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Darrell H. Baldwin
National Aeronautics and Space Administration
Lewis Research Center

and

Jerry Kennard
Sverdrup Technology, Inc.

March 1985

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Darrell H. Baldwin
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Jerry Kennard
Sverdrup Technology, Inc.
Middleburg Heights, Ohio 44130

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Darrell H. Baldwin
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Jerry Kennard
Sverdrup Technology, Inc.
Middleburg Heights, Ohio 44130

SUMMARY

A major segment of the Federal Wind Energy Program sponsored by the Department of Energy (DOE) is the program to develop large, horizontal-axis wind turbines. The NASA Lewis Research Center manages that segment for DOE. The program is directed toward developing the technology for safe, reliable, environmentally acceptable large wind turbines that can generate a significant amount of electricity at costs competitive with those of conventional electricity-generating systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements.

Several ongoing projects in large-wind-turbine development are directed toward meeting the technology requirements for utility applications. The machines based on first-generation technology (Mod-0A and Mod-1) successfully completed their planned periods of experimental operation in June 1982. The second-generation machines (Mod-2) are in operation at selected utility sites. A third-generation machine (Mod-5) is under contract. Erection and initial operation of the Mod-5 in Hawaii should take place in 1986.

Each successive generation of technology has increased reliability and energy capture while reducing the cost of electricity. These advances are being made by gaining a better understanding of the system-design drivers, improving the analytical design tools, verifying design methods with operating field data, and incorporating new technology and innovative designs.

This report is an overview of the large-wind-turbine activities managed by NASA Lewis. These activities include results from the first- and second-generation machines (Mod-0A, -1, and -2), the status of the Department of Interior WTS-4 machine for which NASA Lewis is responsible for technical management, and the status of the third-generation wind turbine (Mod-5).

INTRODUCTION

Since 1973, the United States Government has sponsored a research and development program in wind energy in order to make wind turbines a viable technological alternative to existing electricity-generating capacity. The current Federal Wind Energy Program, under the sponsorship of the Department of Energy, is directed toward the development and production of safe,

reliable, cost-effective machines that will generate significant amounts of electricity.

One segment of the program, the development of large, horizontal-axis wind turbines, is being managed by the NASA Lewis Research Center. This activity is oriented primarily toward utility application. The projects are designated Mod-0A, Mod-1, Mod-2, WTS-4, Mod-5A, and Mod-5B. The machine configurations are shown in figure 1. Table I lists the prime contractors, machine locations, first rotation dates, and design specifications and performance. A supporting research and technology development project utilizes the Mod-0 wind turbine as an experimental test bed (fig. 2).

The machine design and technology development projects have been supported by substantial analysis and testing of hardware and materials. Methods of structural dynamics analysis were improved, utility interface problems were assessed, component materials were tested, new blade concepts were analyzed and evaluated, blade sections were tested in the laboratory, and full-scale blades were tested in operation. This report concentrates on the status of the major wind turbine development projects.

FIRST-GENERATION MACHINES (Mod-0A and Mod-1)

The Mod-0A project (ref. 1) was started in 1975 to obtain experience in operating large wind turbines on a utility grid. The Mod-0 100-kW machine was upgraded to 200 kW, and the first Mod-0A installation was completed in November 1977. A machine was then installed each year at the sites shown in figure 3, with the last installation completed in July 1980. Each machine had a 38-m (125-ft) diameter downwind rotor with fully pitchable blades and was mounted on a 30-m (100-ft) high rigid truss tower. The rated power was 200 kW at a wind speed of 7.5 m/s (18.1 mph). The rated wind speed is measured at 9.1 m (30 ft). The goals of the program were to demonstrate automatic operation, to investigate compatibility with utilities, to assess the reliability and maintenance requirements, and to determine the public and utility reaction.

Some problems of reliability and rotor blade life occurred early in the program. However, the machines were upgraded with good results. The monthly availability of the machines often exceeded the goal of 90 percent, and the last machine installed averaged 80 percent for the first year. The machines were on-line collectively for over 38 000 hr, during which time they generated over 3600 MW-hr of electricity into the participating networks. In June 1982, the Mod-0A machines were shut down. These machines accomplished the engineering and research objectives for which they were designed. The operating experience has had a significant effect on the second- and third-generation machine designs.

