DOE/NASA/20320-47
NASA TM-83444

DOE Large Horizontal Axis Wind Turbine Development at NASA Lewis Research Center

B. S. Linscott
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Work performed for
U.S. DEPARTMENT OF ENERGY
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Kansas City, Missouri, April 25–26, 1983

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes[1]
Printed copy: A02
Microfiche copy: A01

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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-76ET20320

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DOE LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT AT NASA LEWIS RESEARCH CENTER

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ABSTRACT

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

There are several ongoing large wind system development projects directed toward meeting the technology requirements for utility applications. The first generation technology machines (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. Third generation technology machines (Mod-5) are in the design phase and are planned for initial operation in late 1984 or early 1985.

Each successive generation of technology has shown potential to increase 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, improvements in the analytical design tools, verification of design methods with operating field data, and the incorporation of new technology and innovative designs.

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

E-1744

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 electrical generating capacity. The current U.S. Wind Energy Program, under the sponsorship of the Department of Energy, is directed toward the development and production of safe, reliable, cost-effective machines which will generate significant amounts of electricity. One element of the U.S. Wind Energy Program is Large Horizontal Axis Wind Turbine Development which is being managed by the NASA Lewis Research

Center. This activity consists of several wind system developments oriented primarily toward utility application. These projects are designated Mod-OA, Mod-1, Mod-2, WTS-4 and Mod-5A and Mod-5B. These machine configurations are shown in figure 1. In addition to these machine projects, there is a supporting research and technology development project that utilizes the Mod-0 wind turbine as an experimental test bed shown in figure 2.

The machine design and technology development projects have been supported by substantial analysis and hardware/material testing. These include efforts to improve the methods of structural dynamic analysis, assessment of utility interface problems, testing of component materials, evaluation of new blade concepts by analysis, laboratory testing of blade sections, and operational testing of full-scale blades. This paper presents an overview of the NASA wind turbine activities concentrating on the status of the major wind turbine development projects.

LARGE WIND TURBINE PROJECTS

First Generation Mod-OA and Mod-1

The Mod-OA project (ref. 1) was initiated in 1975 to obtain experience in operating large wind turbines on a utility grid. The Mod-0 100 kW machine was uprated to 200 kW and the first Mod-OA installation was completed in November 1977. Since then a machine was 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-diam downwind full pitchable rotor, and was mounted on a (30-m) 100-ft rigid truss tower. The rated power was 200 kW at a wind speed of 18.1 mph (7.5 m/s). The rated wind speed is measured at (9.1-m) 30 ft.

The goals of the program were to demonstrate automatic operation, investigate compatibility with utilities, assess the reliability and maintenance requirements, and determine the public and utility reaction.

There were significant problems early in the program with reliability and, in particular, rotor blade life. However, the machines were upgraded with very significant results. The 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 hours during which time they generated over 3,600 mWh of electricity into the participating networks. In June 1982, the Mod-OA machines were shut down. These machines accomplished the engineering and research objectives for which they were originally designed. The operating experience has had a significant effect on the second and third generation machine designs.

The Mod-1 project was initiated in 1974. The Mod-1, a two-bladed, (61 m) 200-ft diameter wind turbine, had a rated power of 2,000 kW. The blades were steel and the rotor was located downwind of the tower. Full span pitch was used to control the rotor speed at a constant 35 rpm. The gearbox and generator were similar in design to the Mod-OA 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). The Mod-1 provided power, experimentally, on the utility network owned by 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 directed to utility residential users within utility standards. This demonstrated the compatibility of a megawatt wind turbine operating into a utility grid in a stable and well controlled manner. In addition, data from machine testing has verified the performance, loads and structural dynamics codes used to design the MW size Mod-1. During Mod-1 operations at Boone there was also much testing done in support of noise and television interference (TVI) associated with the Mod-1 operating in a mountainous region (ref. 2). The information from these tests is being factored into the design of the newer wind turbines.

