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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind Energy Technology Division

Prepared for
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NOTICE

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DOE/NASA LEWIS LARGE WIND TURBINE PROGRAM

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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 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. First generation technology machines (Mod-0A and Mod-1) and 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 scheduled for initial operation in 1984 if project funding is continued.

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).

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INTRODUCTION

Since 1973, the United States Government has sponsored an expanding 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 ongoing wind system developments oriented primarily toward utility application. These projects are designated Mod-0A, Mod-1, Mod-2, WTS-4 and Mod-5. In addition to these machine projects, there is a supporting research and development project that util-

izes the Mod-0 wind turbine as an experimental test bed. These machine configurations are illustrated in figure 1.

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

Mod-0A 200 kW Wind Turbine Project

The Mod-0A project 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 installation was completed in 1977. Since then a machine has been installed each year at the sites shown in figure 2, with the last installation completed in July 1980. The machine has a (38-m) 125-ft-diam downwind full pitchable rotor, and is mounted on a (30-m) 100-ft rigid truss tower. The rated power is 200 kW at a wind speed of 18.1 mph (7.5 m/s).

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 have been upgraded with very significant results. The four machines have now accumulated over 36 000 hr of operating time and have generated 3500 MW hr of energy. The availability of the machines often exceeds the goal of 90 percent, and the last machine installed averaged 80 percent for the first year.

The continuing machine operations at the four sites are providing very significant data for a wide variety of environment and wind conditions and utility situations (ref. 1). The operating experience has had a significant effect on the second and third generation machine designs.

Mod-1 2000 kW Wind Turbine Project

The Mod-1 project was initiated in 1974. The Mod-1 is a two-bladed, 200-ft-diam wind turbine with a rated power of 2000 kW. The blades are steel and the rotor is located downwind of the tower. Full span pitch is used to control the rotor speed at a constant 35 rpm. The gearbox and generator are similar in design to the Mod-0A but, of course, are much larger. The tower is a steel, tubular truss design. The General Electric Company, Space Division of Philadelphia, Pennsylvania is 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 and began tests synchronized to the Blue Ridge Electrical Membership Corporation in September 1979 (fig. 3). The Mod-1 has 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 with-

in 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 turbine developments.

To reduce rotor noise, the rotor speed was reduced from 35 to 23 rpm. This was accomplished by replacing the 2000-kW 1800-rpm generator with a 1500-kW 1200-rpm generator. Near the completion of the noise experiments, the Mod-1 experienced a failure in the low-speed shaft of the drive train. Since the Mod-1 has met most of its project goals and wind program funding has been reduced, it has not been decided to immediately repair the machine. The future of the Mod-1 is presently under evaluation to determine how it can best support the program.

Mod-2 2500 kW Wind Turbine Project

The Mod-2 wind turbine project 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 Co. 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 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 (fig. 4). Three Mod-2 machines have been clustered at a single site at Goldendale, Washington 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 attainment of the DOE/NASA project goals.

The Mod-2 project is now in the experimental operations phase 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. To date, initial performance of the turbines has been acceptable but also has indicated areas for improvement. Corrective actions have been taken to modify the turbines as necessitated by the June 8, 1981, failure of turbine 1's safety system. Test operations resumed in early fall on turbines 2 and 3. Full three machine cluster operation resumed in May, 1982 (ref. 3). As of May 23, 1982, the three machines have operated a total of 1715 hr and during which they have generated a total of 1939 MWh of electricity.

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 Salerno County, California. These machines are both targeted to be in operation in mid 1982.

WTS-4 4000 kW Wind Turbine Project

NASA Lewis is participating in a joint project with the Department of the Interior (DOI) Bureau of Reclamation to install two megawatt-size system verification units (SVU) wind turbines near Medicine Bow, Wyoming. Operation of the SVU's is expected to verify the concept of integrating wind turbines and hydroelectric facilities as 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. 5). 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 is being built for the Swedisn government with KKRV as the prime 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.

