, T. R.: ERDA/NASA 100-Kilowatt Mod-1 Wind Turbine Operations and Performance. ERDA/NASA/ 1028-77-9, NASA TM-73825, 1977.

10. Hwang, H. H.; and Gilbert, L. J.: Synchronization of the ERDA-NASA 100 kW Wind Turbine Generator with Large Utility Networks. NASA TM X-73613, 1977.

11. Glasgow, J. C.; and Linscott, B. S.: Early Operation Experience on the ERDA/NASA 100 kW Wind Turbine - Rotor Blade Loads. NASA TM X-71601, 1976.

12. Spera, D. A.; Janetzke, D. C.; and Richards, T. R.: Dynamic Blade Loading in the ERDA-NASA 100 kW and 200 kW Wind Turbines. ERDA/NASA/1004-77/2, NASA TM-73711, 1977.

13. Hoffman, J. A.: Coupled Dynamics Analysis of Wind Energy Systems. (PPI-1014-11, Paragon Pacific Inc.; NASA Contract NAS3-19767.) NASA CR-135152, 1977.

14. Wilson, D. J., et al.: Full-Scale Measurements for 100 kW Wind Turbine via Laser Velocimetry. LMSC-HREC-TR-D497001, Lockheed Missiles and Space Co., Inc., 1976.

15. Savino, J. M.; and Wagner, L. H.: Wind Tunnel Measurements of the Tower Shadow on Models of the ERDA/NASA 100 kW Wind Turbine Tower. NASA TM X-73548, 1976.

16. Robbins, W. H.; and Sholes, J. E.: ERDA/NASA 200 kW-Mod-O Wind Turbine Program. Paper presented at Third-Biennial Conference and Workshop on Wind Energy Conversion Systems, sponsored by the Energy Research and Development Administration, Sept. 19-21, 1977.

17. Barchet, R. J., Mod-1 Wind Turbine Generator Program Mid-Way Status Report. Paper presented at Third-Biennial Conference and Workshop on Wind Energy Conversion Systems, sponsored by the Energy Research and Development Administration, Sept. 19-21, 1977.

TABLE I. - ESTIMATED SECOND UNIT COSTS, WEIGHTS AND ENERGY FOR THE MOD-OA, MOD-1, AND MOD-2 WIND TURBINES

	Capital cost, * (k$)	Total weight, (k-lb)	Annual energy, ** (MWh)	
			15 mph mean wind site, (30 ft)	18 mph mean wind site, (30 ft)
Mod-OA	1250	88.9	892	1 103
Mod-1	3200	698	4 590	6 703
Mod-1A	2078	320	4 590	6 703
Mod-2	3877	625	10 395	13 293

*Estimated for second unit.

**Assumes 90 percent machine availability.

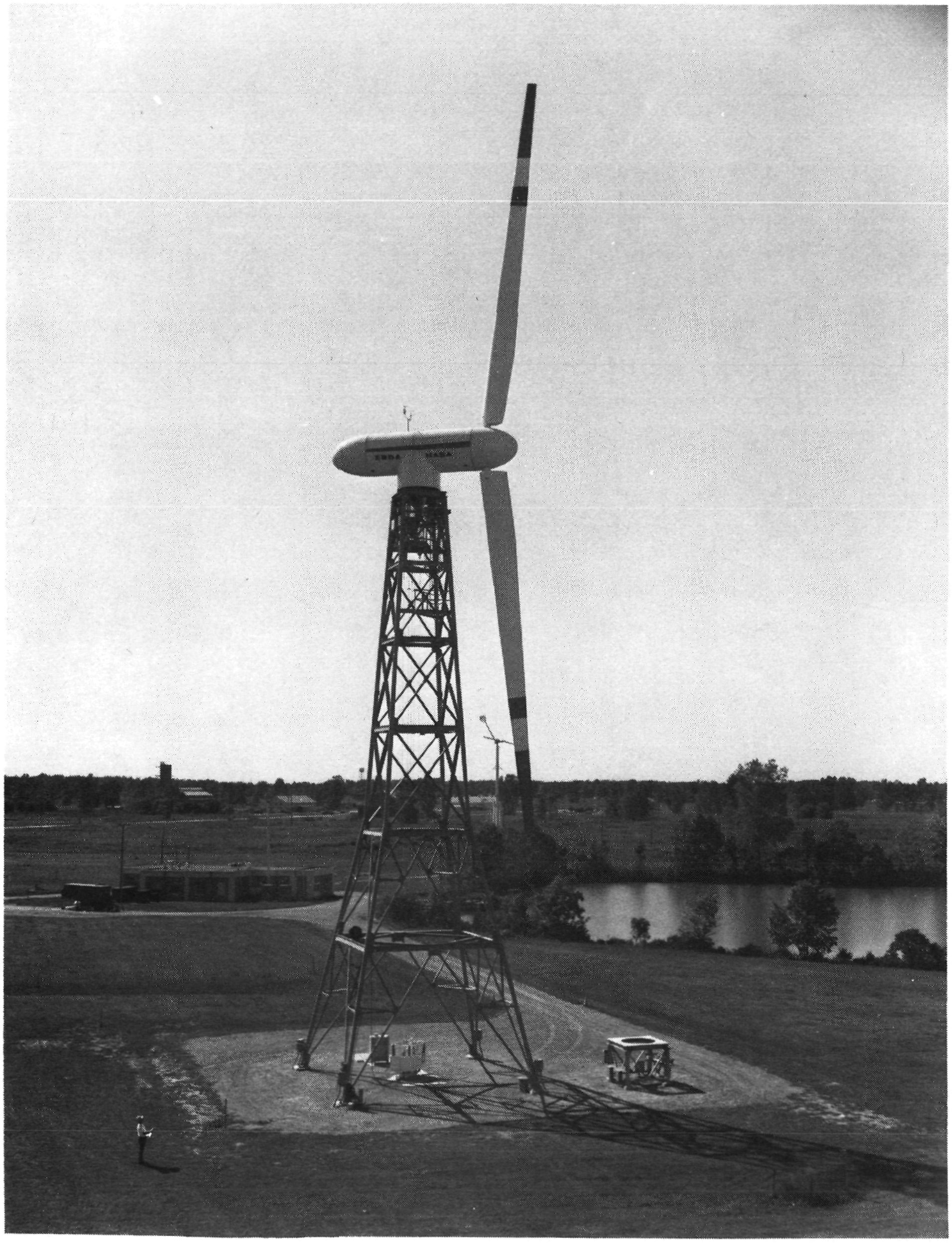


Figure 1. - Photo of 100 kW Mod-0 wind turbine.