In an effort to reduce rotor noise, the rotor speed was reduced from 35 to 23 rpm. This was accomplished by replacing the 2,000-kW 1800-rpm generator with a 1,500-kW 12,000-rmp generator. Experiments were conducted to evaluate the Mod-1 rotor noise at 35 and 23 rpm. Measured rotor noise at 23 rpm was significantly less when compared to the rotor noise at 35 rpm. Near the completion of the noise experiments, the Mod-1 experienced a failure in the low-speed shaft of the drive train. Similar to Mod-0A, the Mod-1 machine has also accomplished its original purpose and was removed from service. The information obtained from these early first generation Mod-0A and Mod-1 machines has been very valuable in the development of second generation designs, called Mod-2, and 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 are not attractive from a commercial point of view, they are presently being removed from the utility sites. Engineering studies conducted during the development and experimental operation of these first generation machines clearly indicated a need for major technology advancements in order to make large machines more economically attractive. Resulting improvements have been incorporated in the second generation Mod-2 and third generation Mod-5 designs.

Second Generation Mod-2 2500 kW and the System Verification Unit (SVU) Wind Turbine Projects

The Mod-2 wind turbine project (ref. 3) is a second generation phase of the large wind turbine program managed by the NASA for DOE. DOE/NASA awarded a competitively bid contract to Boeing Engineering and Construction Company to design and build a second generation, Mod-2 wind turbine in August 1977. The specific objective of the Mod-2 project is to establish the design and performance of a megawatt size wind turbine that can achieve a cost-of-energy (COE) for the 100th unit in production of less than 5 cents/kWh including capital and operating and maintenance costs in 1980 dollars. For purposes of 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 have been clustered at a single site at Goldendale, Washington (fig. 5), to test, evaluate, and demonstrate the interactive aerodynamic and electrical 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. Bonneville Power is a large regional power distributing organization in the Pacific Northwest and has the capability of supplying valuable support in the attainment of the DOE/NASA project goals.

The Mod-2 project is now 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, the power grid, and the environment during the next two years. As of November 1982, the Mod-2 cluster had generated more than 4,000 mWh of energy while synchronized to the Bonneville Power grid for over 3,400 hrs. To date, initial performance of the turbines has been acceptable but also has indicated areas for improvement.

Four nonoperating periods have been experienced during the initial operation of these experimental turbines. These include (1) repair of the generator bearings and addition of a forced lubrication system, (2) the rotor midspan to hub flange was reworked to better transfer the load through this bolted joint, and (3) early in the acceptance operation, the hydraulic, electrical, and controls systems were reviewed and modified as a result of an over-speed incident. Finally in November 1982 fatigue cracks were found in the low speed shaft of each machine. The cracks originated at stress concentrations around holes in the low speed shaft used to install bolts for securing hydraulic and electrical equipment. The primary cause of the failure was due to inadequate design of the low speed shaft, and hole details, resulting in a negative margin of safety. A new low speed shaft was designed and fabrication of the new shafts is underway. The turbine cluster will be retrofitted in late 1983 with the new low speed shafts. Limited attended research tests are continuing until the modifications are completed.

All of these problem areas encountered to date have been hardware oriented and are attributed to fabrication and/or design deficiencies. Such experience is not unusual for the early development of experimental hardware of any kind. The original Mod-2 economic objective of 5 cents/kWh (1980 dollars) when in production and operating in a 25 unit cluster is still considered reasonable and achievable.

In addition to the three Mod-2's at Goodnoe Hills, a fourth Mod-2 has been purchased by Bureau of Reclamation at Medicine Bow, Wyoming, and a fifth by Pacific Gas and Electric for operation in Salano County, California. These machines have been in operation since mid-1982. The modifications made to the Goodnoe Hills machines have been, or are planned to be, incorporated on these two machines.

NASA Lewis is participating with the Department of the Interior (DOI) Bureau of Reclamation to experiment with two 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 their hydropower generation with extensive 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 KKRV 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 bladed fiberglass rotor diameter of (7.1 m) 256.4 ft. The rotor operates downwind of a tubular steel tower. The machine (ref. 5) produces 4.0 MW of power at a wind velocity of (16.1 m/s) 36 mph measured at (80 m) 262 ft, the hub height above the ground line.

