12/82

DOE/NASA/0163-1
NASA CR-165127
AESD-TME-3051

MOD-0A 200-Kilowatt Wind Turbine Generator Design and Analysis Report

Executive Summary

T. S. Andersen, C. A. Bodenschatz,
A. G. Eggers, P. S. Hughes, R. F. Lampe,
M. H. Lipner, and J. R. Schornhorst
Westinghouse Electric Corporation

August 1980

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Under Contract DEN 3-163

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind Energy Technology Division

DOE/NASA/0163-1
NASA CR-165127
AESD-TME-3051

MOD-0A 200-Kilowatt Wind Turbine Generator Design and Analysis Report

Executve Summary

T. S. Andersen, C. A. Bodenschatz,
A. G. Eggers, P. S. Hughes, R. F. Lampe,
M. H. Lipner, and J. R. Schornhorst
Westinghouse Electric Corporation
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, Pennsylvania 15236

August 1980

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-163

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind Energy Technology Division
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-76ET20370

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

A/D	Analog to Digital
AESD	Advanced Energy Systems Division (Westinghouse)
CB	Circuit Breaker
CCW	Counterclockwise
CRT	Cathode Ray Tube
DOE	Department of Energy
ERDA	Energy Research and Development Administration
FM	Frequency Modulation
FMEA	Failure Modes and Effects Analysis
HAWT	Horizontal-Axis Wind Turbine
IEEE	Institute of Electrical and Electronic Engineers
LeRC	Lewis Research Center (NASA)
MCP	Motor Circuit Protector
MOSTAB; MOSTAB-WTE	MOdular STABility Derivative Program; Wind Turbine Empirical
NACA	National Advisory Committee for Aeronautics (now NASA)
NASA	National Aeronautics and Space Administration
NASTRAN	Title of general purpose system computer program used for wind turbine analyses
NEMA	National Electrical Manufacturers Association
OSHA	Occupational Safety and Health Administration
PROP	Title of FORTRAN computer program for the determination of performance, loads, and stability derivatives of wind turbines
RMU	Remote Multiplexer Unit
SAIR	Stand Alone Instrument Recorder
VAR	Volt Amperes Reactive
WTG	Wind Turbine Generator

SUMMARY

This report summarizes the design, analysis, testing, installation, and initial operating performance of the MOD-OA 200 kW wind turbine generator installed at Clayton, NM. The MOD-OA wind turbine was designed and built by the NASA Lewis Research Center for the U.S. Department of Energy as part of the Federal Wind Energy Program. The objective of the MOD-OA project is to obtain early operation and performance data and experience with horizontal-axis wind turbines in utility environments. This report covers the effort from the formation of the MOD-OA project in 1975 to March 1978, when the first MOD-OA wind turbine was released to the Town of Clayton Light and Water Plant for utility operation.

This report summarizes the NASA project requirements and approach, system description, system design requirements, design and analysis, system tests and installation, safety considerations, failure modes and effects analysis, data acquisition, and initial operating performance for the MOD-OA wind turbine. The system description provides an overview of the mechanical and electrical components. The system design requirements provide the basis for the design.

The design and analysis section of the report summarizes the requirements, approach, selected design, and supporting analytical results for the components and systems. These components and systems are the rotor and pitch change mechanism, drive train, nacelle equipment, yaw drive mechanism and brake, tower and foundation, electrical system and components, and the control systems. The rotor consists of the blades, hub, pitch change mechanism, and its hydraulic system. The drive train includes the low speed shaft, speed increaser, high speed shaft, belt drive, fluid coupling, and rotor brake. The section on the tower and foundation also describes the service stand and the equipment and personnel hoist. The electrical system and components are the generator, switchgear, transformer, utility connection, and slip rings. The control systems are the blade pitch, yaw, and generator control, and the safety system. The methods and equipment used for manual control, automatic control, and remote control and monitoring are described. The results of system dynamic loads analyses and fatigue analyses are summarized.

System tests were performed at NASA and at the site. The engineering data acquisition system includes the instrumentation, remote multiplexer units, mobile data system, and a stand alone instrument recorder. Finally, the initial operating performance from November 1977 through March 1978 is summarized.

From the design, analysis, and initial operation (prior to its release for utility operation) of the MOD-OA at Clayton, the following principal conclusions are reached. General agreement is shown between predictions and initial operational measurements for the power output as a function of wind speed and for the structural performance. Satisfactory initial operating characteristics in a utility environment are demonstrated.

INTRODUCTION

ORIGINAL PAGE IS OF POOR QUALITY

HISTORY AND BACKGROUND

Wind energy systems have been utilized for centuries as a source of power for a variety of applications. Some of the more recent applications included sailing ships for transportation and wind turbines (windmills) for grinding grain, pumping water, and generating electricity. In the early 1940's, a Smith-Putnam large Horizontal-Axis Wind Turbine (HAWT) was designed and built to feed power into the existing electrical network of the Central Vermont Public Service Company. This machine consisted of a two-bladed 175 foot (53.3 m) diameter rotor which was capable of producing 1.25 MW of power. In addition, Dr. U. Hütter designed and built a 100 kW Wind Turbine Generator (WTG) in West Germany in the late 1950s and gained operating experience with his machine tied to the utility network. The Hütter machine used a downwind 112 foot (34.1 m) diameter two-bladed rotor. Several of the design criteria and design features of the Smith-Putnam and Hütter WTGs were considered or incorporated into the MOD-0 and MOD-0A HAWTs.

RECENT DEVELOPMENTS

The recent national concern over the increase in energy demand and costs of fossil fuels, the dwindling supplies of domestic gas and oil, and the nation's increasing dependence upon imported oil has made it necessary to develop alternate energy sources. Wind energy conversion has long been recognized as a potentially abundant source of electrical power. Utilization of wind energy is becoming more attractive as the cost differential between wind and the more conventional fossil alternatives narrows.

A Federal Wind Energy Program originated at the National Science Foundation in 1973. The objective of this program is to accelerate the development of reliable and economically viable wind energy systems and achieve early commercialization. Satisfying this objective requires advancing the technology, developing a sound industrial base, and addressing the non-technological issues which could impede its development. In January 1975, the responsibility for managing the program was transferred to the Energy Research and Development Administration (ERDA). These efforts were continued by the Division of Distributed Solar Technology in the U. S. Department of Energy (DOE) after October 1, 1977.

One segment of the Federal Wind Program is the development of large horizontal-axis WTGs. In 1973, the NASA Lewis Research Center (LeRC) was asked by the National Science Foundation (and later by ERDA and DOE) to develop, and provide project management for, the designs of large, experimental, horizontal-axis WTGs and perform the necessary supporting research and technology development. Initially, a review of prior experience in WTGs was performed. Analytical techniques and computer codes were then developed to predict the structural dynamics of large HAWT systems. Analyses and tests were performed on wake interaction and tower shadow effects, and analytical optimization techniques were developed.

MOD-0 WIND TURBINE GENERATOR

As part of the federal wind program, NASA LeRC designed, built, and started testing a 100 kW wind turbine in September 1975. This experimental project, designated the MOD-0, had primary objectives of providing engineering data and serving as a test bed for evaluating advanced wind turbine design concepts. The MOD-0 WTG was designed using available technology and "off-the-shelf" components where possible. Design, fabrication, and assembly were completed in 18 months. The MOD-0 WTG has a 125 foot (38.1 m) diameter downwind rotor which rotates at 40 rpm. The rotor drives a 60 Hz synchronous alternator through a step-up gearbox at 1800 rpm.

The MOD-0 project has been used to help understand the performance and the dynamic behavior of wind turbines. The MOD-0 WTG was utilized to: 1) understand the tower shadow and wind shear effects; 2) assess operational performance; 3) evaluate automatic startup and shutdown capabilities, including synchronization to a large and small utility network; and 4) test various components, such as induction generators and steel spar wind turbine blades.

MOD-0A WIND TURBINE GENERATOR

The MOD-0A 200 kW wind turbine generator is, in most respects, an uprated version of the MOD-0 100 kW WTG and was designed and analyzed by the NASA LeRC for the DOE. The objectives of the MOD-0A Project are: a) to conduct early testing of wind turbines in utility environments so that the machine operating performance and dynamic characteristics can be determined and b) to obtain the utility's and the public's reaction to intermediate size WTGs. The prototype MOD-0 design was simplified and made "field-worthy" as it was uprated to the 200 kW size.

The purposes of this executive summary report are: a) to summarize the design and analysis of the MOD-0A 200 kW wind turbine generator at Clayton, NM and b) to summarize the results on the inital operation of the WTG from November 1977 to March 1978, when operation by the Town of Clayton Light and Water Plant was started. Accordingly, this report summarizes the design requirements and specifications, the design and analysis of all of the components and systems, the systems analyses on dynamic loads and fatigue, the system tests performed, the installation, the safety considerations and the failure modes and effects analysis, the data acquisition system, and the initial operating performance of the MOD-0A machine at Clayton. This report covers the effort from the formation of the MOD-0A project in 1975 until March 1978.

Shown in Figure 0-1 is the MOD-0A wind turbine in operation at the Clayton site. The operational history for the Clayton MOD-0A WTG during its initial phases of use is as follows:

Date	Event
• November 30, 1977 . .	First rotation
• January 19, 1978	First 100 hours (0.36 megaseconds) of operation

Date		Event (Cont'd)
• January 28, 1978	. .	Formal dedication of wind turbine
• March 6, 1978		Turned over for operation by the utility
• May 24, 1978	. . . .	1000 hours (3.6 megaseconds) of operation [94,000 kW-hr (338.GJ)]

A number of other significant milestones have been achieved with the Clayton WTG since May 1978.

NASA
CS-78-284

Figure 0-1. MOD-OA 200 kW Wind Turbine Generator; Clayton, NM

ADDITIONAL WTG SYSTEMS

Additional federally funded wind turbine generator systems have been placed in operation, are being developed, or are planned for development. Besides the MOD-OA WTG at Clayton, three other experimental MOD-OA wind turbines have been installed by the Westinghouse Electric Corporation and are now operating on utility networks. A MOD-OA is operating on Culebra Island, Puerto Rico; Block Island, Rhode Island; and on Oahu Island, Hawaii. The MOD-1 experimental 2.0 MW wind turbine is now operating at Boone, North Carolina. MOD-1 was developed and installed by the General Electric Company for the NASA LeRC. The Boeing Engineering and Construction Company is currently developing a 2.5 MW, 300 foot (91.4 m) diameter WTG called MOD-2 for the NASA LeRC. The MOD-5 and MOD-6H projects are planned for the development of advanced large size (> 1.0 MW) and advanced intermediate size (< 1.0 MW), respectively, wind turbines. Also, the Water and Power Resources Service of the U.S. Department of Interior has initiated the development of an additional MW size horizontal-axis wind turbine, designated the System Verification Unit.

Each of the additional wind turbine projects was started after the initiation of the MOD-0 and the first MOD-0A wind turbine projects.

OTHER MOD-0A REPORTS

Two other reports related to the design and analysis of the MOD-0A wind turbine have been prepared as part of this contract. A detailed report on the design and analysis of the MOD-0A WTG has been published.[1*] This detailed report has a comprehensive list of references which are cited, as well as a bibliography, to provide additional background information. This detailed list of references and bibliography has not been included in this excutive summary report. The engineering drawings for the MOD-0A wind turbine have also been documented.[2]

CONCLUSIONS

Several conclusions were drawn by the NASA Lewis Research Center from the design, analysis, and initial operation (prior to its release for operation by the utility) of the Clayton MOD-0A 200 kW wind turbine. These conclusions are categorized into the following: machine performance, structural performance, and utility interface.

In the machine performance area, general agreement was shown between the predicted and measured values for power output as a function of wind speed. The measured drive train efficiency varied with output power and exceeded the design value as the power approached 200 kW. The average cyclic power varied less than ± 20 kW, due to tower shadow and wind shear effects. An ice detector was found to be necessary for safe operation during potential icing conditions.

The structural performance was generally as predicted. Dynamic blade loads measured during initial operation were in good agreement with loads calculated using the MOSTAB computer code. Cyclic loads caused by tower shadow and wind shear were found to be significant and could cause local wear and fatigue damage in the blades and hub. Close monitoring of the blade loads, structural condition, and interface clearances is required to insure structural integrity.