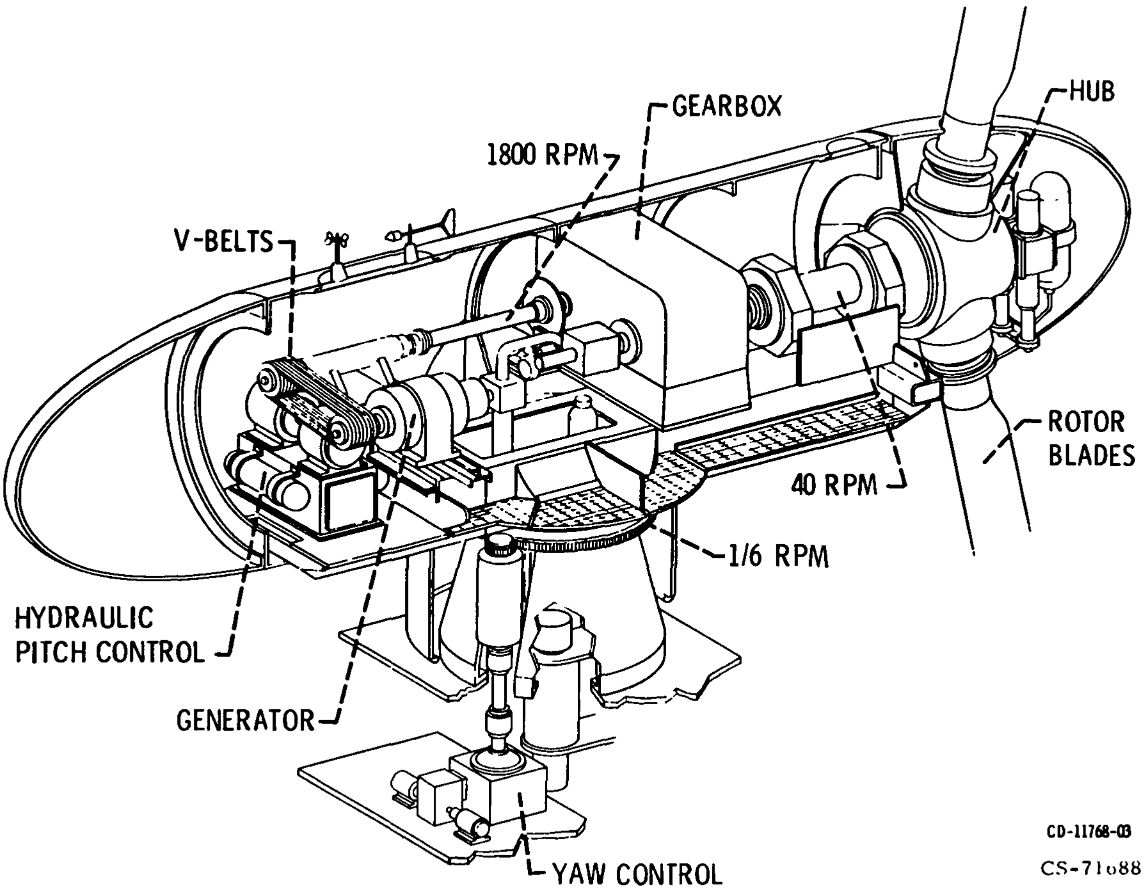
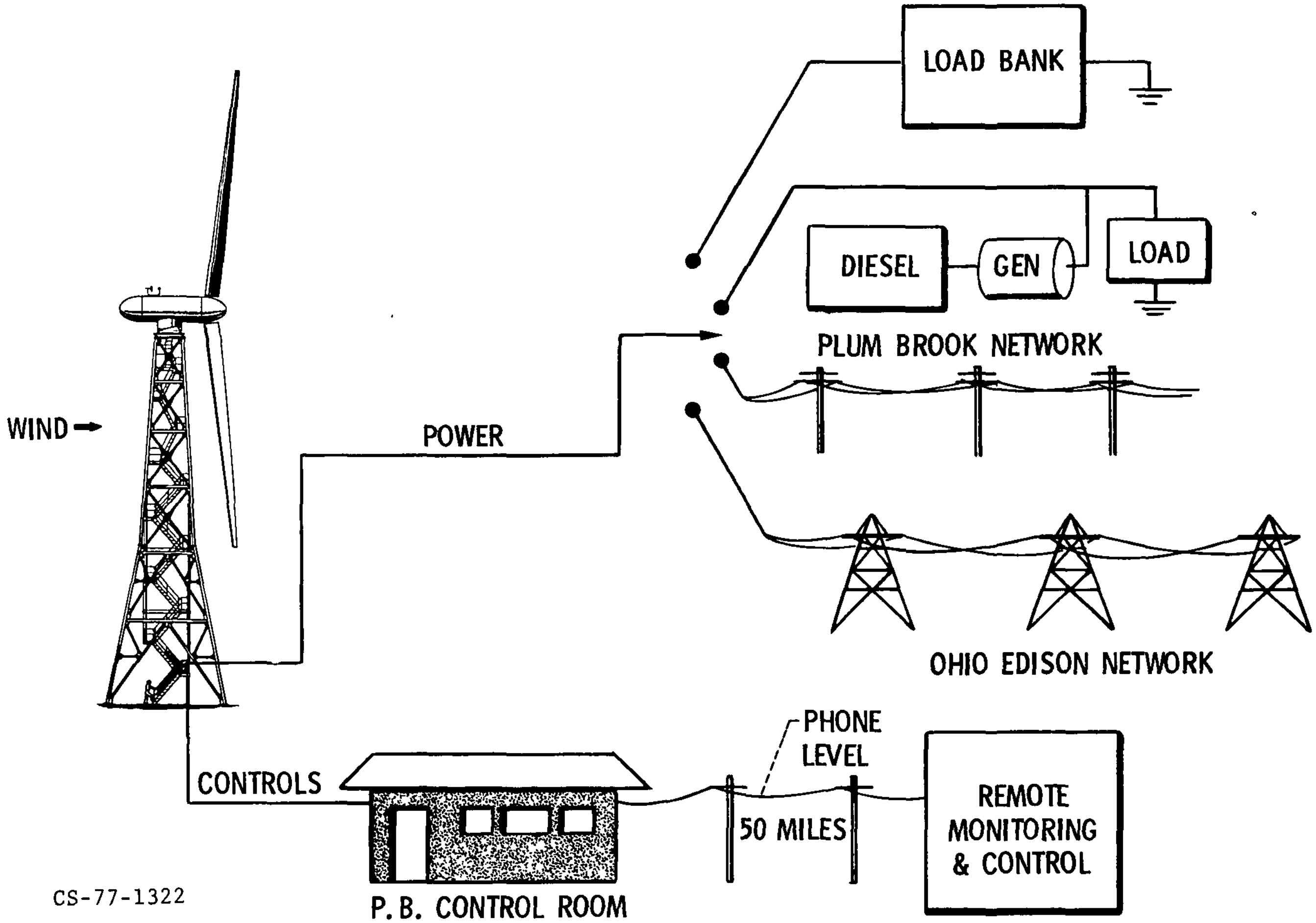


Figure 2. - 100 kW wind turbine drive train assembly and yaw system.