The Mod-2 machine at Medicine Bow was first synchronized with the utility network in June 1982. The WTS-4 machine synchronized with the utility network in October 1982. As of March 1983, the Mod-2 produced over 460 mWh of energy while synchronized over 390 hours on the network. The WTS-4 has produced over 410 Mwh of energy while synchronized a little over 170 hours on the network.

Mod-5 Advanced Multi-MW Wind Turbine Project

The purpose of the Mod-5 project is the development of technology for multi-megawatt wind turbines that have greater potential to be cost competitive than Mod-2. The Mod-5 represents the third in a series of large wind turbine projects sponsored by DOE and it was intended that these designs utilize and 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 following a competitive request for procurement by NASA. Each contract included trade studies to determine optimum size and configuration for minimum cost-of-electricity followed by design, fabrication, installation and test. Due to changes in program plans, however, major cost-share proposals were solicited from both contractors. Both contractors have submitted costshare proposals and these are being negotiated. Continuation of the projects through fabrication, installation and checkout is dependent on continued federal funding and contract cost sharing.

Mod-5A -- The Mod-5A advance design wind turbine is being developed for DOE/NASA by the General Electric Company's Advanced Energy Programs Department. Work on the project was initiated in July 1980. The conceptual design was completed in March 1981; preliminary design is currently in progress with completion planned for late 1983. Machine operation is expected by late 1984 or early 1985.

The primary requirement of this project is to develop a multi-megawatt wind turbine generator that produces electricity for less than 3.75 cents/kWh (1980 dollars) when installed as a cluster of 25 or more machines at a site with a 6.3 m/s (14-mph) average wind speed. During the conceptual design phase many trade studies were performed to establish the size and configuration that would produce the lowest cost of energy. The major trade studies performed included: blade materials; fiberglass versus steel versus laminated wood epoxy composites; blade articulation; independently coned versus teetered rotors; rotor orientation, upwind versus downwind of tower; torque control; ailerons versus tip control; gearbox/nacelle configuration; single speed versus variable speed; integral gearbox versus rotor integrated gearbox and size; both rotor diameter and rated power.

The Mod-5A conceptual design effort produced a wind turbine design with a (122 m) 400-ft diameter laminated wood epoxy rotor (ref. 6) mounted directly on the gearbox. The two speed gearbox drives a 7.3-MW synchronous generator. The soft tubular tower provides a rotor centerline 76.2 m (250 ft) above ground level. Figure 7 shows an artist's conception of the machine.

Mod-5B -- The Mod-5B advance design wind turbine is also being developed by the Boeing Engineering and Construction Company for DOE/NASA. Work started in July 1980. The conceptual design is completed and the preliminary design is in progress with completion planned for late 1983. The Mod-5B wind turbine, like the Mod-5A, is being designed to produce electricity for utilities at the lowest practical cost (3.75 cents/kWh, 1980 dollars) in a wide variety of locations which need to have only moderate 6.3 m/s (14 mph) average annual wind speeds. The Mod-5B concept design is based on the technology developed on the previous Mod-2 wind turbine program. Figure 7 shows an artist's conception of the Mod-5B wind turbine. Advanced technology is featured in rotating light weight wood blade tips and variable speed generator to provide improved system dynamics and 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 low cost epicyclic speed increaser gearbox, and rotor speed control employing only the variable pitchblade tips are retained from the Mod-2 (ref. 7). Machine operation is expected by late 1984 or early 1985.