With regard to utility interface, satisfactory operating characteristics in a utility environment during initial tests from November 1977 to March 1978 were demonstrated. The wind turbine was successfully synchronized to the utility network in an unattended mode. The instantaneous frequency was controlled within a peak-to-peak variation of ~ 1 Hz about the nominal. The wind turbine exhibits a natural mode of oscillation at 1.33 Hz, which is twice the speed of the rotor. Oscillations at this frequency are caused by tower shadow and wind shear effects. Since the dominant frequency of oscillation of the Clayton system is 3 Hz, the wind turbine does not excite the system. As a result of training, utility personnel were able to operate the MOD-0A for the purpose of experimentally supplying power on their utility network.

* NOTE: Superscript numerals refer to the reference number listed in Section 10.0, References.

1.0 PROJECT REQUIREMENTS AND APPROACH

The project requirements are presented in Section 1.1. Discussed in Section 1.2 is the approach taken by the NASA LeRC in fulfilling these requirements. Further details on the project requirements and approach are presented in the MOD-OA design report.[1*]

1.1 PROJECT REQUIREMENTS

The objectives of the MOD-OA project are: a) to design and build relatively large (> 100 kW) WTGs and to operate them in conjunction with existing utility networks and b) to obtain performance data and operating experience in utility environments. Thus, the principal project requirements are:

- To obtain utility operating experience and assess stability and control requirements
- To determine the impact of a variable power output (due to varying wind speeds) on the utility network
- To assess compatibility with other utility requirements, e.g., voltage and frequency control of generated power

The secondary project requirements/objectives include the following:

- Obtain operation and performance data, including dynamic characteristics, and demonstrate automatic, unattended, fail-safe operation
- Resolve any problems from the operation of WTGs in utility systems; and identify utility interface requirements
- Develop and test improved systems and components
- Determine the reliability and assess the required maintenance
- Identify and resolve any potential institutional problems and assess public reaction and acceptance

Several of the requirements and objectives pertain to involving utilities in the project. These requirements were necessary for the future role of the utilities as successful owners/operators of WTGs.

---

*NOTE: Superscript numerals refer to the reference number listed in Section 10.0, References.

1.2 APPROACH

MANAGEMENT OF PROJECT AND APPROACH

The Energy Research and Development Administration (ERDA) initiated the MOD-OA Project in January 1975 and directed the NASA LeRC to design an uprated MOD-O WTG. The MOD-OA program came under the direction of the U.S. Department of Energy (DOE) in October 1977. The NASA LeRC managed the project and performed the design, analysis, assembly, tests, and installation of the Clayton MOD-OA WTG. The MOD-OA was to be an experimental WTG and built quickly to obtain operational experience in utility environments. NASA LeRC decided to utilize the basic MOD-O WTG configuration and uprate that design to 200 kW. Two MOD-OAs were to be deployed initially and this was increased to four WTGs, so as to assess performance in different utilities, environments, and climatic conditions.

The approach in the development of the MOD-OA wind turbine involved machine design, design verification, and system assembly and testing. The system design requirements provided the basis for the mechanical and electrical design. These included the definition of the steady and cyclic loads, in which all computer codes used were validated by measured loads on the MOD-O WTG. Control systems were designed to automatically start the WTG, synchronize it with the utility network, control the power level, and shut the WTG down during various normal and emergency conditions.

The MOD-OA WTG had no formal qualification program for design verification. The mechanical design was validated by design analysis, with the analysis tools verified by the MOD-O test results. The electrical and control systems were basically duplicates of the MOD-O systems and were validated by MOD-O testing. The system assembly and acceptance testing involved the drive train, yaw drive mechanism, rotor hub, and pitch change mechanism. The final assembly and checkout of the WTG were performed at the utility site.

SITE SELECTION

In 1976, ERDA issued a request for proposal to the utility community to identify utility interest and locate high wind sites. From the 65 proposals submitted, 17 sites were selected on the basis of maximizing the information for the Federal Wind Program and the utility industry. At each site, ERDA installed meteorological towers and instrumentation to measure site wind data.

Initially, two sites were selected to receive MOD-OA WTGs and this was later expanded to four. These sites were Clayton, NM, Culebra, PR, Block Island, RI, and Oahu, HI. At each site, the government is supplying: a) the wind turbine and its foundation, b) the controls, instrumentation, and recording equipment, and c) NASA and NASA contractor personnel for the installation, checkout, and non-routine maintenance. The utility companies are providing: a) the site for the wind turbine, b) an access road, security fencing, electrical interface equipment, and a remote control room, c) personnel during site preparation, final assembly, and checkout, and d) personnel for operating, monitoring, and maintaining the WTG and recording performance data.

ORIGINAL PAGE IS
OF POOR QUALITY

Clayton, NM is located in the northeastern corner of the state. The city has a small, municipally owned, independent utility which operates on natural gas or diesel fuel. An aerial view showing the MOD-OA wind turbine site and Clayton, NM is presented in Figure 1-1. The city's general characteristics are given in Table 1-1.

NASA
CS-78-288

Figure 1-1. Aerial View MOD-OA Wind Turbine Site in Clayton, NM

TABLE 1-1: GENERAL CHARACTERISTICS OF CLAYTON, NM (POPULATION, ELEVATION, ENERGY CONSUMPTION, POWER DEMAND, MEAN WIND SPEEDS, AND TEMPERATURES)

Population	3,000
Elevation	5,000 ft. (1520 m)
Annual Energy Consumption (1978) . .	15,100 MW hr
Peak Power Demand	3.8 MW
Average Daytime Power Demand	2.8 MW
Mean Annual Wind Speed (Battelle data for 1979):	
@ 30 ft (9.1 m)	12 mph (5.4 m/sec)
@ Hub Height - 100 ft (30.5 m)	15 mph (6.7 m/sec)
Temperature Range	-10°F(-23°C) to 120°F (49°C)

PROJECT RESPONSIBILITIES

NASA LeRC is responsible for managing all phases of the MOD-OA project. NASA LeRC retained the design, analysis, procurement, assembly, and in plant testing responsibilities for the Clayton wind turbine, and gradually involved an industrial contractor in these responsibilities as the later WTGs were built. The Industry Services Division of the Westinghouse Electric Corporation was selected by competitive bid to be the industrial contractor. The blades for the wind turbine were designed and analyzed by the Lockheed California Company located in Burbank, CA. The Lockheed Aircraft Service Company of Ontario, CA was selected for fabricating the blades. Both NASA LeRC and Westinghouse personnel were involved in the installation, site tests, and checkout of the Clayton WTG. Several responsibilities assumed by the Clayton utility were delineated above under Site Selection. NASA LeRC, with assistance from Westinghouse personnel, trained the utility personnel in the operation and maintenance of the WTG.

ORIGINAL PAGE IS
OF POOR QUALITY

2.0 SYSTEM DESCRIPTION

The MOD-OA Wind Turbine Generator (WTG) is a device for generating electrical power from wind energy. It is designed to operate effectively when wind speeds are between 7 and 34 miles per hour (3 and 15 m/s) at 30 feet (9.1 m) above the ground. The electrical output from the machine is 480 V, 60 Hz, three phase, a type commonly used by utilities in the United States. This type of output power permits the generator to be easily tied in electrically with the generating station of a utility and to supply power to the existing network of that utility.

The MOD-OA WTG is a horizontal-axis type as shown in Figure 2-1. The basic components include a rotor, drive train, generator, and yaw system, and a tower for supporting the equipment at an elevated position. The two blades of the rotor are attached to the rotor hub which is bolted to the low speed shaft. The blades, hub, and low speed shaft rotate at 40 rpm. The drive train between the low speed shaft and generator includes a speed increaser that rotates the generator at 1800 rpm. All of the mechanical and electrical equipment is housed in a fiberglass nacelle supported 100 feet (30.5 m) above ground level by a four-legged truss type structural tower. A hoist provides access to the equipment mounted on top of the tower. The control system and electrical switchgear are housed in the control building at the base of the tower.

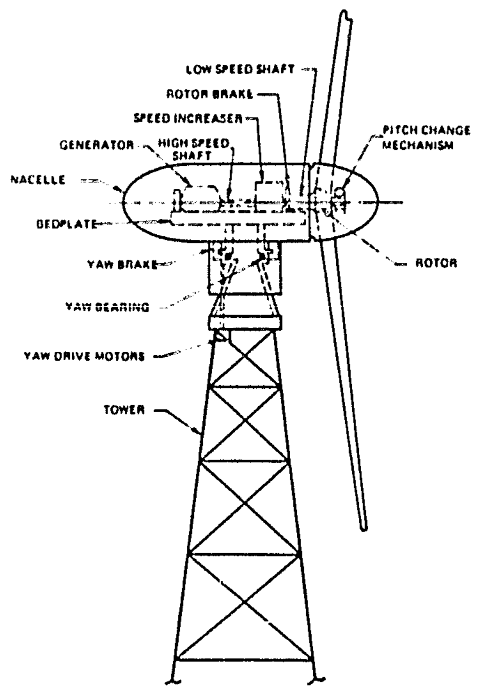


Figure 2-1. Major Components of the MOD-OA Wind Turbine Generator

2.1 FEATURES AND CHARACTERISTICS

The rated power output of the wind turbine is 200 kW. This power is achieved at a rotor speed of 40 rpm and a rated wind speed of 18.3 mph (8.2 m/s) measured at a 30 foot (9.1 m) elevation. The rated wind speed is the lowest wind speed at which full power is achieved. Power output is constant at higher winds up to the cut-out wind speed of 34.2 mph (15.3 m/s) at 30 ft (9.1 m). The rotor blades have pitch control, and are placed in a feathered (no power) position whenever the wind speed is not in the range of 6.9 to 34.2 mph (3.1 to 15.3 m/s) at 30 ft (9.1 m). Directional alignment with the wind is provided by a yaw system that turns the nacelle on a turntable bearing located at the top of the tower. The principal features and characteristics of the wind turbine are listed as follows:

Features and Characteristics

Number of Blades	2
Diameter	125 feet (38.1 m)
Speed	40 rpm
Direction of Rotation	CCW (looking upwind)
Type of Hub	Rigid
Power Regulation Method	Variable Pitch
Cone Angle of Blades	7 degrees
Tilt Angle of Axis	0 degrees
Blade Length	59.9 feet (18.3 m)
Blade Material	Aluminum
Speed of Rotor & Generator	40 & 1800 rpm

2.2 CONFIGURATION

The configuration of the wind turbine is shown in Figure 2-2. It consists of a rotor with blades, nacelle with internal equipment, tower, hoist, and control building. Two propeller type blades rotate about a horizontal axis and are located downwind from the tower. The blades are swept downwind at a seven degree angle to provide clearance from the tower. A cable supported hoist is located within the periphery of the tower and is used to transport equipment and personnel between ground level and the top of the tower. A control building is located inside the tower near one leg of the tower.

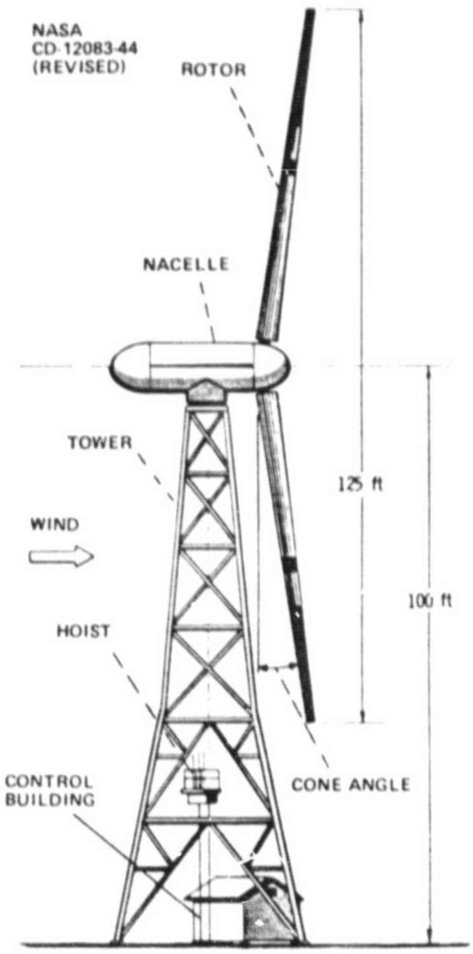
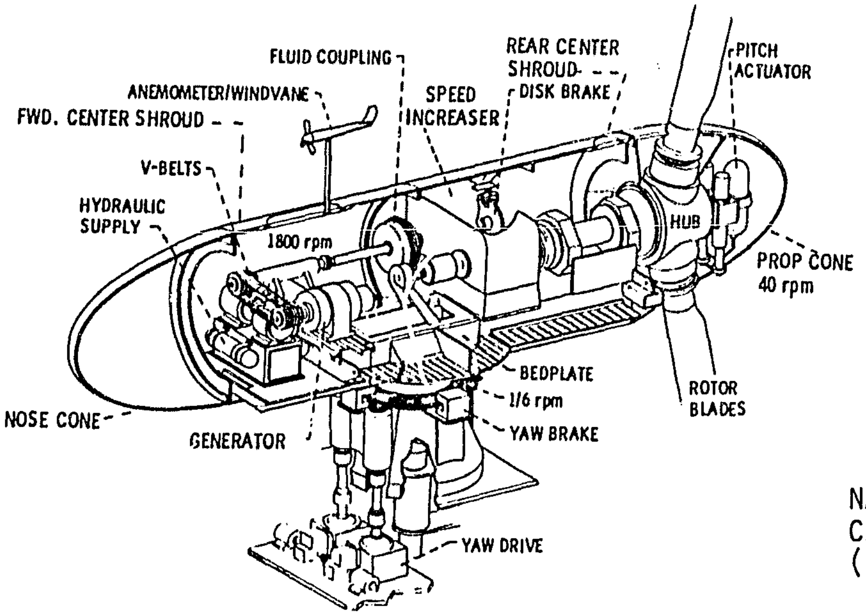


Figure 2-2. Configuration of 200 kW WTG

The arrangement of power generating equipment is shown in Figure 2-3. All of the rotating equipment is located inside a fiberglass nacelle and supported on a large structural bedplate. The nose cone and cylindrical sections of the nacelle are also supported on the bedplate through flange attachments. The rear or prop cone section of the nacelle rotates with the blades and therefore is supported on the rotor hub. Support for the bedplate is provided by a large diameter turntable bearing assembly which is mounted on a support cone on top of the tower. The outer race of the turntable bearing assembly serves a secondary function. It is machined with gear teeth and is driven during yaw maneuvers by pinion gears powered by the yaw drive system.