CS-77-1322

Figure 3. - Mod-0 operation.

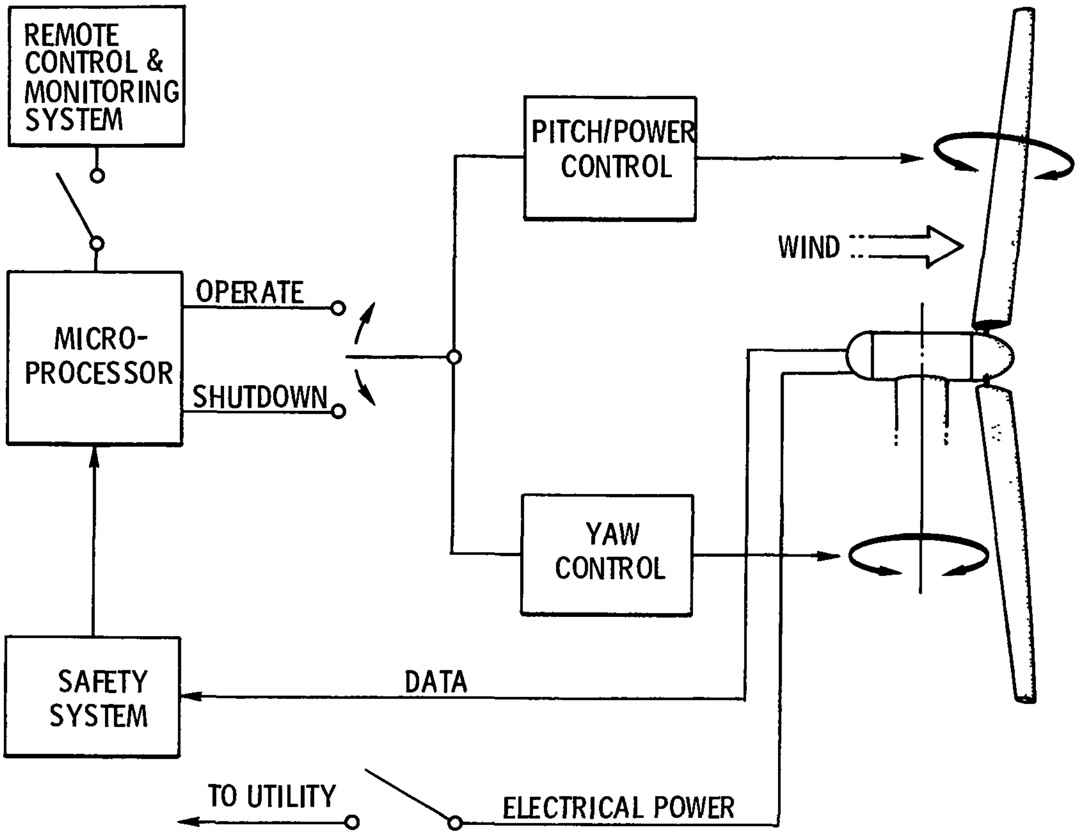


Figure 4. - Mod-0 controls.

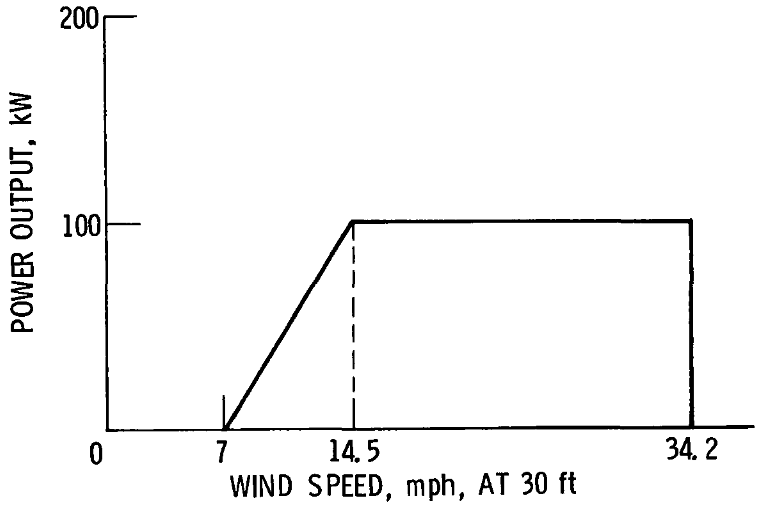


Figure 5. - Mod-0 power output vs wind speed.

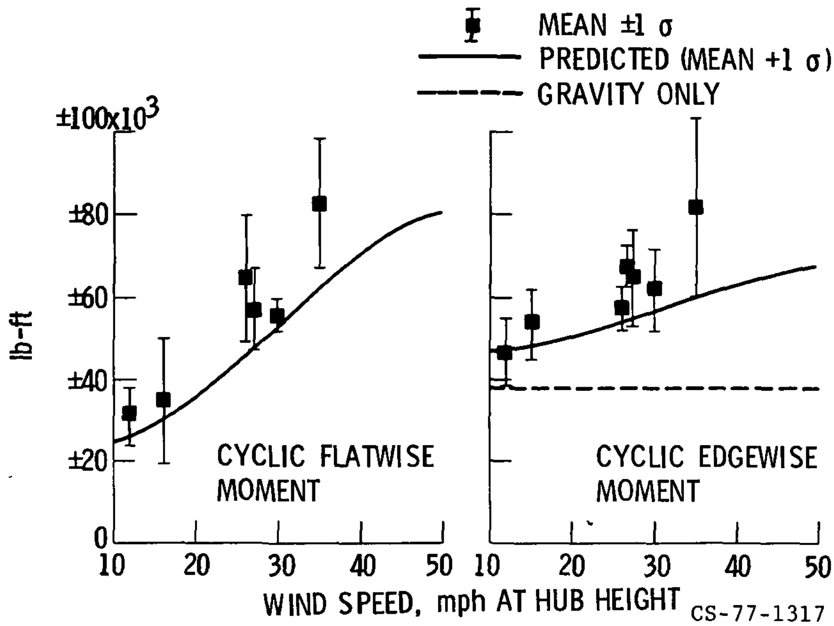


Figure 6. - Mod-0 blade loads.