Summary of Large Wind Turbine Developments

A brief summary of progress to date for large machines is outlined in figure 8. Figure 8 compares key factors for large wind turbines such as $/kW and kWh/lb for the first, second and third generation machines. The Mod-0A is used for first generation, Mod-2 for second generation and Mod-5 for third generation. All numerical values in figure 8 are for the second prototype machine of each generation. As can be seen in the figure, there is a major reduction in $/kW from Mod-0A to Mod-2 with an additional 12 percent reduction from Mod-2 to Mod-5. It is interesting to note that the kWh/lb, which is an indirect measure of revenue to cost, increases with each generation with a factor of 1.6 increase occurring from first to third. This is impressive considering it means increasing the energy output by a factor of 1.6 for the same weight. It is even more important considering the Mod-0A was a fairly lightweight machine and initially utilized aircraft quality lightweight aluminum blades. These gains were made by utilizing advanced technology such as teetered rotors, tip-controlled blades, epicyclic gear-boxes, towers with lower natural frequencies, rotors made with significantly lower cost materials, more economical fabrication methods, improved analysis tools and increased understanding of the major design drivers. It is also interesting to note in figure 8 how the percentage of $/kW for major subsystems has changed from Mod-0A to Mod-5 with the rotor now being a much smaller percentage of the machine cost. Figure 9 provides a summary of government prime contractors, machine locations, first rotation dates, design specifications and performance, for the various NASA LeRC wind turbine projects.

CONCLUDING REMARKS

The large wind turbine portion of the Federal Wind Energy Program is managed by NASA Lewis Research Center for the Department of Energy (DOE). This portion of the program consists of several large wind turbine development projects and a research and technology development project (RaTD). A summary of the progress and status of these projects follows:

1. The four Mod-0A 200 kW wind turbines collectively operated over 38,000 hours and generated over 3,600 mWh of electricity on utility systems. The 2,000 kW Mod-1 wind turbine, designed and built by the General Electric Corporation, successfully validated the analysis methods for predicting power, loads and dynamics for a large MW 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 are not attractive from a commercial point of view, they are presently being removed from the utility sites.

2. The three 2,500 kW Mod-2s, 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 in excess of 4,000 mWh of energy into the network during over 3,400 hours of experiment operation. As a result of structural fatigue damage to the low speed shafts, newly designed shafts are planned to be installed this year. Cluster experiments are planned to continue again in late 1983.

3. The Bureau of Reclamation has a 2,500 kW Mod-2 and a 4,000 kW WTS-4 wind turbine installed and operating at their Medicine Bow site in Wyoming. The Mod-2 machine was first synchronized to the network in June 1982, and the WTS-4 was first synchronized to the network in October 1982. Mod-2 has produced over 450 mWh of energy during over 390 hours of operation by March 1983. WTS-4 produced 410 mWh of energy during 170 hours on the network. The WTS-4 machine is performing within the performance envelope predicted by Hamilton Standard.

4. Two contractors, General Electric and Boeing, are each designing 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 larger size and utilization of advanced technology such as variable speed generators and lightweight wood composite rotors.

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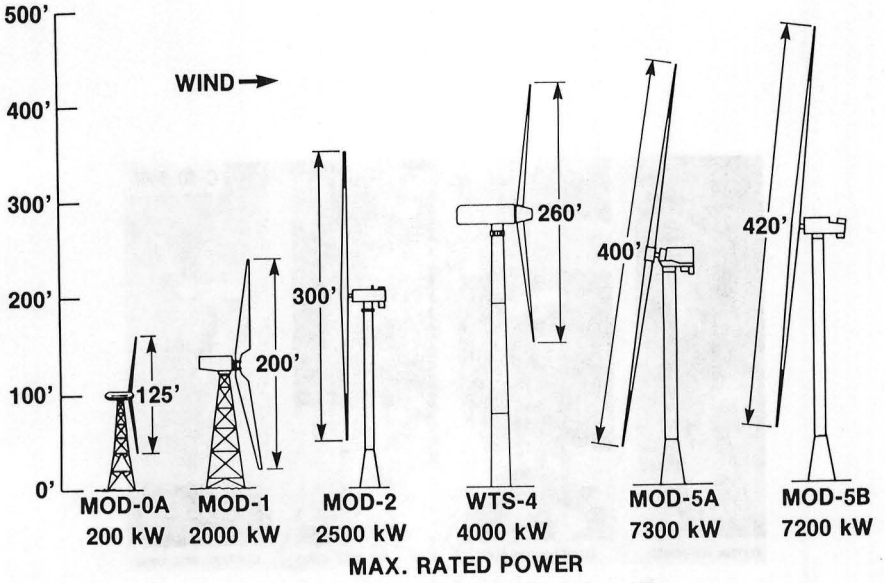


Figure 1. - Large horizontal axis wind turbine experimental projects.