The Mod-1 project began in 1976. The Mod-1, a two-blade, 61-m (200-ft) diameter wind turbine, had a rated power of 2000 kW. The blades were steel and the rotor was located downwind of the tower. Full-span blade pitch was used to control the rotor speed at a constant 35 rpm. The gearbox and generator were similar in design to those of the Mod-0A but, of course, each was much larger. The tower was a steel, tubular truss design. The General Electric Company, Space Division, of Philadelphia, Pennsylvania, was the prime contractor for designing, fabricating, and installing the Mod-1. The Boeing Engineering and Construction Company of Seattle, Washington, manufactured the

two steel blades. A single prototype was installed at Boone, North Carolina, in May 1979 (fig. 4) and was tested with the Blue Ridge Electrical Membership Corporation from July 1979 to January 1981. The Mod-1 (ref. 2) operated successfully in all modes of operation, synchronized in a fully automatic mode with the utility grid, and furnished power to utility residential users within utility standards. This demonstrated the compatibility of a megawatt-size wind turbine to operate in a stable and well-controlled manner on a utility grid. In addition, data from machine testing have verified the performance, loads, and structural dynamics codes used to design the megawatt-size Mod-1. During Mod-1 operations at Boone much testing was done in relation to noise and television interference (TVI) associated with the mountainous terrain (ref. 2). The information from these tests is being factored into the design of the newer wind turbines.

The rotor speed was reduced from 35 rpm to 23 rpm and the 2000-kW, 1800-rpm generator was replaced with a 1500-kW, 1200-rpm generator. Measured rotor noise decreased significantly. Near the completion of the noise experiments, the Mod-1 experienced a failure in the low-speed shaft of the drive train. As did the Mod-0A, the Mod-1 machine accomplished its purpose and was removed from service. The information obtained from these early first-generation machines has been valuable in developing the second-generation designs, called Mod-2, and the third-generation designs, called Mod-5, which are considered to have excellent commercial potential. Mod-2 and Mod-5 are both megawatt-size machines developed specifically as fuel savers for large utility applications.

Since the first-generation (Mod-0A and Mod-1) designs were not commercially attractive, they were removed from the utility sites. Engineering studies conducted during the development and experimental operation of these machines clearly indicated a need for major technology advancements to make large wind turbines more economically attractive. Resulting improvements have been incorporated in the Mod-2 and Mod-5 designs.

SECOND-GENERATION MACHINE (2500-kW Mod-2) AND SYSTEM VERIFICATION UNIT

In August 1977, DOE/NASA awarded a competitively bid contract to Boeing Engineering and Construction Company to design and build the Mod-2 wind turbine. The specific objective of the Mod-2 project (ref. 3) was to establish the design and performance of a megawatt-size wind turbine that could achieve a cost of energy (COE) for the 100th unit in production of less than 5 ¢/kW-hr, including capital and operating and maintenance costs, in 1980 dollars. In estimating COE the wind turbines are assumed to be deployed in a 25-unit cluster at a site having an annual mean wind speed of 6.3 m/s (14 mph) measured at a height of 9.1 m (30 ft). Three Mod-2 machines (fig. 5) have been clustered at a single site at Goldendale, Washington, to test and evaluate the interactive aerodynamic and electric grid effects of multiple machines integrated into a utility network.

The DOE selected the Bonneville Power Administration (BPA) as the participating utility for the Mod-2 wind turbine project. BPA is a large regional power distributing organization in the Pacific Northwest and can supply valuable support in attainment of the DOE/NASA project goals.

The Mod-2 project is in the experimental operations phase (ref. 4), which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, with the power grid, and with the environment during the next 2 yr. As of January 1985, the Mod-2 cluster had generated more than 5100 MW-hr of electricity while synchronized to the BPA grid for over 4100 hr. Initial performance of the turbines has been acceptable but has shown areas for improvement.