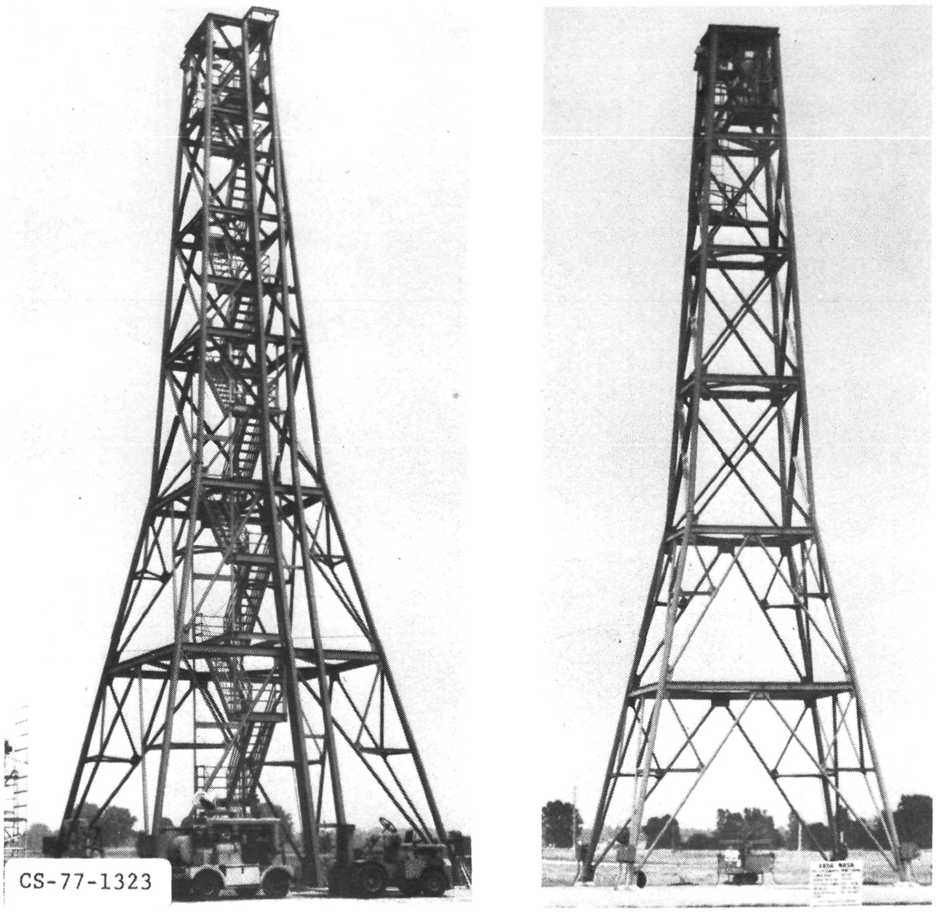


Figure 7. - Mod-0 tower with and without stairs.

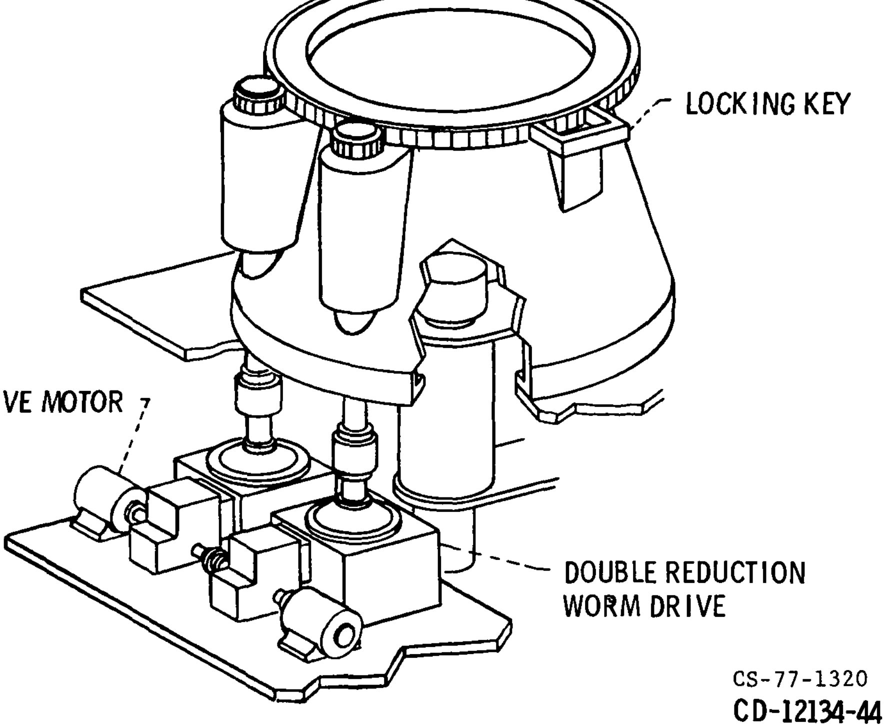


Figure 8(a). - Mod-0 dual yaw drive system.