Currently, the WTS-4 nacelle has completed final factory checkout and testing and is being shipped from Sweden to Medicine Bow. It is scheduled to arrive in Medicine Bow in May 1982 when it will be rechecked before being installed on the tower which was erected in October 1981. The two single piece filament wound fiberglass blades have been fabricated at the dedicated Hamilton Standard winding facility in East Granby, Connecticut. They will be trucked to Medicine Bow and installed on the WTS-4 prior to nacelle erection. Two identical blades have already been completed and shipped to Sweden. First rotation of the WTS-4 is scheduled for August 1982 (ref. 4).

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 the potential to be cost competitive. 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 reduced funding, however, major cost-share proposals were solicited from both contractors near the end of 1981. Both contractors have submitted cost-share proposals and these are being negotiated. Continuation of the projects through fabrication, installation and checkout is dependent on receiving fiscal 1983 funding.

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 scheduled for summer of 1982. It is anticipated that the design will be complete, and fabrication initiated early in 1983 and machine operation initiated by the fall of 1984 subject to continued program funding.

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 30 machines at a

site with a 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 wood epoxy; blade articulation, independently coned versus teetered; orientation, upwind versus downwind; torque control, flaps versus partial span control; tower height; system rpm, single speed versus multi-speed; gearbox/nacelle configuration, integral gearbox versus rotor integrated gearbox and size, and both rotor diameter and rated power.

The conceptual design effort produced a wind turbine design with a 400-ft-diam wood epoxy rotor (ref. 5) mounted directly on the gearbox. The two speed gearbox drives a 7.3-MW synchronous generator. The soft tubular tower provides a rotor centerline 250 ft above ground level. Figure 6 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 and scheduled to be completed in summer of 1983. The Mod-5B wind turbine 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 (14 mph) average annual wind speeds. It is based on the technology developed on the previous Mod-2 wind turbine program, but it has roughly twice the rotor area (420 ft diam versus 300 ft) and almost three times the power (7.2 MW versus 2.5 MW) compared to the Mod-2 (fig. 7). Advanced technology is featured in rotating light weight wood blade tips and variable rotor speed operation 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 increasing gearbox, and rotor speed control employing only the variable pitch-blade tips are retained from the Mod-2 (ref. 6).

This project is in preliminary design stage now and detailed design is scheduled for completion in early 1983. Erection and operation should take place in early 1984 subject to continued program funding.

Summary of Large Wind Turbine Developments

Much understanding and progress has been made in designing more efficient, lighter weight, and lower cost wind turbines since the first Mod-0A started operations in 1977 at Clayton, New Mexico. Figure 8 shows the first rotation dates for each of the large wind turbines. A brief summary of progress to date for large machines is outlined in figure 9. Figure 9 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 9 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 20 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 doubling occurring from first to third. This is impressive considering it means doubling the energy output for the same weight or maintaining equal energy out with a machine at half the weight. It is even more important considering the Mod-0A was a fairly lightweight machine and utilized aircraft quality lightweight aluminum blades. These gains were made by

utilizing advanced technology such as teetered rotors, tip-controlled blades, epicyclic gearboxes, towers with lower natural frequencies, rotors made with significantly lower cost materials and methods and improved analysis tools and increased understanding of the major design drivers. It is also interesting to note in figure 9 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.

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 supporting research and technology project (SR and T). A summary of the progress and status of these projects follows:

1. Four Mod-0A 200 kW wind turbines have now operated over 36 000 hr and generated 3500 MW hr of electricity on utility systems. The Westinghouse Corporation under contract to NASA Lewis is primarily responsible for regularly reporting on performance of these machines and for providing any necessary servicing over and above the routine maintenance provided by the utility.

2. The 2000 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.

3. The three 2500 kW Mod-2s designed and built by Boeing Engineering and Construction Company, have been installed on the Bonneville Power Administration system and acceptance testing is in progress. An overspeed incident on one machine on June 8, 1981, caused some major damage, but the problem has been corrected and all three machines were back in generation in April 1982. As of May 23, 1982 the three machines have operated 1715 hr and generated 1939 MWh of electricity.

4. The Bureau of Reclamation has a 2500 kW Mod-2 and a 4000 kW WTS-4 wind turbine in fabrication and construction for verification testing at their Medicine Bow site in Wyoming. The WTS-4 wind turbine is being designed and built by Hamilton Standard. NASA has technical management responsibility for both wind turbines. Boeing will furnish the Mod-2 machine. Both machines are planned to be operating by mid-1982.