Four nonoperating periods have been experienced during the initial operation of these experimental turbines. Early in the acceptance operation the hydraulic, electric, and control systems were reviewed and modified as a result of an overspeed incident. Two other delays were caused (1) by the rework of the rotor midspan-to-hub flange to better transfer the load through this bolted joint and (2) by the repair of the generator bearings and the addition of a forced-lubrication system. The most recent nonoperating period was in November 1982, when fatigue cracks were found in each machine. The cracks originated at stress concentrations around holes in the low-speed shaft used to install bolts for securing hydraulic and electric equipment. The failure occurred primarily because inadequate design of the low-speed shaft and hole details resulted in a negative margin of safety. A new low-speed shaft was designed and fabricated. This redesigned shaft, being considerably stiffer radially, also corrected a related deficiency regarding the large (1.2-m (4-ft) diameter) radial support bearing on the shaft. The original shaft permitted sufficient flexing at the bearing-shaft interface to eventually loosen the bearing on the shaft, as well as possibly to fatigue the hardened inner race. Consequently new bearings were fabricated and installed as part of the installation of the new low-speed shaft.

All of the problems encountered to date have been hardware oriented and are attributed to fabrication or design deficiencies. Such experience is not unusual for the early development of experimental hardware of any kind.

In addition to the three Mod-2's at Goodnoe Hills, a fourth Mod-2 has been purchased by the Department of the Interior (DOI), Bureau of Reclamation, and erected at Medicine Bow, Wyoming, and a fifth by Pacific Gas and Electric for operation in Solano County, California. These machines have been in operation since mid-1982.

NASA Lewis is participating with the Bureau of Reclamation to experiment with two other machines that are located near Medicine Bow, Wyoming. Experimental operation of these system verification units (SVU) is expected to verify the concept of integrating wind turbines with hydroelectric facilities. This is a key step in Reclamation's long-range program to supplement hydropower generation with wind turbine capacity.

The Hamilton Standard Division of United Technologies Corporation was selected by competitive procurement to design, fabricate, install, and test a 4-MW WTS-4 machine (fig. 6). A Swedish company, Karlskronavarvet (KKRV), is a major subcontractor responsible for the design and fabrication of the nacelle hardware. A 3-MW version of the same basic design was built and installed for the Swedish government with KKRK as the prime contractor and Hamilton Standard as the major subcontractor. The second SVU is a 2.5-MW Mod-2 built by Boeing of the same design as the Goodnoe Hills machines. The WTS-4 (fig. 6) has a two-blade fiberglass rotor 78.2 m (256.4 ft) in diameter. The rotor operates downwind of a tubular steel tower. The machine (ref. 5) produces 4 MW of

power at a wind velocity of 16.1 m/s (36 mph) measured at the hub height, 80 m (262 ft) above the ground line.

The Mod-2 machine was first synchronized with the utility network in June 1982. The WTS-4 machine was synchronized with the utility network in October 1982. As of January 1985, the Mod-2 produced over 1790 MW-hr of electricity while synchronized for over 1300 hr on the network. The WTS-4 has produced over 3300 MW-hr of electricity while synchronized for about 1600 hr on the network.

Mod-5 ADVANCED MULTIMEGAWATT WIND TURBINE

The purpose of the Mod-5 project was to develop technology for multimegawatt wind turbines that would be more cost competitive than the Mod-2. The Mod-5 is the third in a series of large-wind-turbine projects sponsored by DOE, and it was intended that these designs build upon the information gained from the first- and second-generation designs. In the summer of 1980 parallel contracts were initiated with General Electric and Boeing. Each contract included tradeoff studies, to determine the optimum size and configuration for minimum COE, followed by design, fabrication, installation, and testing. Because of changes in Federal funding levels and planning, however, cost-sharing proposals were later solicited from both contractors, with the Government funding the design and the contractors or their utility customers funding the hardware. Both contractors submitted cost-sharing proposals contingent on finding utility partners.

Mod-5A

The Mod-5A advanced-design wind turbine was developed for DOE/NASA by the General Electric Company. Work on the project began in July 1980. The conceptual design was completed in March 1981 and the final design (except for the rotor) was completed in 1983.

The purpose of this project was to develop a multimegawatt wind turbine generator that would produce electricity (in quantity) for less than 3.75 ¢/kW-hr (in 1980 dollars) when installed in a cluster at a site with an annual average wind speed of 6.3 m/s (14-mph). During the conceptual design phase many tradeoff studies were performed to establish the size and configuration that would produce the lowest COE. The major tradeoff studies were machine size, blade materials, blade articulation, independently coned versus teetered rotors, rotor orientation, ailerons versus blade tip control, gearbox-nacelle configuration, single speed versus variable speed, and integral gearbox versus rotor-integrated gearbox.