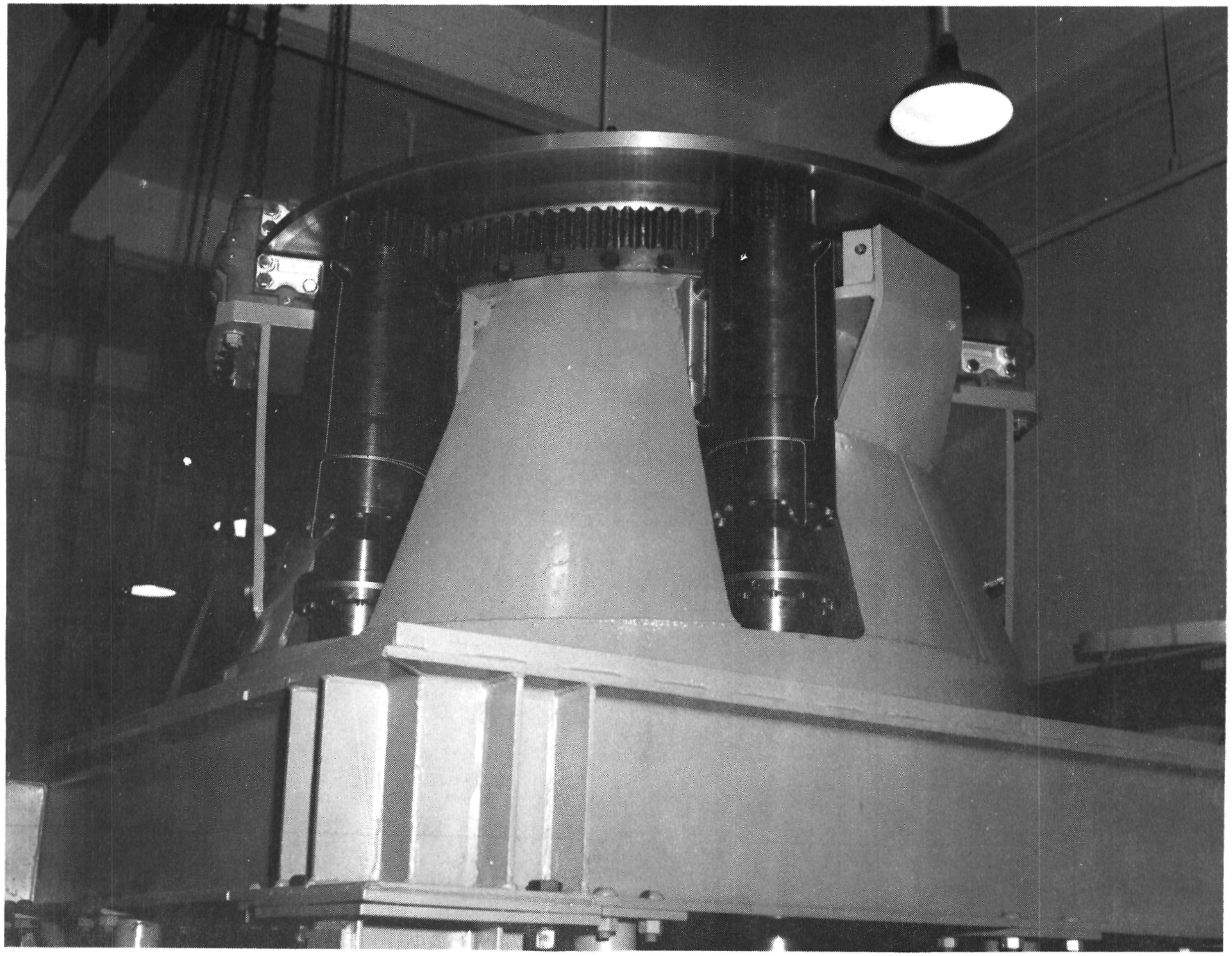


Figure 8 (b). - Mod-0 dual yaw system with yaw brakes.

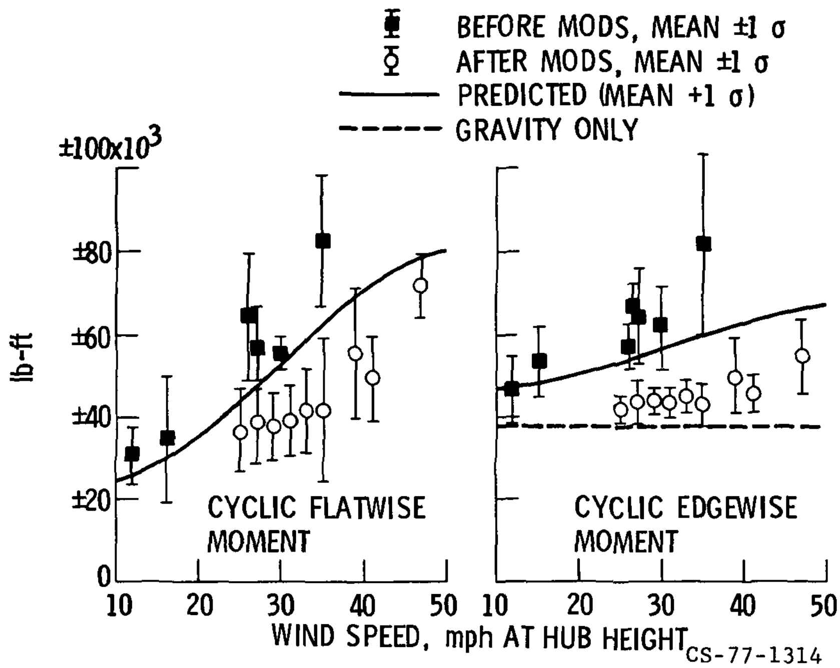
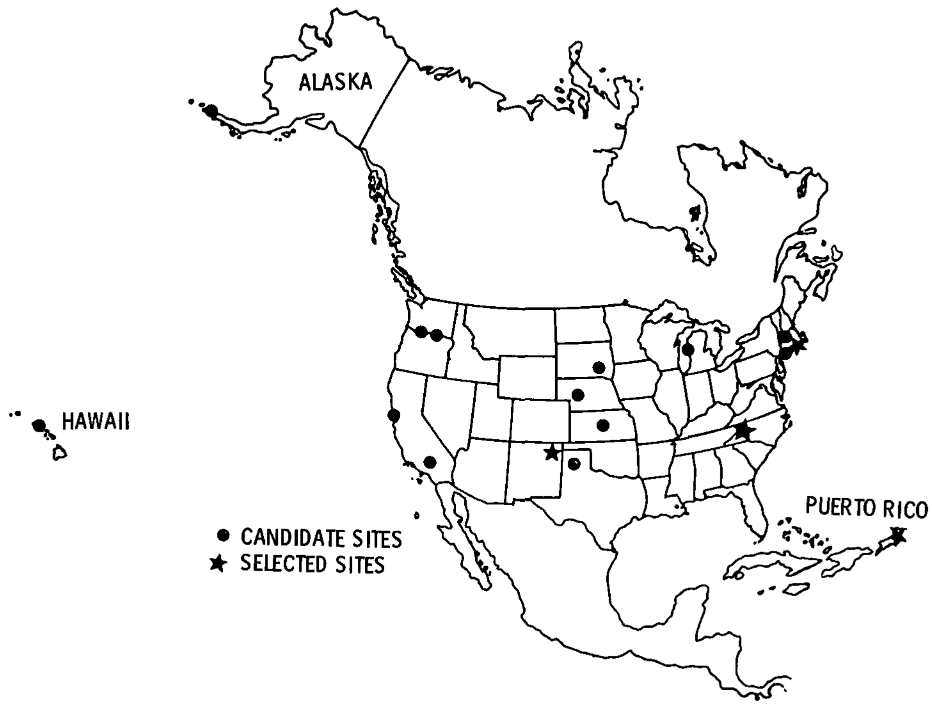


Figure 9. - Mod-0 blade loads before and after modifications.



SITE	ORGANIZATION	SITE	ORGANIZATION
COLD BAY, ALASKA	ALASKA BUSSELL ELECTRIC CO.	MONTAUK POINT, LONG ISLAND, NEW YORK	LONG ISLAND LIGHTING CO.
POINT ARENA, CALIFORNIA	PACIFIC GAS AND ELECTRIC CO.	BOONE, NORTH CAROLINA[b]	BLUE RIDGE ELECTRICAL MEMBERSHIP CORPORATION
SAN GORGONIA PASS, CALIFORNIA	SOUTHERN CALIFORNIA EDISON	BOARDMAN, OREGON	PORTLAND GENERAL ELECTRIC CO.
KAENA POINT, OAHU, HAWAII	HAWAIIAN ELECTRIC CO.	ISLAND OF CULEBRA, PUERTO RICO[a]	PUERTO RICO WATER RESOURCES AUTHORITY
RUSSELL, KANSAS	CITY OF RUSSELL, KANSAS	BLOCK ISLAND, RHODE ISLAND[a]	BLOCK ISLAND POWER CO.
HOLYOKE, MASSACHUSETTS	CITY OF HOLYOKE GAS AND ELECTRIC DEPARTMENT	HURON, SOUTH DAKOTA	EAST RIVER POWER COOPERATIVE
LUDINGTON, MICHIGAN	CONSUMERS POWER CO.	AMARILLO, TEXAS	SOUTHWESTERN PUBLIC SERVICE CO.
KINGSLEY DAM, NEBRASKA	CENTRAL NEBRASKA PUBLIC POWER AND IRRIGATION DISTRICT	AUGSPURGER MOUNTAIN, WASHINGTON	BONNEVILLE POWER ADMINISTRATION
CLAYTON, NEW MEXICO[a]	TOWN OF CLAYTON		

[a]THREE SITES SELECTED FOR 200-kW SYSTEMS.
[b]SITE SELECTED FOR FUTURE INSTALLATION OF 2000-kW SYSTEM.