NASA
CD-12082-44
(Revised)

Figure 2-3. Nacelle Arrangement for MOD-0A Wind Turbine Generator

2.3 PREDICTED PERFORMANCE

The rated power output of the wind turbine is 200 kW, which is achieved at a rotor speed of 40 rpm and a rated wind speed of 18.3 mph (8.2 m/s) at a 30-foot (9.1 m) elevation. 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, as shown in Figure 2-4, 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 6.9 mph (3.1 m/s) at a 30 ft (9.1 m) elevation. The cut-out wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade loads, is 34.2 mph (15.3 m/s) at 30 ft (9.1 m).

The calculated annual energy output for the 200 kW wind turbine operating in various average wind speed environments is shown in Figure 2-5. The average wind speed is the arithmetic average of all hourly wind speeds in a given year at that particular site measured 30 feet (9.1 m) above ground level. The energy output is a strong function of the average wind speed, since the available energy in the wind is proportional to the cube of the wind speed. The energy output was computed using the power output shown in Figure 2-4. Velocity profile curves for the wind were assumed to be Weibull distributed. Energy capture by the rotor was computed using the wind speed occurring at the hub height of 100 feet (30.5 m). Wind speeds at various elevations were calculated by using the wind shear gradient typical of most of the candidate wind turbine sites. It was estimated that the machine would be shut down ten percent of the time when the wind velocity was between cut-in and cut-out speeds. This shutdown time was allowed for both scheduled and unscheduled maintenance.

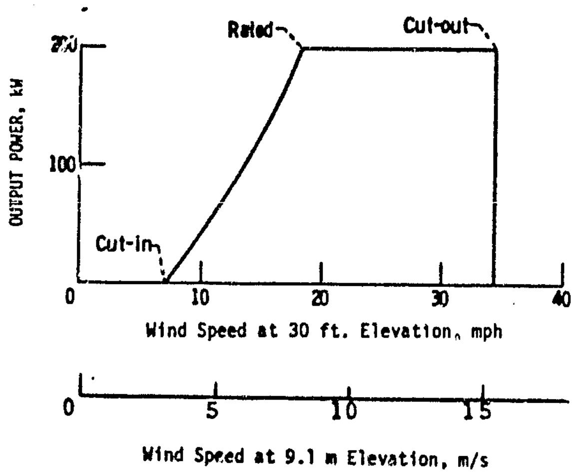


Figure 2-4. Predicted Performance of MOD-0A Wind Turbine

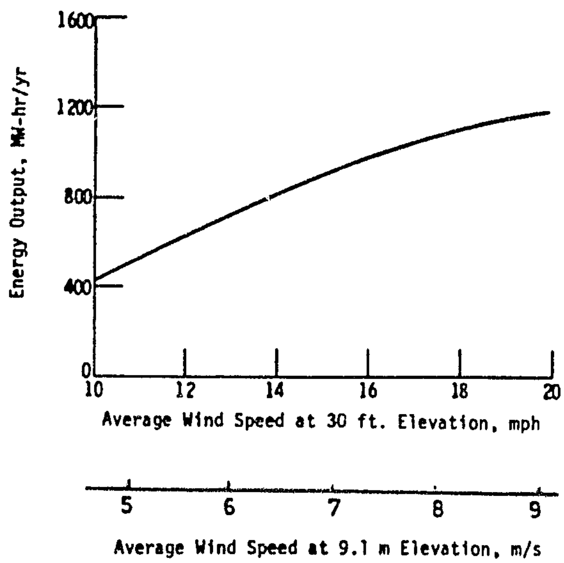


Figure 2-5. Annual Energy Output for 200 kW Wind Turbine

2.4 COST AND WEIGHT

The total cost of the Clayton MOD-OA wind turbine (in 1978 dollars) was $1.7 million. A breakdown of the costs is given in Table 2-1. The blades were manufactured by the Lockheed Aircraft Service Co., Ontario, CA, under a NASA contract. NASA LeRC managed the procurement of the long lead parts. The assembly and in plant testing was conducted by NASA at the LeRC. Site installation and some of the startup operations were performed by the Westinghouse Electric Corporation under a NASA contract.

The total system weight is 89,000 pounds (40.400 kg). The rotor, including blades, weighs 12,300 pounds (5,580 kg). Above the tower weight is 45,000 pounds (20,400 kg), while the tower weight is 44,000 pounds (20,000 kg). Further details on the weights of some of the components are provided in Table 3-1.

TABLE 2-1
MOD-OA 200 kW Wind Turbine Costs ($K)
(1978 Dollars - Clayton, NM)

Blades (2)	450
Hub and Pitch Change	160
Mechanical Equipment	230
Electrical Equipment	110
Control Systems	40
Tower and Hoist	140
Shipping	40
Installation	200
Startup Operations	150
Engineering Data System	180
Total cost	$1700K

ORIGINAL PAGE IS
OF POOR QUALITY

3.0 SYSTEM DESIGN REQUIREMENTS AND SPECIFICATIONS

The principal design requirements for the MOD-0A WTG system are summarized in Section 3.1. Section 3.2 summarizes the system specifications that were developed to satisfy these requirements. Further details on these requirements and specifications are given in the MOD-0A design report.[1]

3.1 SYSTEM DESIGN REQUIREMENTS

The system design requirements include those requirements that were delineated at the initiation of the project and those that were developed (or upgraded) during the project. These requirements have been divided into the following categories: General, Mechanical Components and Systems, Electrical Components and Systems, Control Systems, Engineering Data Acquisition, Environmental, and Safety and Failure Modes and Effects Analysis.

GENERAL

The general requirements for the MOD-0A design included the following:

- Develop an experimental horizontal-axis WTG that is an uprated version of the MOD-0 wind turbine. The rated electrical power output was selected to be 200 kW.

- The high cut-out wind speed (the wind speed above which the machine is shut down) was selected to be 40 mph (17.9 m/s) at hub height.

- Provide fail-safe shutdown capabilities; design the WTG for operation compatible with existing utility networks.

- All static components must be designed for a 50-year life. All dynamic components, except the blades, are to be designed for a 30-year life. The blades are to be designed to withstand the loads measured on the MOD-0 machine.

- Provide a design which meets all of the applicable design codes and standards.

- Provide a design that permits flexibility in the selection of the rotor speed, and develop the criteria for that selection. The baseline design was then selected to be 40 rpm.

MECHANICAL COMPONENTS AND SYSTEMS

The mechanical design requirements included the following:

- Provide a design of the MOD-0A WTG with a 125 foot (38.1 m) diameter rotor, a rigid hub, and two blades located downwind of the tower at a seven degree cone angle.

ORIGINAL PAGE IS
OF POOR QUALITY

- Develop the requirements for wind gust and wind shear, including tower shadow effects.

- Develop the requirements for the steady and cyclic loads, and especially for the loads on the rotor, including the aerodynamic, gravitational, and inertial effects.

- Design a pitch change mechanism for the blades to control the power level and rotational speed of the WTG.

- A speed increaser must be designed or selected to convert the wind power from the blades rotating at 40 rpm to the high speed shaft and generator rotating at 1800 rpm.

- A rotor brake must be designed for shutting the rotor down and bringing it to a full stop in the event of a catastrophic failure or other critical shutdown condition.

- A fluid coupling must be designed to provide a small amount of slip in the drive train to damp out the torsional variations in wind power.

- Design a yaw (orientation) drive mechanism with no backlash and high stiffness for rotating the nacelle into the wind. A yaw brake must be designed to provide damping and yaw restraint when the yaw motors are both on and off.

- Design a pipe truss tower and its foundation that provide rigid support for the components on the top of the tower and handle all of the static and dynamic loads that are transmitted to the tower.

ELECTRICAL COMPONENTS AND SYSTEMS

The design requirements for the electrical components and systems included the following:

- Select a synchronous generator that rotates at 1800 rpm, is rated at 250 kVA continuous, and operates in the motoring mode for drive train testing.

- Select the switchgear to control and protect the generator, synchronize the WTG to the network, and provide the parasitic power requirements.

- Provide a design which is compatible with the Clayton network and which protects both the wind turbine and the utility with standard devices and practices, including protection against electrical faults.

ORIGINAL PAGE IS
OF POOR QUALITY

CONTROL SYSTEMS

The control system design requirements included the following:

- The blade pitch control system must operate in position control, speed control, and closed loop power control.
- The yaw control system must maintain alignment between the nacelle and its wind vane within a ± 25° deadband angle.
- A safety system must be designed which monitors various parameters and effects a safety shutdown.
- The WTG must be capable of manual, automatic (unattended), and remote control operation.
- The automatic control system, using a microprocessor, must be capable of a) monitoring wind conditions and starting, synchronizing, operating, and stopping the WTG, b) monitoring essential parameters for operation within specified tolerances, and c) providing a remotely located operator with the capability of starting, stopping, and monitoring the performance of the WTG.
- The remote control and monitoring system must provide a remote operator with a control link, status indicator, and performance monitor.

ENGINEERING DATA ACQUISITION

The data acquisition system design requirements included the following:

- Develop a system which determines and/or monitors aerodynamic, mechanical, electrical, structural, control system, safety system, and utility interface performance.
- Provide an upgraded version of the MOD-0 data system with 96 channels of instrumentation for monitoring essential parameters.

ENVIRONMENTAL

The environmental design requirements included the following:

- Operating temperature range of -10°F (-23°C) to 120°F (49°C).
- Design the WTG to sustain, with the blades feathered, a maximum hurricane wind speed of 150 mph (67 m/s) at the hub.
- Specific requirements for rain, snow, hail, ice buildup on the blades, and high humidity.

ORIGINAL PAGE IS
OF POOR QUALITY

- Provide lightning strike protection and a design for seismic loads and windborne objects.

SAFETY AND FAILURE MODES AND EFFECTS ANALYSIS

The safety and failure modes and effects analysis (FMEA) design requirements included the following:

- Implement a safety program which reviews the design and identifies, evaluates, and either eliminates or controls all hazards with the potential to: injure personnel, visitors, or the general public; damage the system; or cause loss of program objectives.

- The safety design criteria shall be that no major damage, or personnel, visitor, or general public hazard should occur because of a single point failure or a single failure following an undetected failure.

- Develop a safety shutdown system which monitors specific parameters.

- Perform an FMEA on all mechanical and electrical components to identify failure modes that could be hazardous to life or result in injury or major damage.

3.2 SYSTEM SPECIFICATIONS

System and component specifications for the MOD-OA WTG design were developed to satisfy the above design requirements. Presented in Table 3-1 is a summary of the principal system and component specifications. These specifications have been categorized under the following major headings: Performance; Rotor; Blade; Balance of Rotor; Low Speed Shaft and Bearings; Speed Increaser; High Speed Shaft and Associated Components; Generator; Nacelle Equipment; Yaw Drive Mechanism and Brake; Slip Rings; Tower and Foundation; Switchgear; Transformer and Oil Circuit Recloser; Control Systems; Engineering Data Acquisition; Auxiliary Equipment; Design Life; and Overall Weight.