The conceptual design effort produced a wind turbine design with a 122-m (400-ft) diameter wood-epoxy rotor (ref. 6) mounted directly on the gearbox. The two-speed gearbox drove a 7.3-MW synchronous generator. The soft tubular tower provided a rotor centerline 76.2 m (250 ft) above ground level.

In December 1983 the General Electric Company decided to withdraw from their participation in wind energy. General Electric based the decision on their inability to conclude a satisfactory financial agreement with the Hawaiian Electric Company for the sale of a prototype Mod-5A wind turbine. They also cited that the expected expiration of Federal energy tax credits

would mean little additional private sector investment in wind energy. The design of this innovative machine will be preserved in a final report. Research is continuing to explore the applicability to future large wind turbines of aileron rotor control and methods of field assembly of large wood-epoxy rotors.

Mod-5B

The Mod-5B advanced-design wind turbine is being developed by the Boeing Aerospace Company for DOE/NASA. Work started in July 1980. The Mod-5B wind turbine is being designed to produce electricity for utilities at the lowest practical cost (3.75 ¢/kW-hr, in 1980 dollars) in a wide variety of locations that have only moderate (6.3 m/s; 14 mph) average annual wind speeds. It is based on the technology developed in the Mod-2 program. The major technology advancement over the Mod-2 is the use of a full-variable-speed generator to extract the maximum power at different wind speeds. Proven concepts such as a teetering rotor supported from the drive shaft by elastomeric bearings, a lightweight epicyclic speed-increasing gearbox, and rotor speed control employing only variable-pitch blade tips are retained from the Mod-2 (ref. 7).

A contract has been negotiated with the Boeing Aerospace Company to fabricate, erect, and check out a Mod-5B wind turbine on the Island of Oahu, Hawaii. A purchase agreement has been negotiated with the local utility, the Hawaiian Electric Company, to purchase the machine after successful acceptance testing. The scheduled date for turnover to the Hawaiian Electric Company is early 1987.

CONCLUDING REMARKS

The large-wind-turbine segment of the Federal Wind Energy Program is managed by the NASA Lewis Research Center for the Department of Energy (DOE). This segment comprises several large-wind-turbine development projects and a research and technology development project (R&TD). The program highlights and the current status of the projects are as follows:

1. The four 200-kW Mod-0A wind turbines collectively operated over 38 000 hr and generated over 3600 MW-hr of electricity on utility systems. The 2000-kW Mod-1 wind turbine, designed and built by the General Electric Company, successfully validated the analytical methods for predicting power, loads, and dynamics for a megawatt-size wind turbine. This validation was important for the follow-on development of the advanced large wind turbines. In addition, key environmental experiments on television interference and rotor noise were conducted, and the results factored into the advanced wind turbine designs. Since the first-generation (Mod-0A and Mod-1) designs were not commercially attractive, they have been removed from the utility sites.

2. The three 2500-kW Mod-2's, designed and built by Boeing Engineering and Construction Company, have been installed and are operating on the Bonneville Power Administration system. To date, the cluster has generated over 5100 MW-hr of electricity into the network during over 4100 hr of experimental operation. As a result of structural fatigue damage to the low-speed shafts,

newly designed shafts have been installed and the machines are again operating. Cluster experiments are planned to continue through 1985.

3. The Bureau of Reclamation has a 2500-kW Mod-2 and a 4000-kW WTS-4 wind turbine installed and operating at their site in Medicine Bow, Wyoming. The Mod-2 was first synchronized to the network in June 1982, and the WTS-4 in October 1982. Mod-2 had produced over 1790 MW-hr of electricity during over 1300 hr of operation by January 1985. WTS-4 produced 3300 MW-hr of electricity during 1600 hr on the network. WTS-4 is performing within the performance envelope predicted by Hamilton Standard.