Figure 2. - MOD-0 experimental wind turbine.

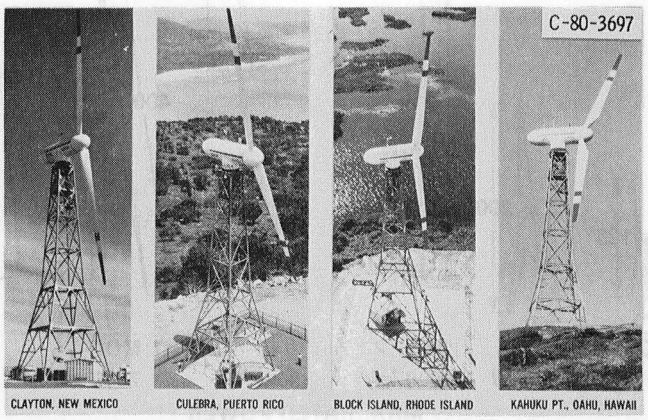


Figure 3. - MOD-OA experimental wind turbines.

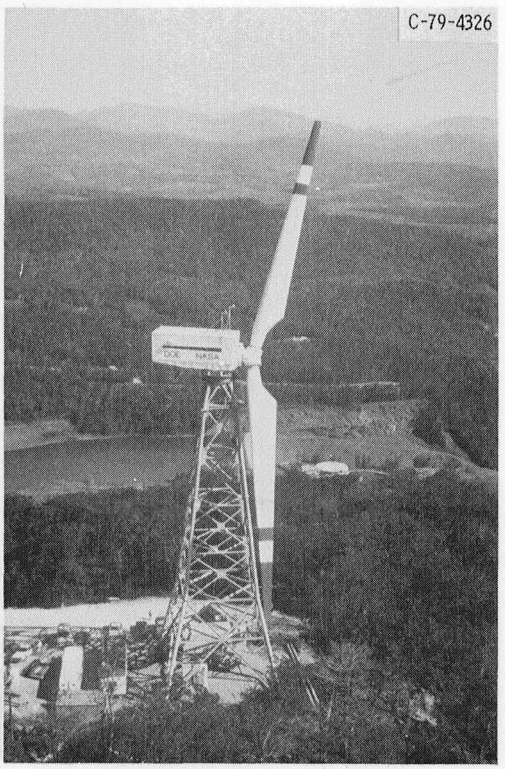


Figure 4. - MOD-1 experimental wind turbine.

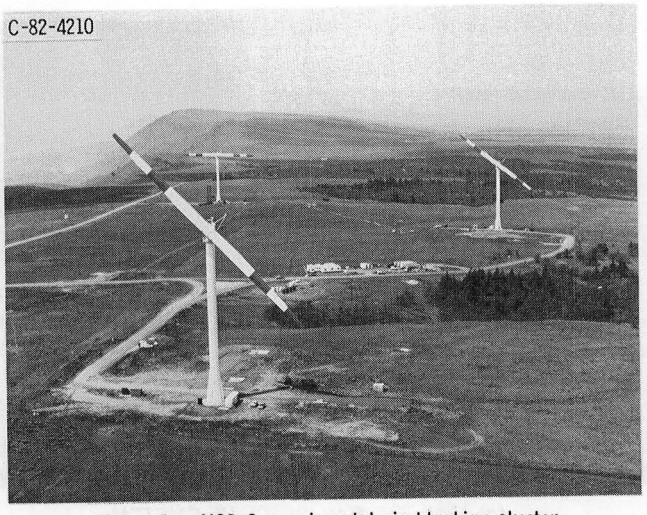


Figure 5. - MOD-2 experimental wind turbine cluster.