TABLE 3-1: PRINCIPAL SYSTEM SPECIFICATIONS FOR MOD-OA 200 kW WTG

PERFORMANCE		
Rated Power	200 kW	
Wind Speed at:	30 ft. (9.1 m)	hub, 100 ft. (30.5 m)
Cut-in	6.9 mph (3.1 m/s)	9.5 mph (4.2 m/s)
Rated	18.3 mph (8.2 m/s)	22.4 mph (10.0 m/s)
Cut-out	34.2 mph (15.3 m/s)	40 mph (17.9 m/s)
Maximum design (Hurricane)	125 mph (55.9 m/s)	150 mph (67.0 m/s)
ROTOR (GENERAL)		
Number of Blades/Diameter	2 / 125 ft. (38.1 m)	
Speed, (constant, when synchronized)	40 rpm	
Direction of Rotation	Counterclockwise (looking upwind)	
Location Relative to Tower	Downwind	
Cone Angle (Swept downwind)/Tilt Angle (Inclination of Rotor Axis Relative to Horizontal)	7° / 0°	
BLADE		
Length/Weight (per blade)	59.9 ft (18.26 m) / 2350 lbs (1066. kg)	
Materials: Primary/Cylindrical blade root shank	2024T3 Aluminum / 4340 Steel	
Airfoil/Twist (non-linear)	NACA 23000 / 33.8°	
Solidity (airfoil area density)	2.9%	
Root Chord/Tip Chord	4.5 ft (1.37 m) / 1.5 ft (0.46 m)	
Chord Taper	Linear	
First flapwise/chordwise natural frequency (normal to chord plane/ in the plane of the chord)	1.5 Hz / 2.9 Hz	
BALANCE OF ROTOR (HUB, PITCH CHANGE MECHANISM, AND PITCH HYDRAULIC SYSTEM)		
Hub: Type of Hub/Material	Rigid / 4340 steel forging	
Pitch Change Mechanism:		
Method of Power Regulation/Maximum Rate of Pitch Change	Variable Pitch (Full span) / 8°/sec	
Pitch Actuator	Hydraulic / pressure control valve / rack and pinion / gears	

BALANCE OF ROTOR (CONT'D)	
Pitch Hydraulic System:	
Pump	10 hp (7.46 kW) high pressure pump, motor driven
Routing	Through rotating hydraulic union to pitch change mechanism
LOW SPEED SHAFT AND BEARINGS	
Low Speed Shaft:	
Type/Material	Hollow / Grade 4340 Alloy Steel
Outside Diameter	10.23 in (26.0 cm)
Bearings:Type	Spherical Roller Bearings
SPEED INCREASER	
Type/Ratio	Three-stage conventional / 45:1
Output Speed/Rating	1800 rpm / 450 hp (336 kW)
Mechanical efficiency/Weight	≥ 90% / 5500 lbs (2500 kg)
HIGH SPEED SHAFT AND ASSOCIATED COMPONENTS, (ROTOR BRAKE, BEARINGS, COUPLINGS, FLUID COUPLING AND BELT DRIVE)	
High Speed Shaft: Speed/Diameter	1800 rpm / 2.75 in (6.98 cm)
Rotor Brake:	
Type/Actuation/Location	Disk with two calipers / Pressurized N_2/ Downwind of speed increaser on high speed shaft
Disk Diameter/Thickness	18. in (45.7 cm) / 0.50 in (1.27 cm)
Stopping Time	6.3 sec (Critical shutdown from 1800 rpm)
Bearings. Quantity/Type	2 / Pillow Block Assembly
Coupling: Quantity/Type	2 / Gear

ORIGINAL PAGE IS OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3-1: PRINCIPAL SYSTEM SPECIFICATIONS FOR MOD-OA 200 kW WTG (CONT'D)

HIGH SPEED SHAFT AND ASSOCIATED COMPONENTS (CONT'D)	
Fluid Coupling: Type/Percent Slip	Vaned Impeller and Vaned Runner / ~2.25
Belt Drive: Type/Number of Belts	Pulley Sheaves and V-Belts / 10 max.
GENERATOR	
Type/Rating/Power Factor	Synchronous ac / 250 kVA continuous / 0.8
Voltage/Frequency/Speed	480 V (Three Phase) / 60 Hz / 1800 rpm
NACELLE EQUIPMENT (BEDPLATE, NACELLE, TURNTABLE BEARING, SUPPORT CONE, AND MOUNTING FRAME)	
Bedplate:	
Material/Weight	SAE 1010-1020 Steel / 8310 lbs (3370 kg)
Center of Gravity of bedplate and all equipment supported by bedplate, including rotor (with respect to tower centerline)	3.59 ft (1.095 m) downwind; 0.124 ft (0.038 m) to right looking upwind
Nacelle (Includes Stationary Parts and Rotating Part [Prop Cone])	
Material/Shell Thickness (min.)	Fiberglass Shell / 0.312 in (0.792 cm)
Length/Diameter	31.3 ft (9.54 m) / 7.95 ft (2.42 m)
Turntable Bearing:	
Axis of Rotation/Inner Ring	Vertical / Stationary
Bolt Circle Diameter: Inner Ring/Outer ring	44.0 in. (1.12 m) / 51.0 in. (1.30 m)
Support Cone: Diameter of base/Diameter at Top/Height	71 in. (1.80 m) / 46.4 in. (1.18 m) / 36.9 in. (0.937 m)
Mounting Frame: Shape (Plan View)/Length of Sides	Square / 7. ft. (2.13 m)
YAW (ORIENTATION) DRIVE MECHANISM AND BRAKE	
Yaw Drive Mechanism:	
Type/Yaw Drive/Rating	Dual mechanical drives/Electric motors (2) / 10 hp (7.46 kW) ea.
YAW DRIVE MECHANISM AND BRAKE (Cont'd)	
Yaw Drive Mechanism: (Cont'd)	
Yaw Rate/Control Deadband	1/6 rpm (1.0°/sec) / ± 25°
Shaft Preload	50,000 in-lbs. (5,650 Nm)
Yaw Brake:	
Quantity/Type/Disk Diameter	3 / Hydraulic / 72.0 in. (1.83 m)
Hydraulic Power Source	3/4 hp (560 W) pump, motor driven
Clamping Pressure/Drag Pressure (hydraulic)	1500 - 2500 psig (10.3 - 17.2 MPa) when not yawing / 100 psig (0.69 MPa), during yaw maneuver
SLIP RINGS (POWER, INSTRUMENTATION AND CONTROL)	
Low Speed Shaft Slip Ring: Number of Contacts/Rating	36 / 5A, 120V, 60 Hz
Tower Slip Ring: Number of Contacts/Rating	4 / 350A, 480V, 60 Hz; 10 / 50A, 480V, 60 Hz; 90 / 5A, 120V, 60 Hz
TOWER AND FOUNDATION	
Tower:	
Type/Materials/Access to Top	Four-legged pipe truss / ASTM A53 pipe and A36 plate steel / Hoist
Height/Hub Height (Rotor Centerline)	93 ft (28.3 m) / 100 ft (30.5 m)
Ground Clearance for Blades	37.5 ft (11.43 m)
Base Span/Cap Span	30 ft (9.14 m) / 7 ft (2.13 m)
Fundamental Natural Frequency	2.2 Hz
Foundation: Type/Dimensions/Thickness	Reinforced Concrete Slab / 34 ft (10.36 m) square / 4 ft (1.22 m)
SWITCHGEAR	
Type/Voltage	Indoor / 480V (Three Phase)
Fault Current/Rating of Bus	22 kA rms symmetrical / 600A

TABLE 3-1: PRINCIPAL SYSTEM SPECIFICATIONS FOR MOD-OA 200 kW WTG (CONT'D)

TRANSFORMER AND OIL CIRCUIT RECLOSER	
Transformer:	
Type/Rating	3 Phase, Oil Cooled, Padmounted / 300 kVA
Configuration (Primary/Secondary) .	2400 V Delta / 480V Delta
Oil Circuit Recloser: Type/Rating/ Interrupting Capacity	W (Oil) / 560A, 14.4 kV / 10 kA rms symmetrical
CONTROL SYSTEMS (BLADE PITCH CONTROL, GENERATOR CONTROL, YAW CONTROL, MICROPROCESSOR, SAFETY SYSTEM, AND REMOTE CONTROL AND MONITORING)	
Blade Pitch Control: Type	Closed loop servo
Generator Control: Type	Voltage/VAR/PF controller and synchronizer
Yaw Control (Orientation): Operating Modes/Method/Filter	Automatic and Manual / Standard relay logic / 10 sec. time constant
Microprocessor: Function	Automatic control
Safety System: Type/Types of Shutdown	Redundant and fail-safe / Safety; Emergency; and Critical
Remote Control and Monitoring:	
Control functions and capabilities/ Performance monitoring	On and off command pulses and initiating/ an emergency shutdown / By analog data section, six channels displayed in digital format
ENGINEERING DATA ACQUISITION (REMOTE MULTIPLEXER UNITS, MOBILE DATA SYSTEM, AND STAND ALONE INSTRUMENT RECORDER):	
Remote Multiplexer Units (RMUs):	
Quantity/Location/Total Number of Data Channels	3 / hub, bedplate, control building / 96

ENGINEERING DATA ACQUISITION (CONT'D)	
Mobile Data System:	
Input patch panel	Receives six FM multiplexes
Stand Alone Instrument Recorder (SAIR):	
Types of Data Channels	3 FM multiplex signals from RMUs
AUXILIARY EQUIPMENT (SERVICE STAND, EQUIPMENT AND PERSONNEL HOIST, AND CONTROL BUILDING)	
Service Stand: Supported Weight/ Height, Length, Width	45,000 lbs (20,400 kg) / 4.75 ft (1.45 m), 8. ft (2.4 m), 8. ft (2.44 m)
Equipment and Personnel Hoist:	
Capacity/Drive	1500 lbs (680 kg) / Self powered by electric motors
Location/Height of Travel	Within framework of tower / 74 ft. (22.6 m)
Control Building: Location/Provisions	Within framework of tower / heating and ventilating
DESIGN LIFE	
Static components/Dynamic components (Except blades)	50 years / 30 years
Blades	Designed to withstand loads measured on MOD-0 WTG
OVERALL WEIGHT	
Rotor (including blades)	12,300 lbs. (5,590 kg)
Above Tower	45,000 lbs. (20,400 kg)
Tower	44,000 lbs. (20,000 kg)
Total	89,000 lbs. (40,400 kg)

ORIGINAL PAGE IS OF POOR QUALITY

4.0 DESIGN AND ANALYSIS

The basic features and characteristics of the MOD-OA wind turbine design are summarized in Section 2.0. This section of the report summarizes the requirements, approach, selected design, and supporting analytical results for the components and systems. These components and systems are the rotor and pitch change mechanism, drive train, nacelle equipment, yaw drive mechanism and brake, tower and foundation, electrical system and components, and the control systems. The results of system dynamic loads analyses and fatigue analyses are also summarized.

4.1 ROTOR AND PITCH CHANGE MECHANISM

The MOD-OA WTG uses a 125 foot (38.1 m) diameter, two-bladed, horizontal-axis rotor system. The wind turbine operates at a constant rotor speed of 40 rpm and the power output is regulated by varying the pitch angle of the blades.

BLADES

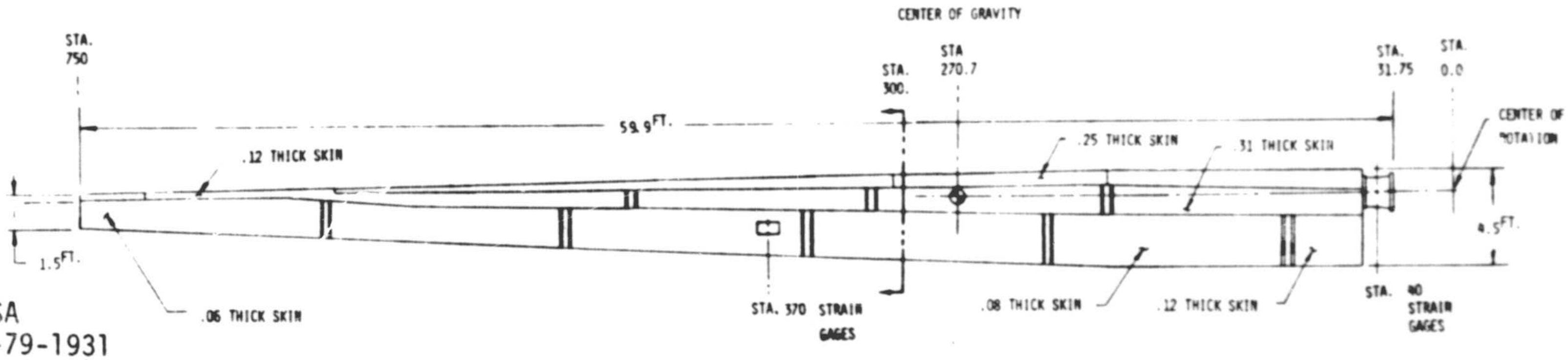
Each blade is a 59.9 foot (18.3 m) long aluminum structure that has leading and trailing edges, formers, stringers, ribs, webs, and skin. The blades conform to a prescribed aerodynamic shape that has a total twist of 33.8°. The blade chord length varies from 4.5 feet (1.4 m) at the root to 1.5 feet (0.5 m) at the tip, and the thickness varies from 1.5 feet (0.5 m) at the root to two inches (5.1 cm) at the tip. Figure 4-1 shows the design planform of the blade. Figure 4-2 shows a cross section of the blade, taken at station 300, also called out in Figure 4-1. Figure 4-3 shows one of the MOD-OA blades during final non-destructive testing at Lockheed.