4. Two contractors, General Electric and Boeing, have designed third-generation large wind turbines, designated Mod-5. Both machine designs show potential for significant cost reduction over the earlier machines. These estimated cost reductions are due primarily to the larger size and the utilization of advanced technology such as variable-speed generators and lightweight wood-composite rotors. The Boeing machine, the Mod-5B, is under contract and should be operational in early 1987.

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TABLE I. - DATA FOR LARGE, HORIZONTAL-AXIS WIND TURBINES

	Mod-0A	Mod-1	Mod-2	Mod-5A	Mod-5B	SVU WTS-4
Prime contractor	Westinghouse Electric Corp., Pittsburgh, PA	General Electric Co., Philadelphia, PA	Boeing Aerospace Co., Seattle, WA	General Electric Co., Philadelphia, PA	Boeing Aerospace Co., Seattle, WA	Hamilton Standard Div., United Technologies Corp., Windsor Locks, CT
Location	Clayton, NM Culebra, PR Block Island, RI Oahu, Hawaii	Boone, NC	Goodnoe Hills, WA (3) Medicine Bow, WY (1)	Project terminated 12-83	Oahu, HI	Medicine Bow, WY
Date of first rotation (location and unit)	11-77 (NM) 6-78 (PR) 5-79 (RI) 5-80 (HI)	5-79	11-80 (WA 1) 3-81 (WA 2) 5-81 (WA 3) 12-81 (WY-SVU)		9-86	8-82
Center of blade rotation (hub height), m (ft)	30.5 (100)	42.7 (140)	61.0 (200)	71.6 (235)	61.0 (200)	80 (262)
Rotor blade diameter, m (ft)	38.1 (125)	61.0 (200)	91.0 (300)	122 (400)	97.5 (320)	78 (256)
Rated power, kW	200	2000	2500	7300	3200	4000
Rated wind speed at hub height, m/s (mph)	9.8 (22)	14.7 (33)	12.5 (28)	14.3 (32)	12.5 (28)	16.1 (36)
Annual electricity output, ^a MW-hr:						
At 5.4-m/s (12-mph) site	640	2400	7000	14 400	8100	7000
At 6.3-m/s (14-mph) site	820	3700	9300	19 500	10 600	9900
At 7.2-m/s (16-mph) site	980	5100	11 300	24 600	13 000	13 000
Cut-in speed at hub height, m/s (mph)	5.4 (12)	7.2 (16)	6.3 (14)	6.3 (14)	5.4 (12)	6.7 (15)
Cutout speed at hub height, m/s (mph)	17.9 (40)	19.2 (43)	20 (45)	22.3 (50)	26.8 (60)	26.8 (60)
Weight on foundation, kg (lb)	40.6x10 ³ (89.5x10 ³)	295x10 ³ (650x10 ³)	281x10 ³ (619x10 ³)	638x10 ³ (1407x10 ³)	420x10 ³ (925x10 ³)	353x10 ³ (778x10 ³)
Weight per rated power, kg/kW (lb/kW)	203 (447)	148 (325)	112 (247)	87 (193)	131 (289)	88 (194)

^a 90 Percent of available wind energy measured at 9.1 m (30 ft) above sea level; Weibull distribution.

^b 26.8 m/s (60 ft/s) at Medicine Bow, WY.

^c Proposed.