5. 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 (7 MW with rotor diameters of 400 ft or more) and utilization of advanced technology such as variable speed generators and lightweight wood composite rotors.

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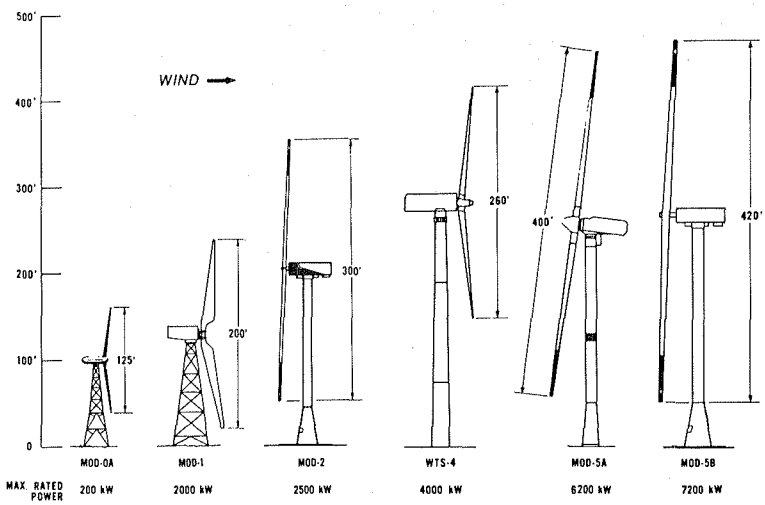

Figure 1. - Large horizontal axis wind turbines.

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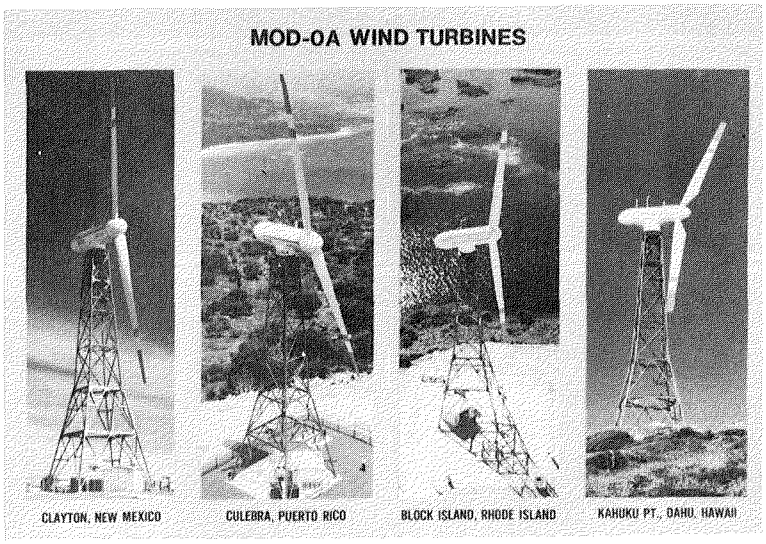


Figure 2. - Mod-OA 200 kW wind turbines.

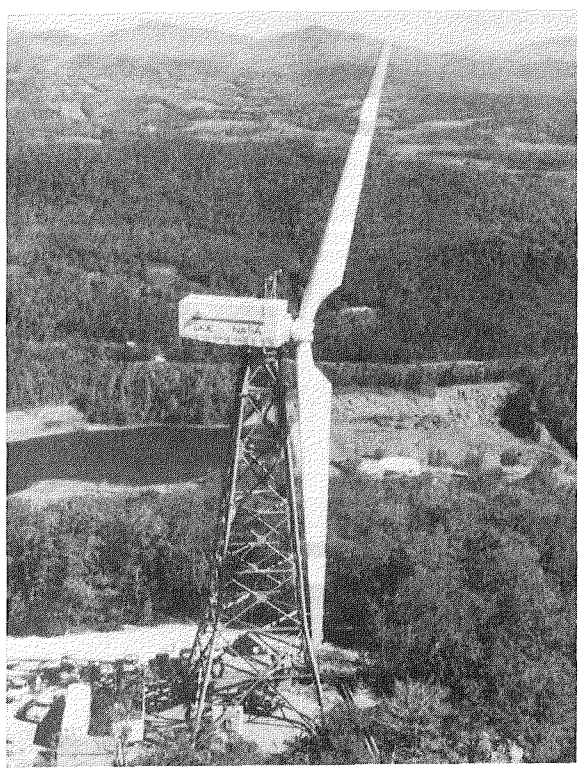


Figure 3. - Mod-1 2000 kW wind turbine.