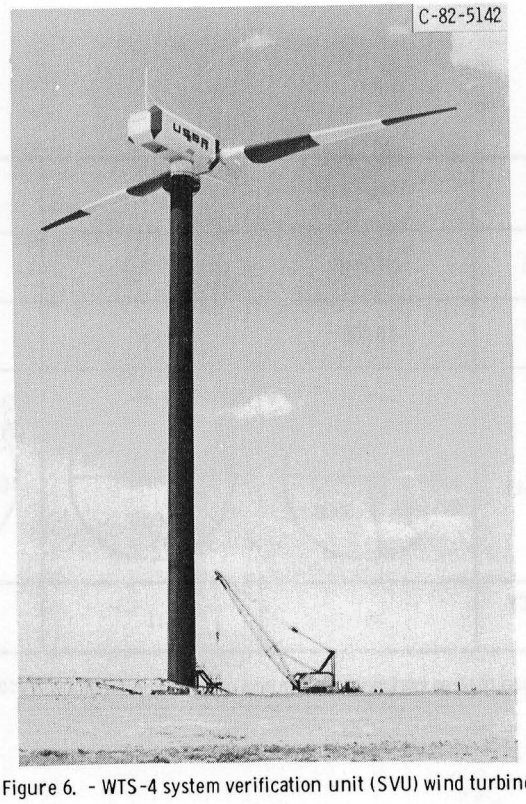
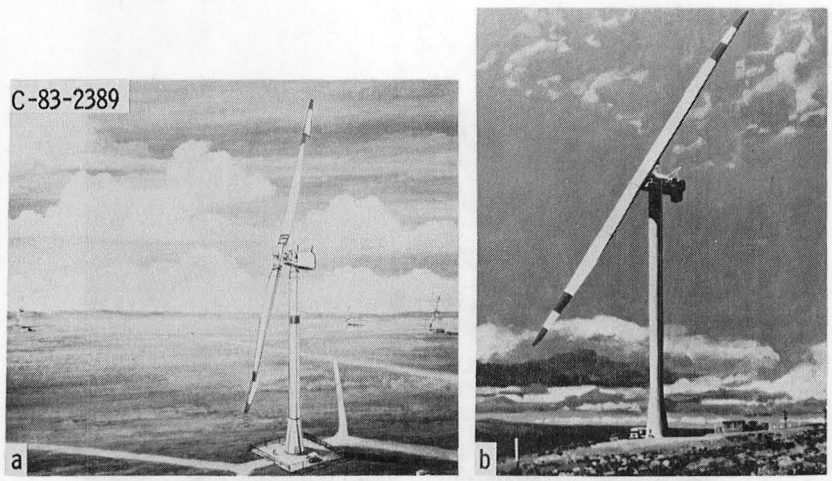


Figure 6. - WTS-4 system verification unit (SVU) wind turbine.



(a) MOD 5A WIND TURBINE SYSTEM
(b) MOD 5B WIND TURBINE SYSTEM

Figure 7. - MOD-5A and MOD-5B wind turbine concept design.

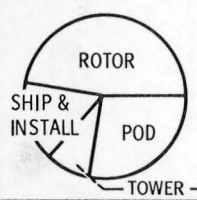
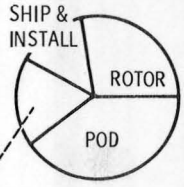
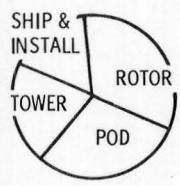
GENERATION	FIRST	SECOND	THIRD
WIND TURBINE	MOD-0A	MOD-2	MOD-5
COST ($/kW)	10 000	1700	1500
COMPONENT COST (% OF TOTAL)			
DESIGN EFFICIENCY (kWh/lb)	9	11	14

Figure 8. - Comparison of large horizontal axis wind turbine designs based on second unit prototype costs.