Figure 10. - Candidate wind turbine sites.

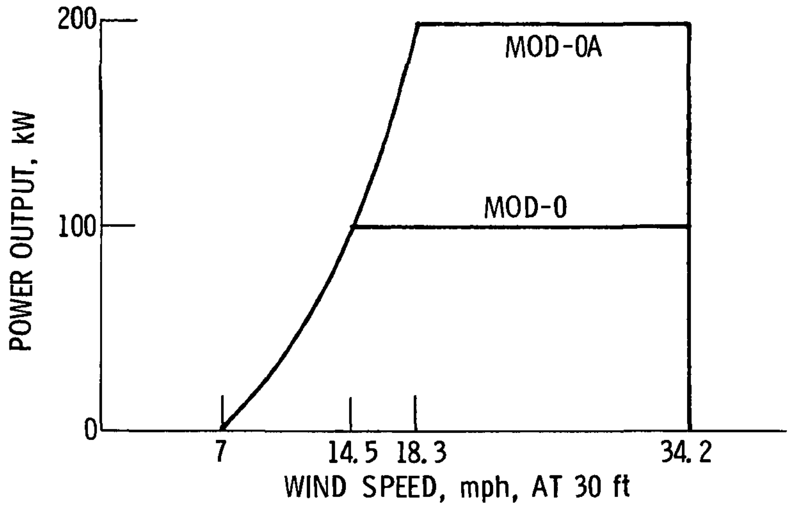


Figure 11. - Mod-0, -0A power output versus wind speed.

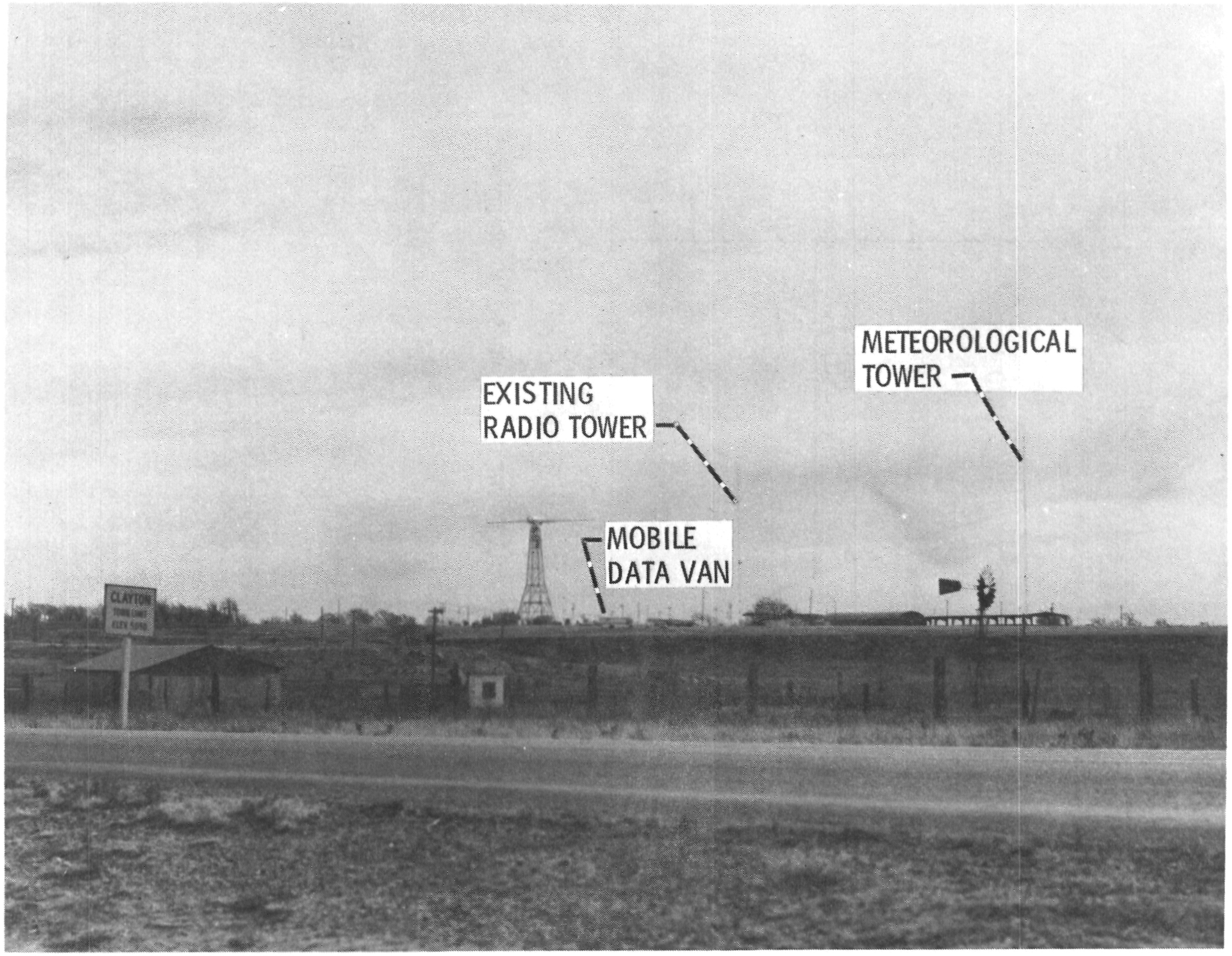


Figure 12. - Overall view of Clayton wind turbine site.