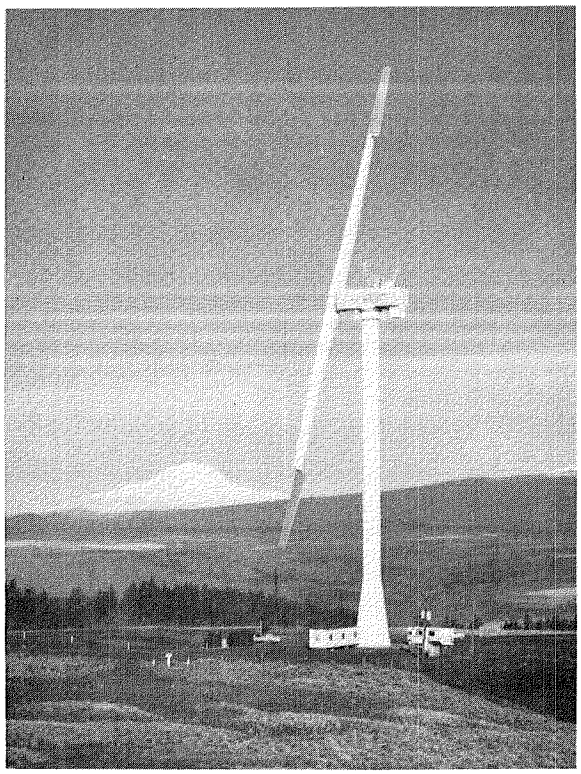


Figure 4. - Mod-2 2500 kW wind turbine.

Figure 5. - WTS-4 4000 kW wind turbine.

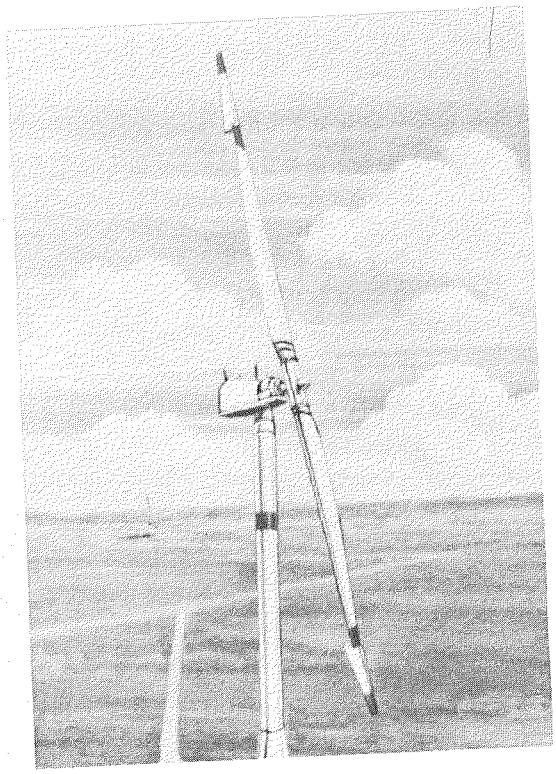


Figure 6. - Mod-5A 7300 kW wind turbine.