	MOD-0A	MOD-1	MOD-2	MOD-5A ≠	MOD-5B ≠	SVU WTS-4
PRIME CONTRACTOR	WESTINGHOUSE ELECT. CORP. PITTSBURGH, PA	GENERAL ELECTRIC Co. PHILADELPHIA, PA	BOEING ENGINEERING & CONSTRUCTION Co. SEATTLE, WA	GENERAL ELECTRIC CO. PHILADELPHIA, PA	BOEING ENGINEERING & CONSTRUCTION CO. SEATTLE, WA	HAMILTON STANDARD DIV. UNITED TECHNOLOGIES CORP. WINDSOR LOCKS, CT
LOCATION	CLAYTON, NM CULEBRA, PR BLOCK IS., RI OAHU, HI	BOONE, NC	GOODNOE HILLS, WA (3) MEDICINE BOW, WY (1)	T. B. D.	MEDICINE BOW, WY	MEDICINE BOW, WY
DATE OF FIRST ROTATION (LOCATION AND UNIT)	11-77 (NM) 6-78 (PR) 5-79 (RI) 5-80 (HI)	5-79 (NC)	11-80 (WA #1) 3-81 (WA #2) 5-81 (WA #3) 12-81 (WY-SVU)	T. B. D.	8-82	8-82
HUB HT., CTR. OF BLADE ROT. (ft)	100	140	200	235	250	262
ROTOR BLADE DIA. (ft)	125	200	300	400	420	256
RATED POWER (kW)	200	2000	2500	7300	7200	4000
RATED WIND SPD. @HUB HT. (mph)	22	33	28	32	31	36
ANNUAL ELECTRICAL OUTPUT (MWh) 12 mph SITE*	640	2400	7000	14400	18 200	7000
14mph SITE*	820	3700	9300	19500	23 800	9900
90% AVAILABILITY 16 mph SITE*	980	5100	11 300	24600	29 200	13000
CUT-IN WIND SPD. @HUB HT (mph)	12	16	14	14	9	15
CUT-OUT WIND SPD. @HUB HT (mph)	40	43	45 (60)**	50	60	60
WEIGHT, ON FOUNDATION (lb)	89.5×10^3	650×10^3	619×10^3	1407×10^3	1612×10^3	778×10^3
WEIGHT/RATED POWER (lb/kW)	447	325	247	193	224	194

* SITE ANNUAL MEAN WIND SPEED MEASURED AT 30 ft ABOVE SEA LEVEL, WEIBULL DISTRIBUTION ASSUMED

** MOD-2 AT MEDICINE BOW, WY

≠ CONCEPT DESIGN DATA

Figure 9. - Intermediate and large size horizontal axis wind turbine data.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83444		

4. Title and Subtitle	5. Report Date
DOE Large Horizontal Axis Wind Turbine Development at NASA Lewis Research Center	6. Performing Organization Code 776-33-41

7. Author(s)	8. Performing Organization Report No.
B. S. Linscott	E-1744
	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	13. Type of Report and Period Covered Technical Memorandum

12. Sponsoring Agency Name and Address	14. Sponsoring Agency ~~Code~~ Report No.
U.S. Department of Energy Wind Energy Technology Division Washington, D.C. 20545	DOE/NASA/20320-47

15. Supplementary Notes

Prepared under Interagency Agreement DE-AI01-76ET20320. Prepared for 1983 Wind/Solar Energy Conference, Kansas City, Missouri, April 25-26, 1983.

16. Abstract

The large wind turbine program is a major segment of the Federal Wind Energy Program sponsored by the Department of Energy (DOE). The NASA Lewis Research Center manages the large horizontal axis wind turbine program for DOE. The large wind turbine program is directed toward development of the technology for safe, reliable, environmentally acceptable large wind turbines that have the potential to generate a significant amount of electricity at costs competitive with conventional electric generation systems. In addition, these large wind turbines must be fully compatible with electric utility operations and interface requirements. There are several ongoing large wind system development projects directed toward meeting the technology requirements for utility applications. The first generation technology machines (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. Third generation technology machines (Mod-5) are in the design phase and are planned for initial operation in late 1984 or early 1985. Each successive generation of technology has shown potential to increase 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, improvements in the analytical design tools, verification of design methods with operating field data, and the incorporation of new technology and innovative designs. This paper provides an overview of the large wind turbine activities managed by NASA Lewis. These activities include results from the first and second generation field machines (Mod-0A, -1, and -2), the status of the Department of Interior WTS-4 machine for which NASA is responsible for technical management, and the design phase of the third generation wind turbines (Mod-5).

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind power Wind energy Wind turbines	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	8	A02

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