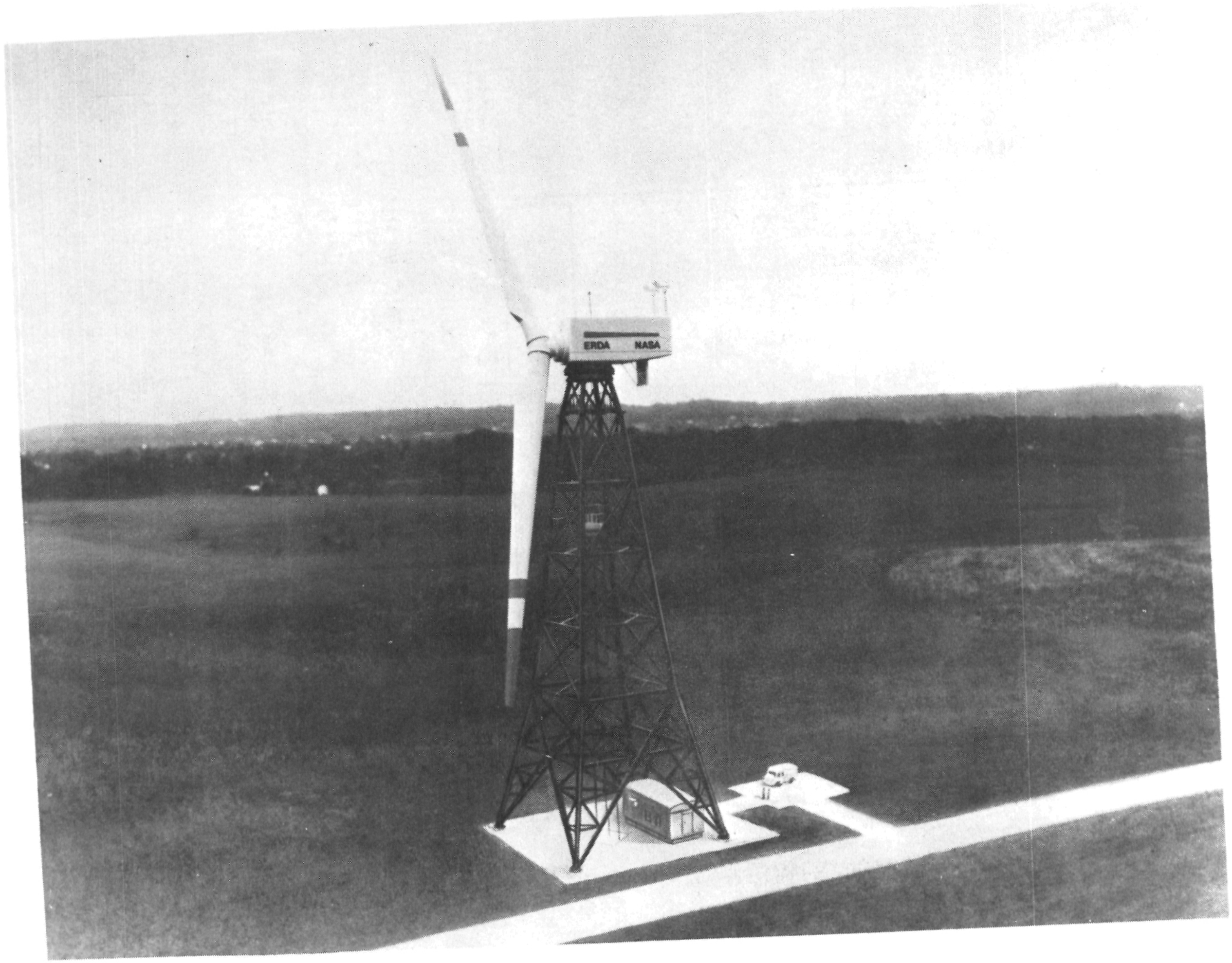


Figure 13. - Mod-1 wind turbine.

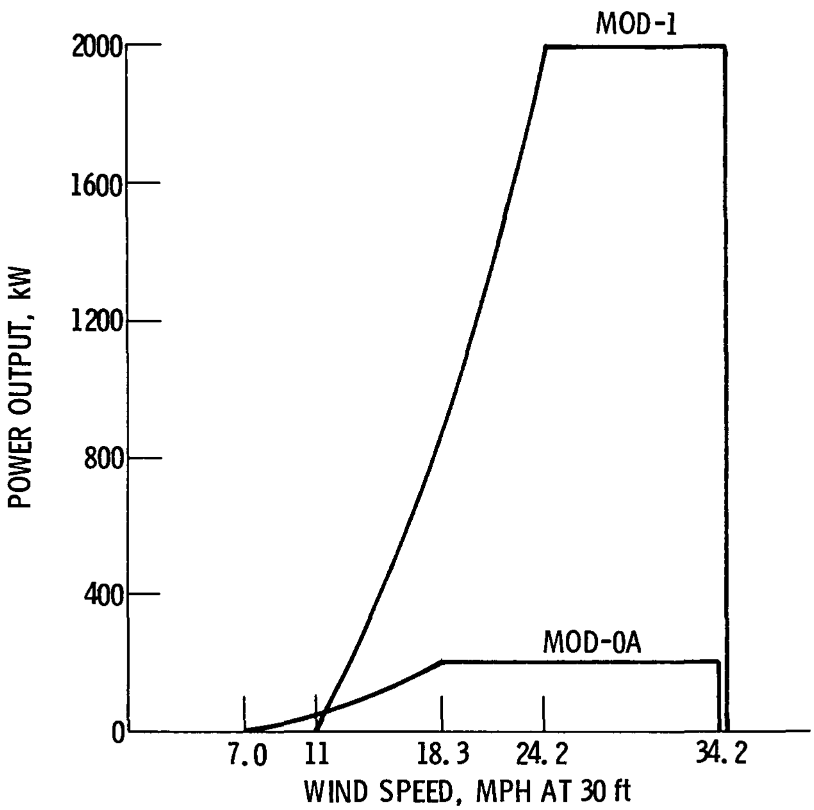


Figure 14. - Mod-0A, Mod-1 power output versus wind speed.

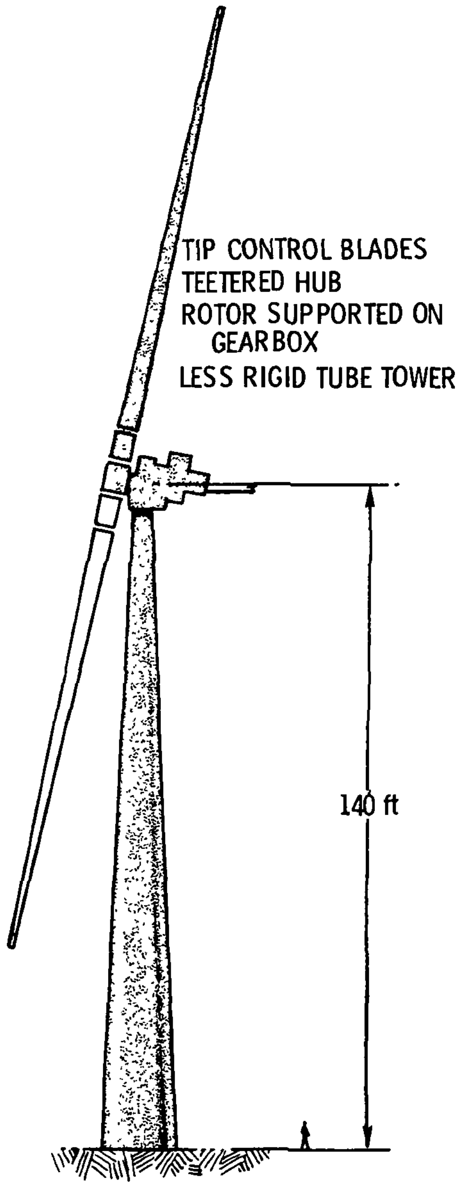


Figure 15. - Mod-1A wind turbine.

Figure 16. - Mod-2 wind turbine.