The chosen blade design was based primarily on MOD-0 since that machine proved to be stable and to operate satisfactorily. Since MOD-OA is intended to operate for long periods of time and since MOD-0 experienced higher than predicted blade loads, structural modifications were made to extend the fatigue life of the MOD-OA blades.

The modifications from the MOD-0 design, incorporated to improve the fatigue strength of the MOD-OA blades, can be summarized as:

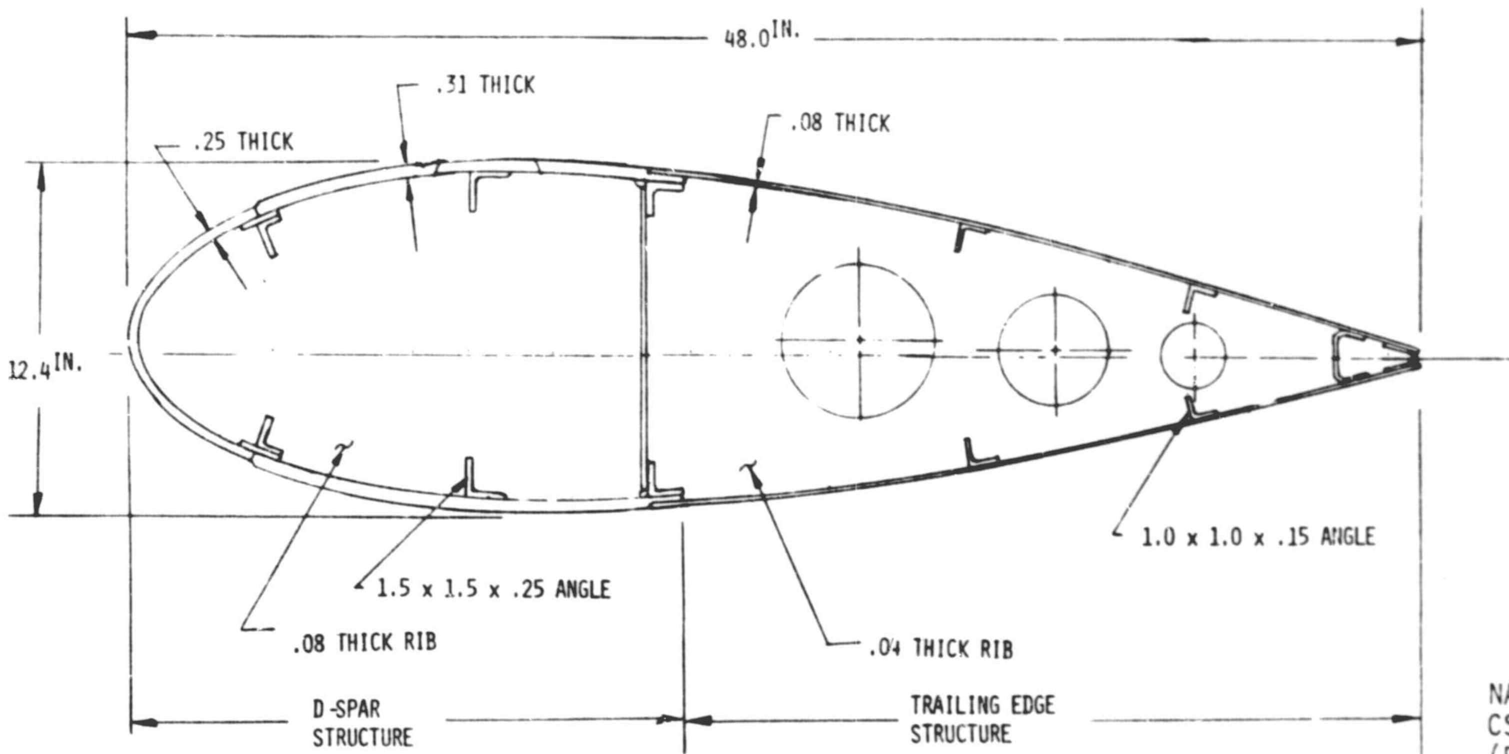
- The spar cap thickness was increased,
- Several trailing edge thickness changes were made,
- Two stringers were added to each trailing edge surface,
- The root end fitting wall thickness was increased,
- A closure plate was added to an inboard rib to seal the interior of the blade from the hub (to protect the hub mechanism),
- External doublers were added to all D-spar and trailing edge spanwise structural joints to increase the fatigue life.

Load calculation methods verified by MOD-0 experience were used to predict blade loads for the MOD-OA wind turbine. The blade fatigue analysis, summarized in Section 4.8, concluded that the blades should withstand these loads indefinitely.



NASA
CS-79-1931
(Revised)

Figur^ 4-1. MOD-OA Blade Configuration - Planform



NASA
CS-79-1929
(Revised)

Figure 4-2. MOD-OA Blade Typical Cross Section

ORIGINAL PAGE IS
OF POOR QUALITY

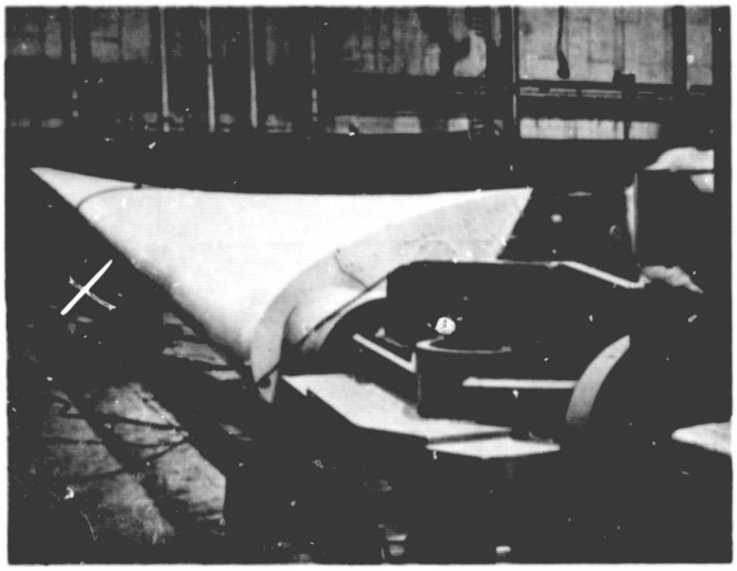


Figure 4-3. MOD-OA Blade During Final Non-Destructive Testing at Lockheed

HUB ASSEMBLY

The hub assembly is the supporting link between the blades and the low speed shaft. It is directly connected to and rotates with the low speed shaft. The blades are cantilevered from the hub at a seven degree coning angle. The hub assembly consists of the hub forging, gears, bearings, blade spindles, and bearing housings of the pitch change mechanism, all of which rotate about the centerline of the low speed shaft.

PITCH CHANGE MECHANISM

The pitch change mechanism is used to control the electrical power output and rotational speed of the blades during startup, normal operation, and shutdown by changing the pitch of the blades. The rate at which the pitch is changed depends on wind conditions and the resisting load of the generator. When changes in load or wind speed are slow, pitch is changed slowly. When the wind is gusting or when a load failure occurs, pitch is changed rapidly to prevent overspeeding the rotor which could damage the blades. Therefore, safe operation of the wind turbine depends on the ability of the pitch change mechanism and its hydraulic and electrical control systems to properly sense and respond to the various transient conditions.

The pitch change mechanism gears internal to the hub are shown in Figure 4-4. These gears are driven by a hydraulically actuated rack and pinion. Figure 4-5 shows the major components of the pitch change mechanism after they have been assembled on the downwind side of the rotor hub. A rotating hydraulic union is used to permit transfer of hydraulic fluid from the pitch hydraulic system (see Figure 4-11 in Section 4.3 below), which is stationary, to the hydraulic actuators which rotate with the blades. This hydraulic union is located upwind of the speed increaser and is in-line with the low speed shaft.

ORIGINAL PAGE IS
OF POOR QUALITY

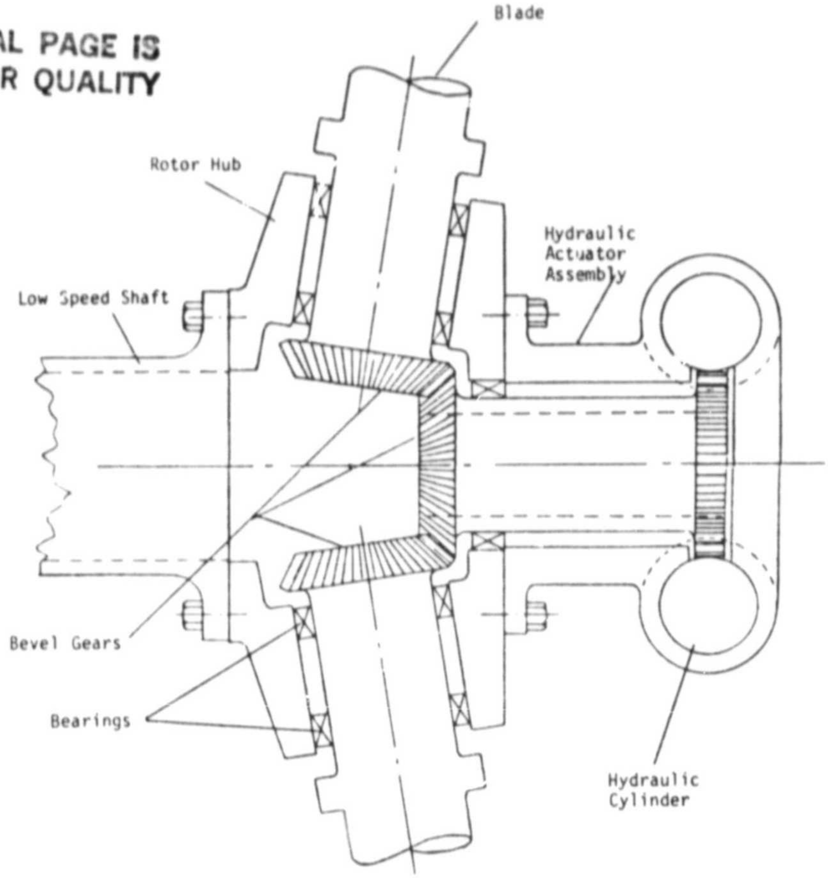


Figure 4-4. Pitch Change Mechanism (Simplified)

4.2 DRIVE TRAIN

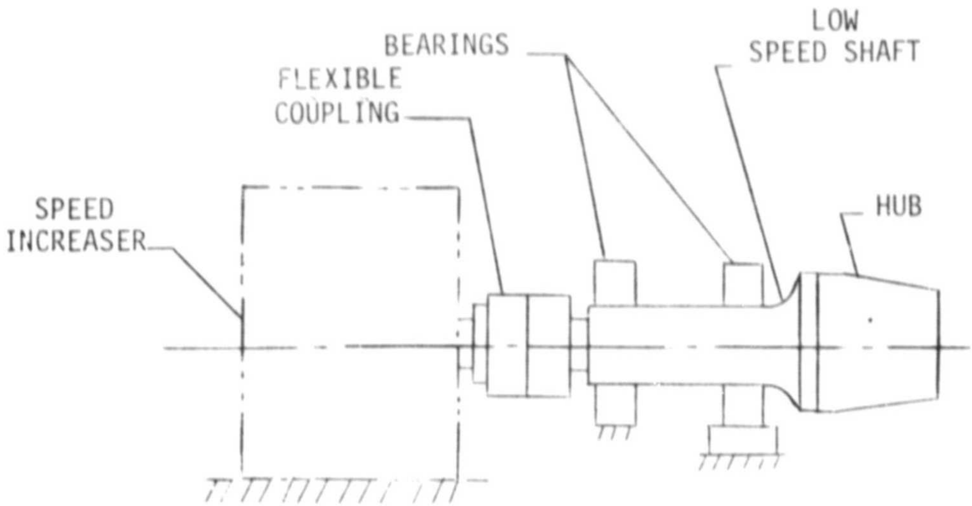
The drive train consists of a series of mechanical components that use the rotational energy of the blades to turn the generator. The drive train connects the blade/hub assembly to the generator shaft. To get the best aerodynamic efficiency at the design wind speed, the rotor speed is selected as 40 rpm during normal operation. The gear ratio of the drive train is chosen at 45:1 to allow for this rotor speed and to permit the use of commercial generators which rotate at 1800 rpm.