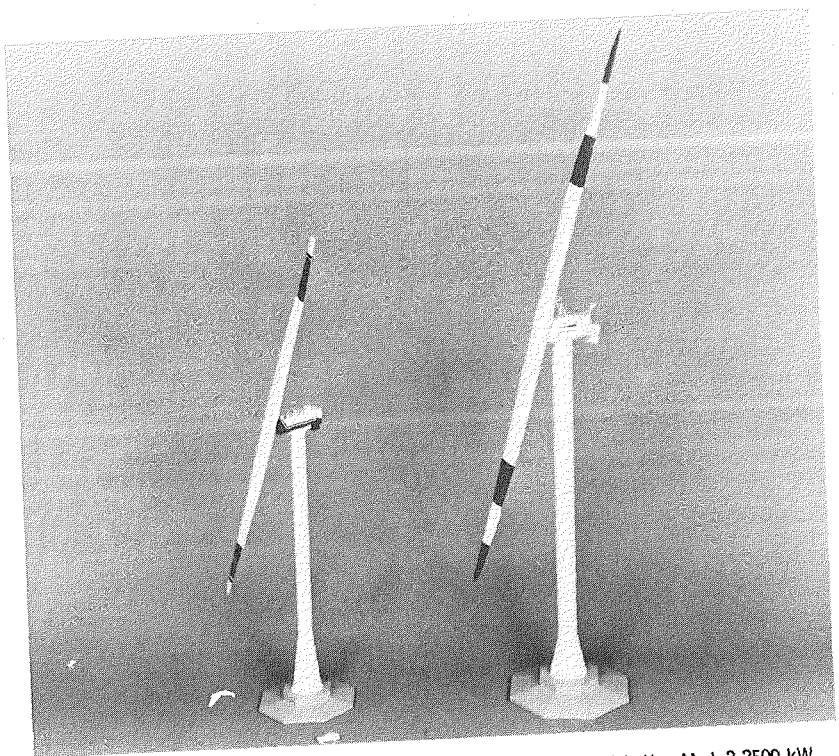


Figure 7. - Comparison of the Mod-5B 7200 kW wind turbine with the Mod-2 2500 kW.

LARGE WIND TURBINE PROGRAM SCHEDULE FOR FIRST ROTATIONS

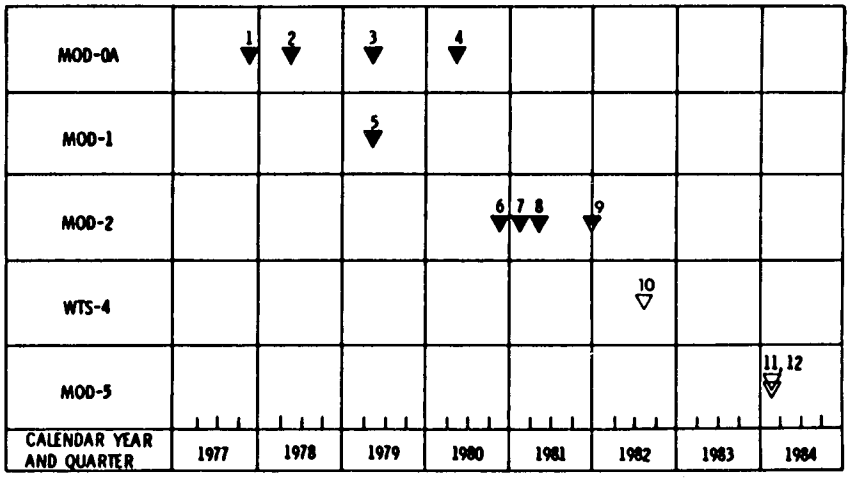
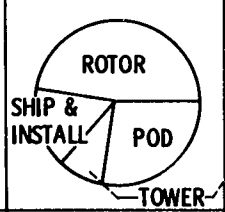
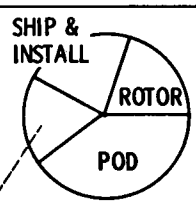
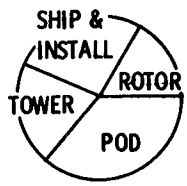


Figure 8. - Schedule of first rotation dates for large wind turbines.

COMPARISON OF LARGE WIND TURBINE DESIGNS*

GENERATION	FIRST	SECOND	THIRD
WIND TURBINE	MOD-0A	MOD-2	MOD-5
COST ($/kW)	10,000	1700	1300
COMPONENT COST (% OF TOTAL)			
DESIGN EFFICIENCY (kWh/lb)	9	15	18

* BASED ON SECOND UNIT PROTOTYPE COSTS

Figure 9. - Key factors for large wind turbines.

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