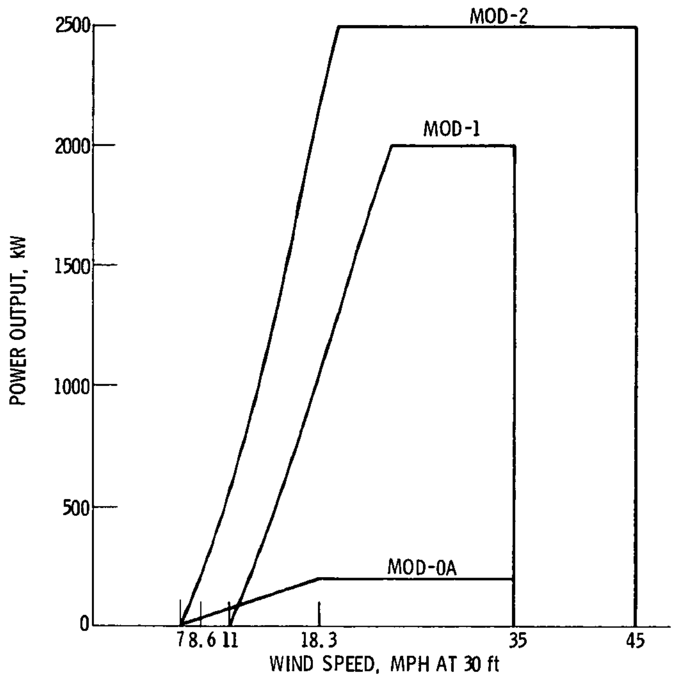


Figure 17. - Power output versus wind speed.

	1977		1978												1979											
	W	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
MOD-0A																										
CLAYTON, NEW MEXICO	▼																									
CULEBRA PUERTO RICO						▼																				
BLOCK ISLAND, RHODE ISLAND											▼															
MOD-1, BOONE, NORTH CAROLINA													▼													
MOD-2 (SITE NOT SELECTED YET)																										▼

Figure 18. - Schedule for first rotation for the large experimental wind turbines.

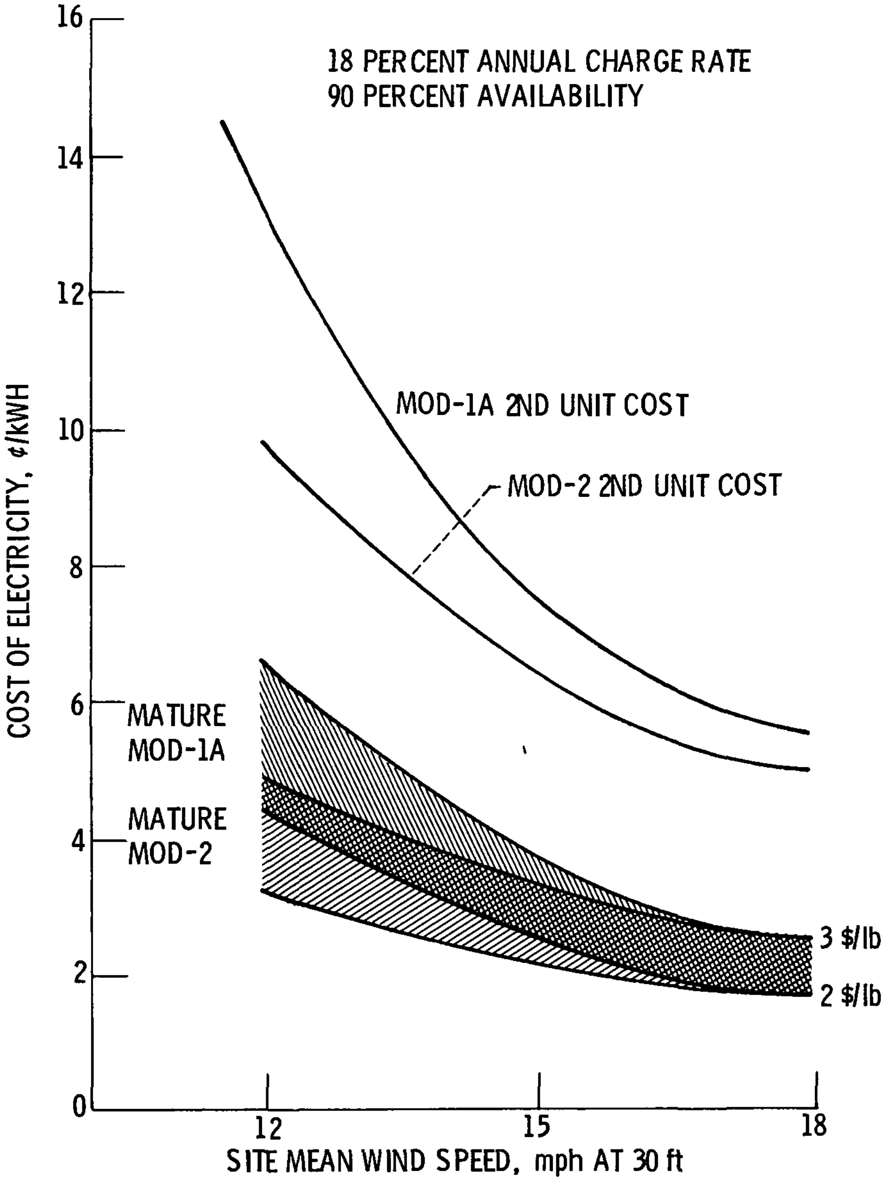


Figure 21. - Estimated cost-of-electricity for second unit and mature products.

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA TM-73767		

4 Title and Subtitle	5 Report Date
LARGE WIND TURBINE GENERATORS	February 1978
	6 Performing Organization Code
7 Author(s)	8 Performing Organization Report No
Ronald L. Thomas and Richard M. Donovon	E-9553
9 Performing Organization Name and Address	10 Work Unit No
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11 Contract or Grant No
	13 Type of Report and Period Covered
12 Sponsoring Agency Name and Address	Technical Memorandum
U.S. Department of Energy Division of Solar Energy Washington, D.C. 20545	14 Sponsoring Agency ~~Code~~ Report No. DOE/NASA/1059-78/1

15 Supplementary Notes

Prepared under Interagency Agreement E(49-26)-1059.

16 Abstract

The National Aeronautics and Space Administration (NASA), under interagency agreement with the Department of Energy, is managing the development associated with large wind turbine systems at the Lewis Research Center in Cleveland, Ohio. This paper briefly describes the scope of this activity which includes the development of several large wind turbines ranging in size from 100 kW to several megawatt levels. A description of the wind turbine systems, their programmatic status and a summary of their potential costs is included.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Wind turbines; Wind mills; Wind generators; Wind energy; Alternate energy sources; Solar energy	Unclassified - unlimited STAR Category 44 DOE Category UC-60

19 Security Classif (of this report)	20 Security Classif (of this page)	21. No of Pages	22 Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161