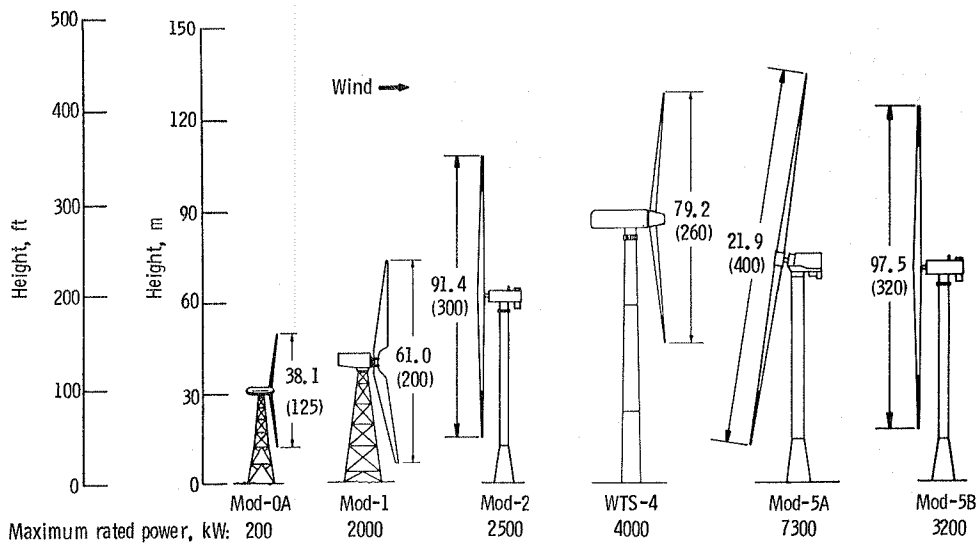


Figure 1. - Large, horizontal-axis wind turbines.

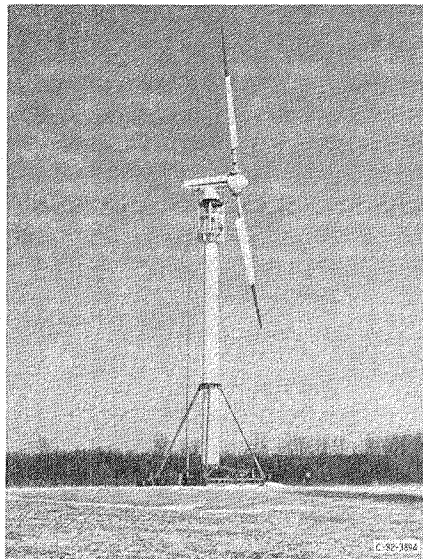
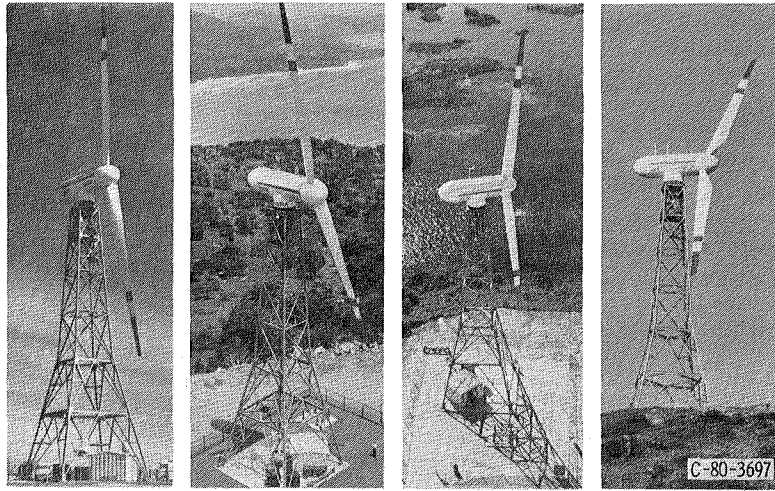


Figure 2. - Mod-0 experimental wind turbine.



Clayton, New Mexico

Culebra, Puerto Rico

Block Island,
Rhode Island

Kahuku Point,
Oahu, Hawaii

Figure 3. - Mod-0A experimental wind turbines.