The drive train is subdivided into the following parts which are described separately:

- Low Speed Shaft, Bearings, and Coupling
- Speed Increaser
- High Speed Shaft and Associated Components
- Rotor Brake

LOW SPEED SHAFT, BEARINGS, AND COUPLING

The low speed shaft is the shaft that turns with the rotor blades at 40 rpm during normal operation. It is supported by two large bearings and coupled to the input shaft of the speed increaser. The two bearings also support the hub and blades of the machine since the blades are attached to the hub and the hub is attached to the low speed shaft. The general arrangement of these components is shown in the accompanying sketch.



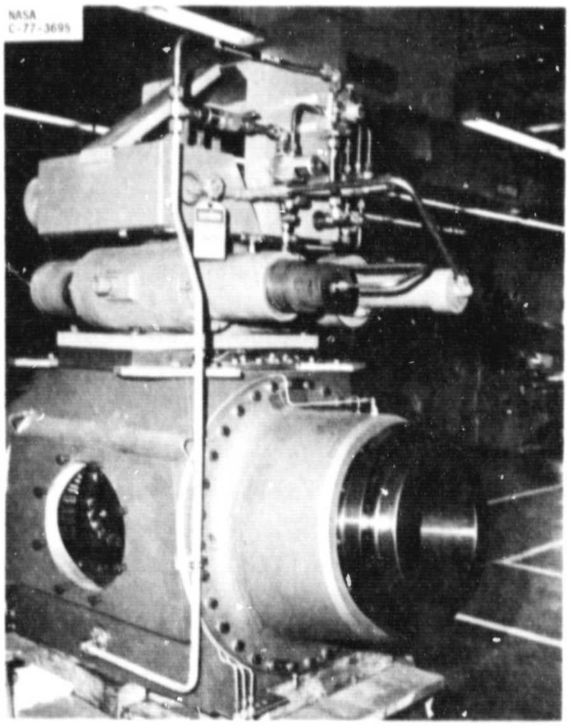


Figure 4-5. Pitch Change Mechanism Mounted on Hub

The low speed shaft provides complete support for the rotor hub and blades. The shaft is supported by two large bearings housed in structural members which are supported by the bedplate. The bending moment represents the most critical loading of the shaft and plays a major part in determining the fatigue life of the shaft. Strain gages are attached to critical stress regions of the shaft to monitor stress levels and thereby better understand the actual structural condition of the shaft during the lifetime of the machine. The low speed shaft is approximately ten inches (25.4 cm) in diameter and five feet (1.5 m) long. The downwind end is enlarged to form a flange for bolting to the rotor hub. A double engagement, gear type of coupling is used to connect the low speed shaft to the speed increaser. Figure 4-6 is a photograph of the low speed shaft, bearings, bearing housings, and coupling after assembly.

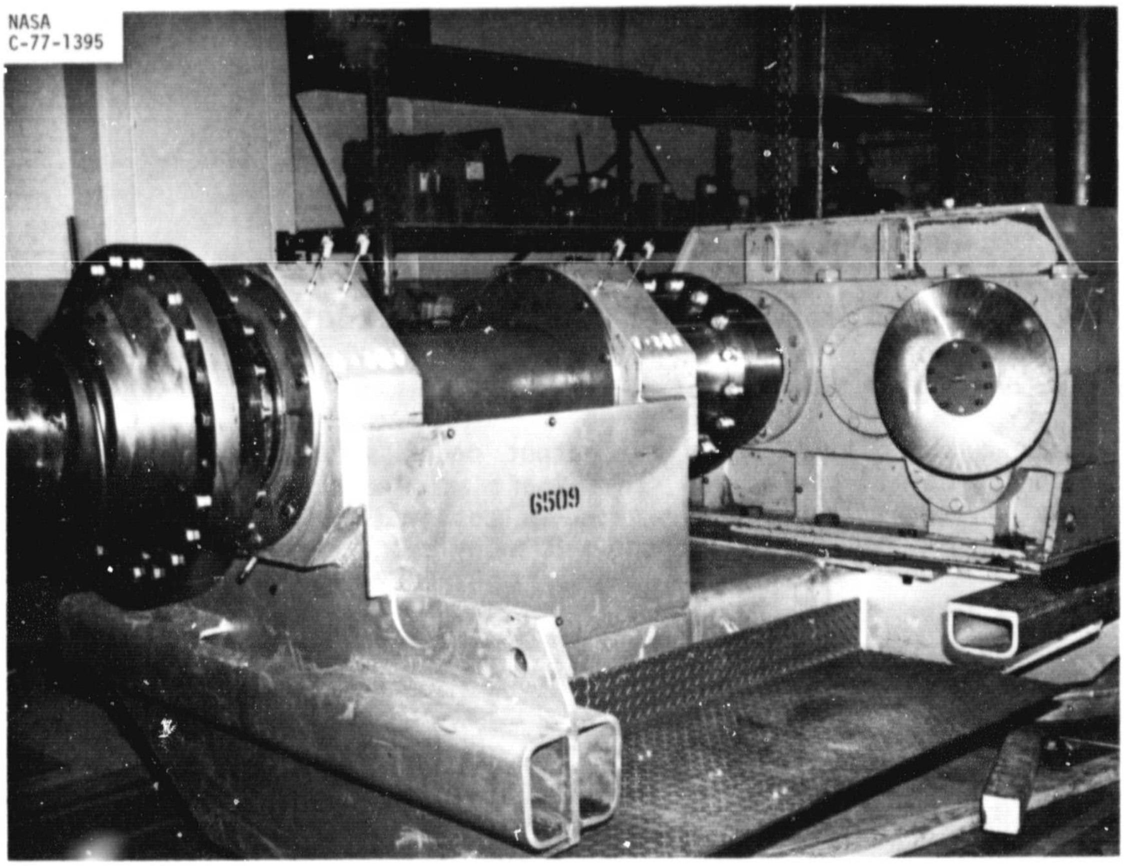


Figure 4-6. Low Speed Shaft, Bearings, Bearing Housings, and Coupling

SPEED INCREASER

The speed increaser consists of four parallel shafts and associated gearing, all housed in a casing that is 34.5 inches (87.6 cm) high, 54.0 inches (137.2 cm) wide and 30 inches (76.2 cm) deep (axial dimension). The unit weighs 5500 pounds (2500 kg) and is mounted on its base with the parallel shafts horizontal.

ORIGINAL PAGE IS
OF POOR QUALITY

Helical gears are used throughout the unit for quiet operation and to maximize power transmission capability. The speed increaser has a turning ratio of 45.24 to 1 and is rated at 450 horsepower (336 kW) at 1800 rpm. Figure 4-7 presents a photograph of the speed increaser unit as it appeared during shop assembly of the wind turbine. Manufacturer of the speed increaser was Horsburgh & Scott Company, Cleveland, Ohio.

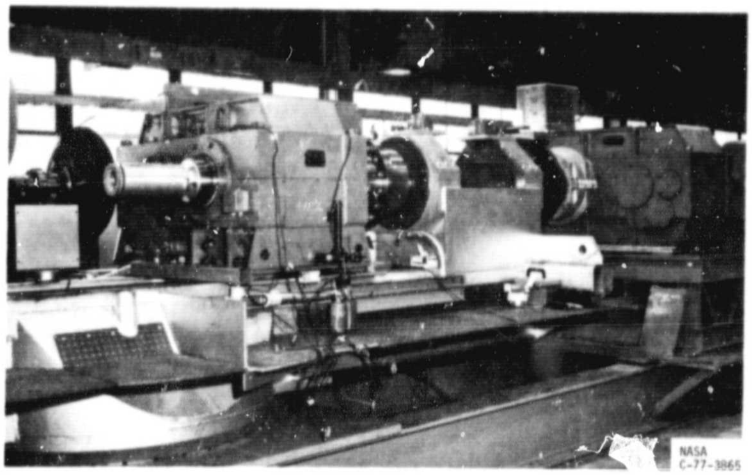


Figure 4-7. Speed Increaser Unit During Shop Assembly of Wind Turbine

HIGH SPEED SHAFT, BEARINGS, COUPLINGS, BELT DRIVE, AND FLUID COUPLING

The high speed shaft turns with the output shaft of the speed increaser at 1800 rpm during normal operation. This shaft and the other components covered in this section transmit torque from the output shaft of the speed increaser to the shaft of the generator. Figure 4-8 shows the arrangement of components.

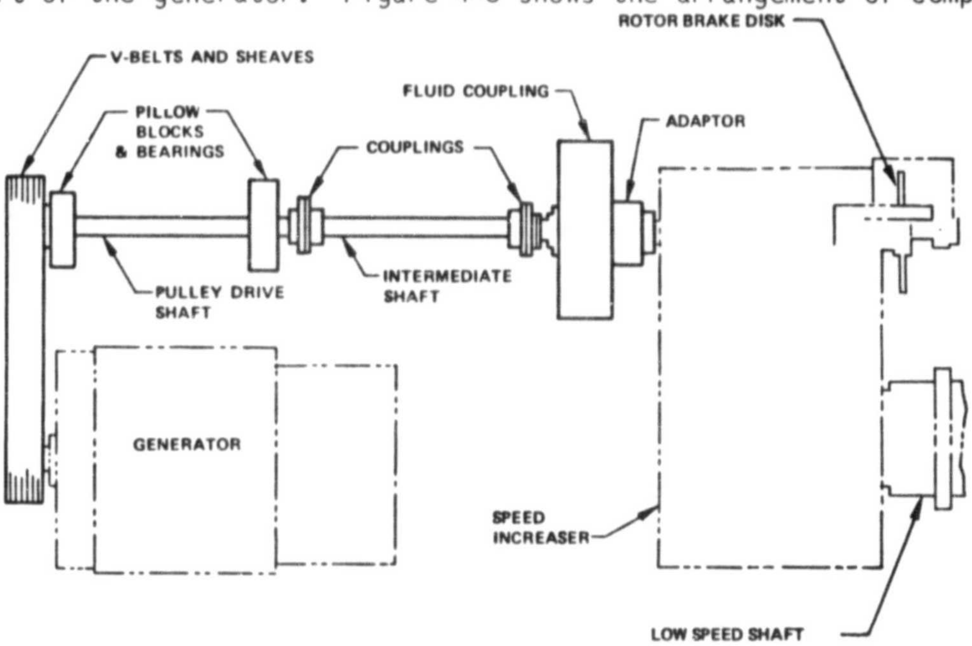


Figure 4-8. Arrangement of High Speed Shaft Components (Plan View)

ORIGINAL PAGE IS
OF POOR QUALITY

The fluid coupling has a vaned impeller and a vaned runner. This coupling is used to reduce the magnitude of the oscillations in the drive train that are transmitted to the generator as a result of wind gusts. The fluid coupling is shown in the photograph of Figure 4-9.

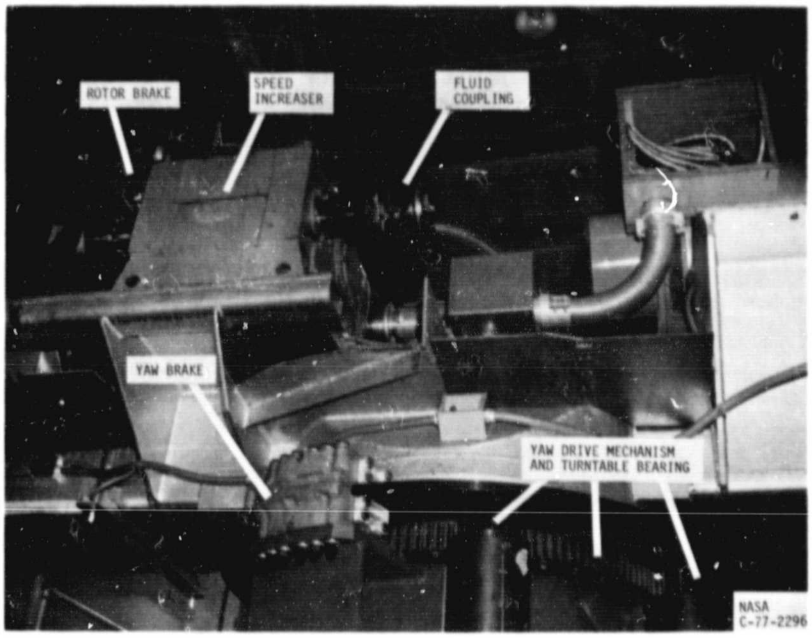


Figure 4-9. Fluid Coupling, Speed Increaser, Rotor Brake, Yaw Drive Mechanism, Turntable Bearing, and Yaw Brake

The intermediate shaft connects the fluid coupling to the pulley drive shaft. A gear type coupling is used at each end of the shaft for torque transmission. These couplings can tolerate some misalignment while operating, thus eliminating the need for costly, precision alignment. Ten V-belts are provided for transmitting torque from one sheave to the other and thus into the generator.

ROTOR BRAKE

The rotor brake is located just downwind of the speed increaser, on the high speed shaft of the speed increaser, as shown in Figures 4-8 and 4-9. It functions as a static brake and prevents rotation of the blades when the machine is shut down. It also serves as a dynamic brake in an emergency case where shutdown is necessary. For safety considerations, the rotor brake is fail-safe, i.e., on loss of power, the brake is automatically applied. The brake was designed to stop rotation of the blades in the event that the pitch change system fails while wind speeds is increasing. For this event, the brake was sized to stop rotation in about six seconds. Two calipers are used for retarding the motion of the disk when the brake is activated. The calipers are actuated by pressurized nitrogen that is stored on the machine in a commercial gas storage cylinder. The nitrogen supply system is completely independent from the pitch control system to insure that a single failure cannot make both the rotor brake and pitch control system inoperative.

ORIGINAL PAGE IS
OF POOR QUALITY

4.3 NACELLE EQUIPMENT

The nacelle equipment is the equipment mounted on top of the tower for the purpose of supporting and housing the power generating equipment. It includes the fiberglass nacelle, the structural bedplate, the yaw bearing support cone, and the mounting frame.

The fiberglass nacelle is a cylindrical shell structure as shown in Figure 4-10. It is 7.96 feet (2.4 m) in diameter and 31.3 feet (9.5 m) in overall length. The nacelle provides a streamlined housing for the power generation and other equipment located atop the tower.

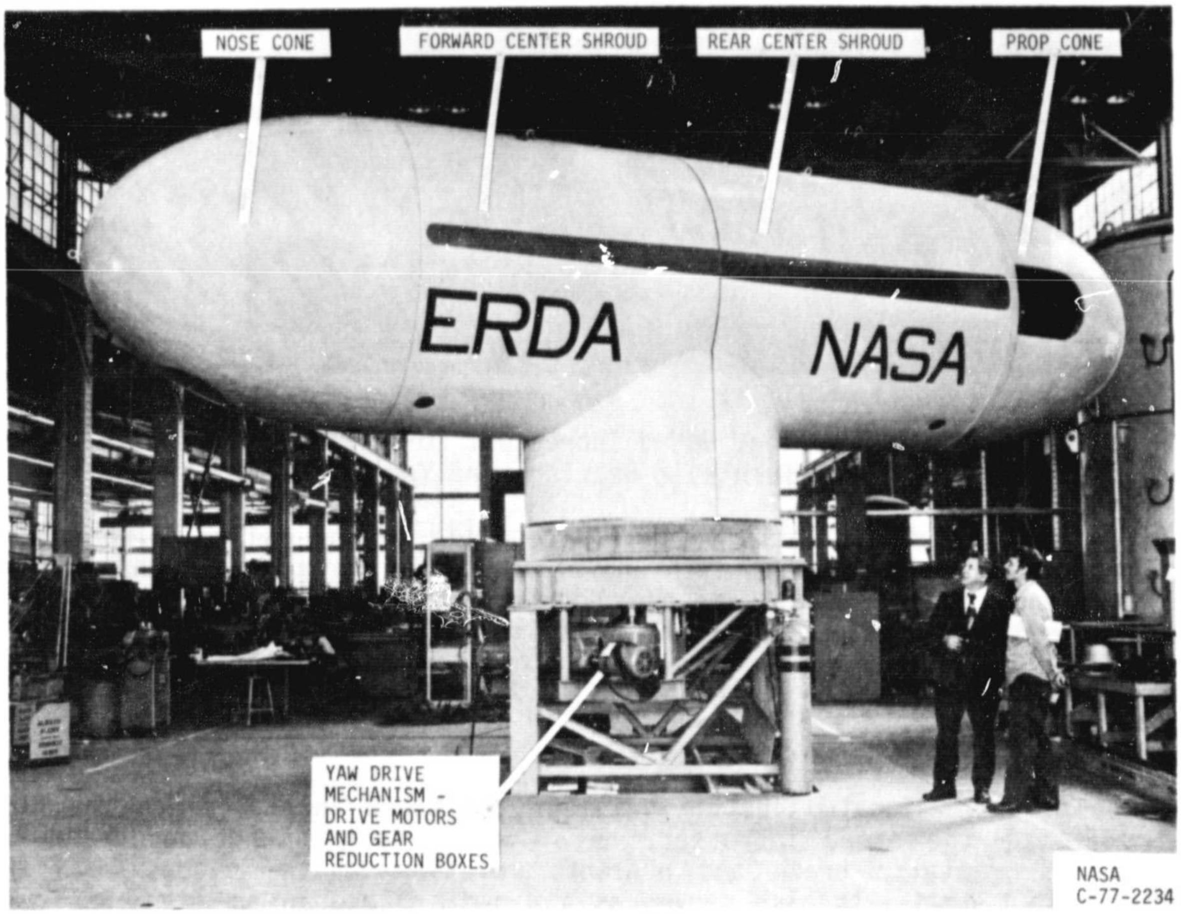


Figure 4-10. Nacelle and Yaw Drive Mechanism

The bedplate is a large steel weldment that serves as a mounting structure for the power generating equipment. It consists of a long box beam with brackets and outriggers welded where necessary to provide support for the various pieces of equipment that make up the wind turbine generator. Figure 4-11 shows the bedplate and how it supports the various pieces of equipment.

ORIGINAL PAGE IS
OF POOR QUALITY

The yaw bearing support cone, as shown in Figure 4-11, provides support for the nacelle, bedplate, and all of the power generating equipment by supporting the inner race of a larger diameter turntable bearing (see Figure 4-9). Figure 4-12 shows the structural and mechanical arrangement in the area of the turntable bearing. The support cone has two openings or windows in its sidewall to permit passage of the two drive shafts for the yaw drive mechanism. Three heavy structural brackets are welded to the outside of the cone near the top to provide mounting surfaces for the three yaw brakes that are used to prevent unwanted yaw motions of the nacelle.

The mounting frame (see Figure 4-11) is a structural assembly that mates with the bottom of the circular support cone and the top of the square tower. It provides support for all of the equipment mounted atop the tower and a surface for mounting the drive motors for the dual yaw drive mechanism. As shown in Figure 4-11, the mounting frame is assembled to a service stand for in plant and site assembly and testing operations.

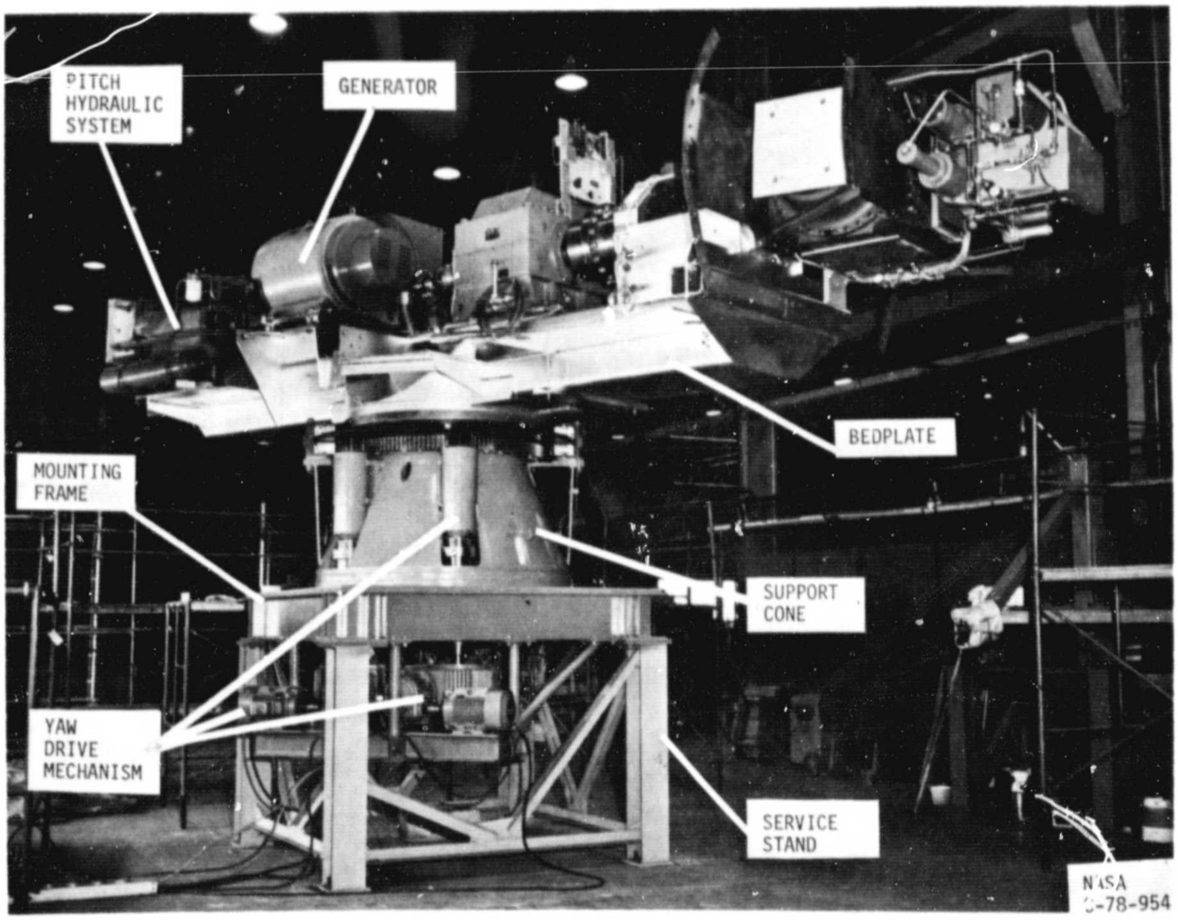


Figure 4-11. Components of MOD-OA Wind Turbine Assembly

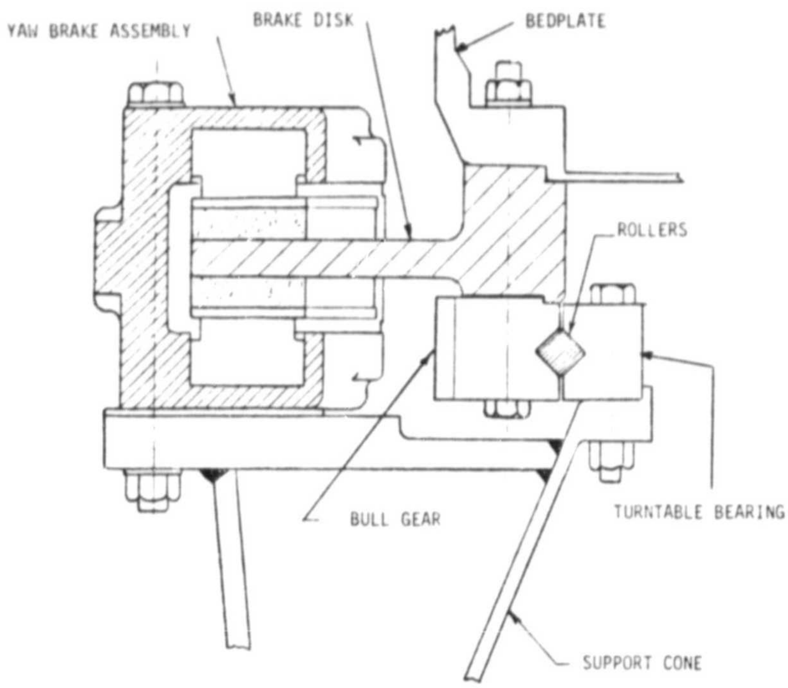


Figure 4-12. Turntable Bearing and Yaw Brake

4.4 YAW DRIVE MECHANISM AND BRAKE

The MOD-0A wind turbine components mounted atop the tower are supported on a large turntable bearing which permits the machine to be rotated when the wind direction changes. This yawing action is achieved by a yaw drive mechanism having two drive shafts and two drive motors. When turning is not required, that is when the wind direction is not changing, the machine is held from turning by three yaw brakes. The yaw control system synchronizes the operation of the yaw drive mechanism with the yaw brakes.