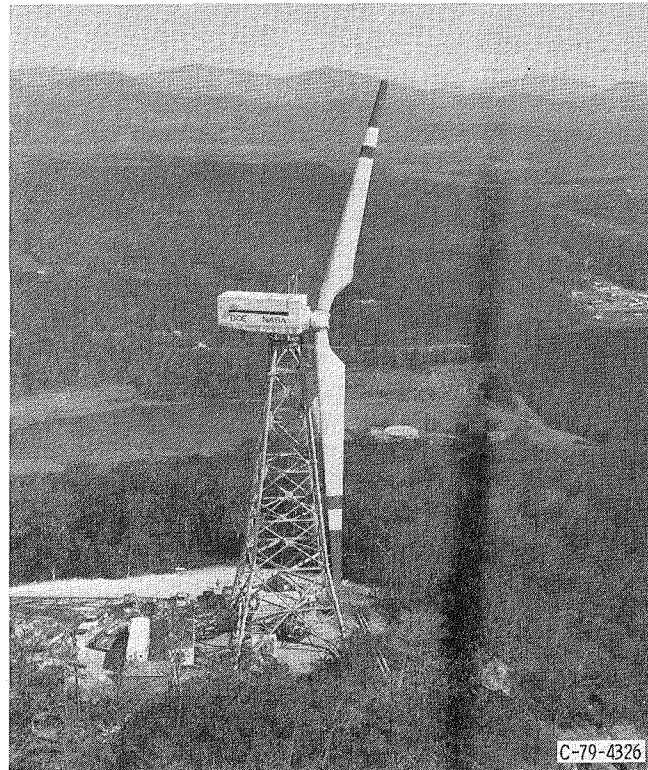


Figure 4. - Mod-1 experimental wind turbine.

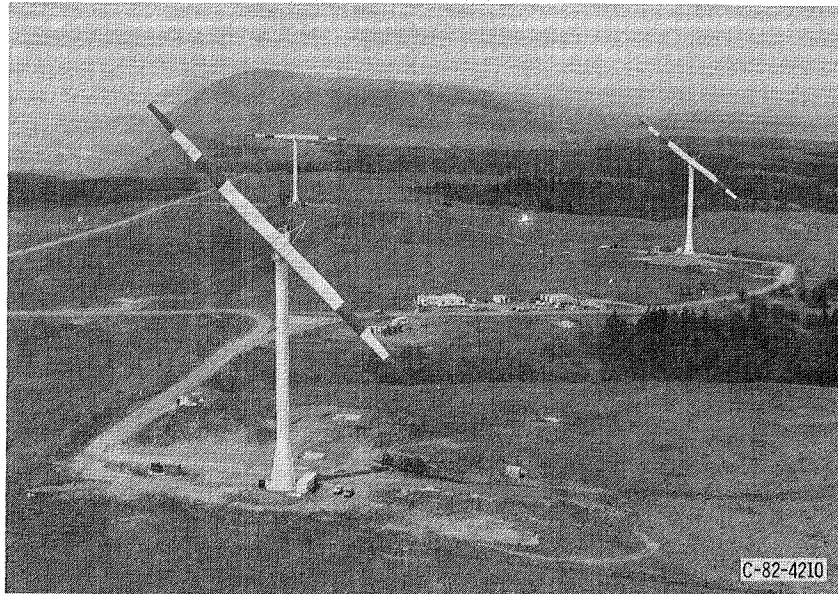


Figure 5. - Mod-2 experimental wind turbine cluster.

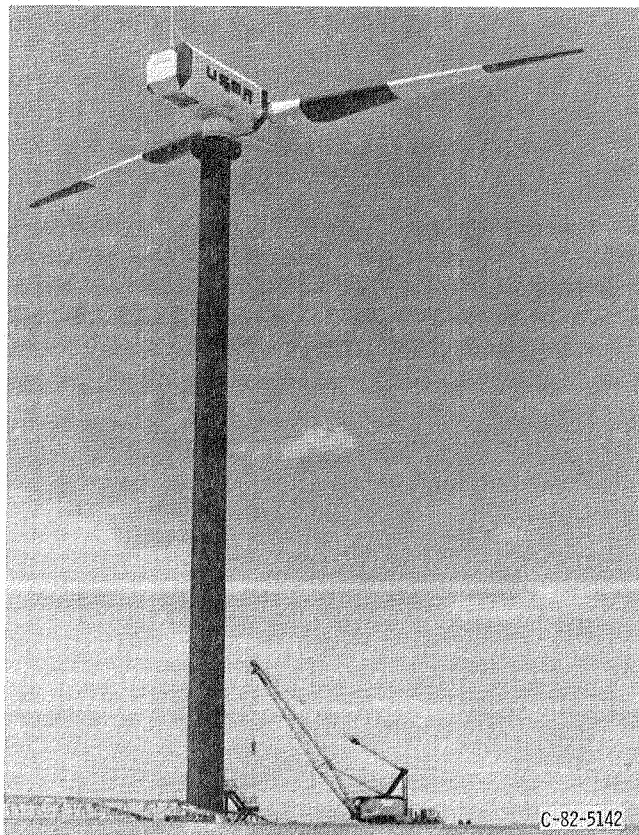


Figure 6. - WTS-4 system verification unit (SVU) wind turbine.

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