YAW DRIVE MECHANISM

The yaw drive mechanism performs two principal functions:

- Rotates the entire nacelle assembly about a vertical axis to achieve alignment with the prevailing wind direction.
- Provides torsional stiffness to reduce unwanted yawing oscillations during a yaw maneuver.

The tendency for the oscillating motion is produced by wind loads on the blades as they rotate. These loads induce a yawing torque on the bedplate that is cyclic in nature. As a result, yawing oscillations must be restrained to minimize bending stresses in the blades.

ORIGINAL PAGE IS
OF POOR QUALITY

To reduce the edgewise bending loads on the blades, it was decided that the single yaw drive used on the MOD-0 wind turbine be replaced by a dual yaw drive system on MOD-0A. Oscillating motions would then be reduced, because of three factors: (1) avoidance of a resonance, which was of greatest significance, (2) stiffening the nacelle-to-tower connection, and (3) eliminating the free play present in the single yaw drive system.

Figures 4-9, 4-10, and 4-11 show the yaw drive mechanism installed on the MOD-0A wind turbine. The drive motors and gear reduction boxes are located on a structure that is underhung from the mounting frame. Two drive shafts extend vertically upward from the gear boxes, through cut-outs in the side wall of the support cone, and provide torque for the pinion gears that engage the bull gear teeth that are machined in the outer race of the main yaw bearing.

The yaw drive mechanism uses two worm drive gear boxes, each driven by a ten horsepower (7.46 kW) motor. The gear boxes and pinion drives are pretorqued against each other at assembly to eliminate backlash in the gear drive members and to increase the torsional stiffness of the yaw drive system.

YAW BRAKE

The yaw brake system, consisting of three brake assemblies, is mounted on brackets outside the support cone, as shown in Figures 4-9 and 4-12. The brakes prevent the bedplate from yawing when they are fully applied.

Three hydraulic brake assemblies are mounted 90° apart on brackets welded to the outside of the support cone. The nacelle/bedplate assembly is made with a thick brake disk that is positioned horizontally and bolted to the bull gear which rotates with the nacelle. Braking action is produced when hydraulic fluid is forced into the brake assemblies, thereby activating the brakes and causing them to grip the brake disk and prevent yaw motion of the nacelle.

4.5 TOWER AND FOUNDATION

The MOD-0A tower and foundation are designed to provide support for the nacelle, the blades, and the equipment housed in the nacelle. Figure 4-13 shows the nacelle and wind turbine assembly prepared for installation onto the completed tower/foundation. The tower and foundation support the WTG machinery at a 100 foot (30.5 m) hub height, providing ample ground clearance for the 125 foot (38.1 m) diameter rotor.

TOWER

The tower arrangement is shown in Figure 4-13. The tower is seven feet (2.1 m) square at the top, providing broad supporting points for the support cone and mounting frame. Also, this provides sufficient space in the top area of the tower for the yaw drive system, for access to this system, and for access to the nacelle through the support cone. The tower width increases only slightly down to the 40 foot (12.2 m) elevation, maintaining ample rotor blade/tower clearance. Below this level, the tower size gradually increases to about 30 feet (9.1 m) square at the bottom. This results in a broad, stable tower base with reasonable interface loads at the tower/foundation interface. In the upper section of the tower, where the wake or "tower shadow" affects the rotor blades, round pipes are used for all of the structural members. Based on wind tunnel tests on a model of the MOD-OA tower, the average range of tower shadow effects was between 72 and 85 percent, i.e., local wind velocities downstream of the tower were reduced to 72 to 85 percent of the free stream velocity.

Figure 4-13. Nacelle and Wind Turbine Assembly Installation on Tower

The upper portion of the tower was factory assembled and shipped to the site as a unit. The lower corner legs, horizontal members, and diagonals were assembled to the upper tower section at the site. Gussets, bolted joints, channels, and angles are used in this lower section of the tower since the rotor does not pass through the air flowing through this portion of the tower. The tower uses ASTM A53 pipe and A36 plate material. It is painted to provide corrosion protection. The tower legs are bolted to grounded mounts to protect the entire WTG against lightning strikes. The hollow tower corner legs are used to house the electrical power and instrumentation wires to keep the tower as open as possible. By doing this, tower interference to airflow is not affected by electrical conduit.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

FOUNDATION

The tower is mounted on a reinforced concrete mat foundation as shown schematically in Figure 4-14. The mat is 34 feet (10.4 m) square and the thickness is four feet (1.2 m). Integral features of the mat include the four tower mount pads, wiring conduits, and the control building base. A mat type foundation was developed so that it could be used at nearly any site more or less independent of the nature of the soil or the depth to bedrock. This foundation can be used for the entire family of MOD-OA wind turbines with minimal site related redesign. The mat was sized to prevent sliding over its soil bed or tipping and bearing locally on the soil with excessive pressures. Sufficient steel reinforcing bars are used near the upper and lower mat surfaces to provide bending and shear strengths exceeding applied loads.

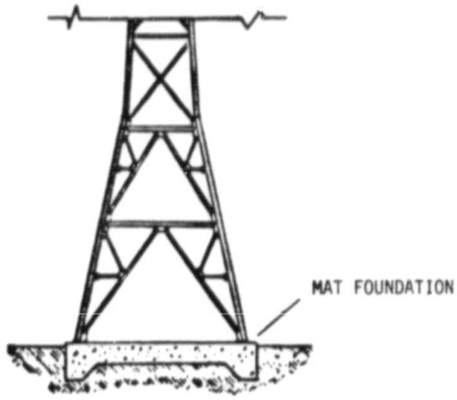


Figure 4-14. MOD-OA Wind Turbine Foundation

Figure 4-15 shows the mat foundation complete and ready for the installation of the tower and control building and final site grading.

Figure 4-15. Completed Mat Foundation with Control Building Base

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE IS
OF POOR QUALITY

4.6 ELECTRICAL SYSTEM AND COMPONENTS

The MOD-OA wind turbine electrical power system must produce power at a voltage and frequency compatible with the interfacing utility network, protect both the wind turbine and the utility with standard devices and practices, and provide for unattended operation to synchronize and automatically disconnect the systems as required. The power generation requirement imposed on the MOD-OA design is 200 kW at a rated wind speed of 22.4 mph (10 m/s) at 100 feet (30.5 m).

A simplified one-line diagram of the MOD-OA wind turbine power distribution system is illustrated in Figure 4-16. The electrical power necessary to start the wind turbine is not provided as part of the wind turbine. The utility network must provide the power to initiate operation.

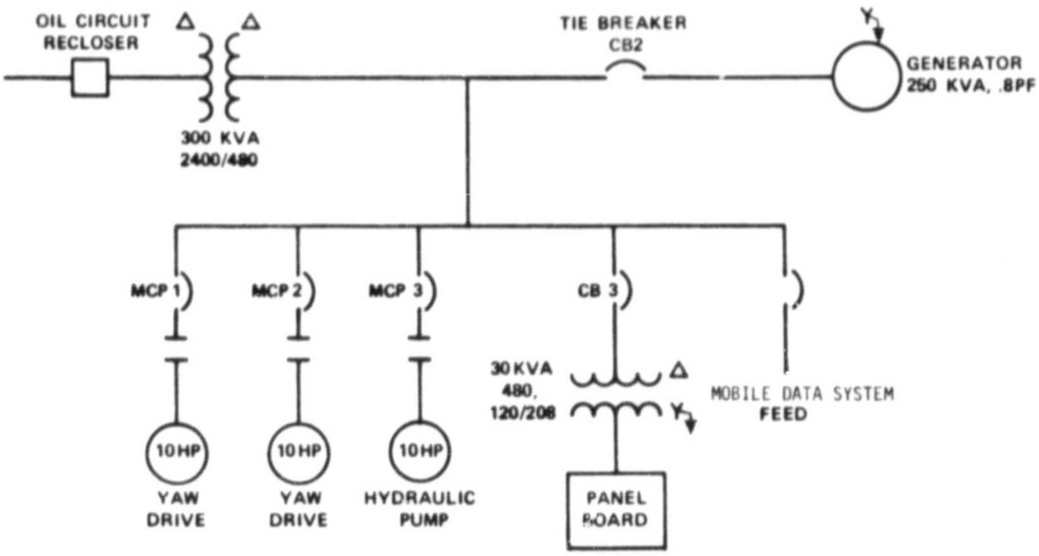


Figure 4-16. Simplified One-Line Diagram of the Electrical Power Distribution System

The electrical power system for the MOD-OA wind turbine consists of the generator, the generator controller, the utility interface switchgear, and associated protective equipment. The MOD-OA generator is a 250 kVA, 0.8 power factor, synchronous machine with a rated output voltage of 480 V, three phase, four wire, 60 Hz and a rated input of 1800 rpm (see Figure 4-11 above). The exciter is a brushless type which is directly connected to the generator.

Electric power is transmitted from the generator, through slip rings to a cable, to the base of the tower. At the tower base, the cable is run to the switchgear in the control building, through the tie breaker, through a step-up transformer, and to the utility network through an oil circuit recloser. A photograph of the MOD-OA switchgear is shown in Figure 4-17.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

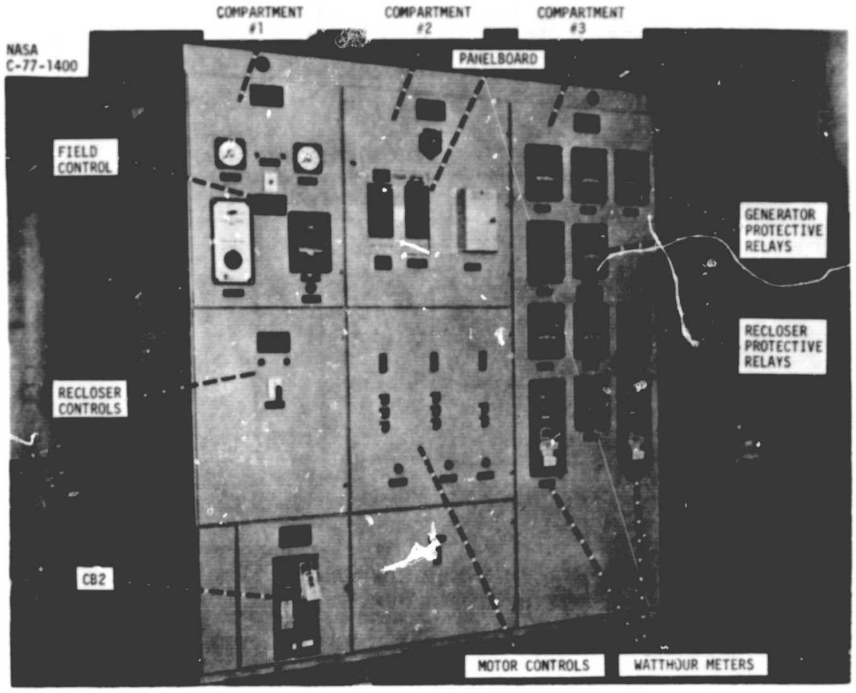


Figure 4-17. MOD-OA Switchgear

Synchronization of the wind turbine with the utility network is accomplished with an automatic synchronizer. The synchronizer monitors the phase angle between and the frequencies of the systems and provides a corrective signal to the wind turbine speed controller to match the wind turbine output with that of the utility network. When both systems are within specification, the synchronizer provides the intelligence to close the tie breaker and mate the wind turbine with the utility.

4.7 CONTROL SYSTEMS

The MOD-OA wind turbine was designed to be a fully automatic power generation system tied to a utility network. To achieve this objective, the wind turbine control system is capable of monitoring wind conditions, maintaining nacelle alignment with the wind, controlling rotor speed and power level, and starting, synchronizing, and stopping the wind turbine in a safe manner. In addition, the control system must monitor essential parameters throughout the wind turbine to assure that critical components are operating within specified tolerances. The control system also provides a remotely located operator with the capability of starting, stopping, and monitoring the wind turbine.

The control system to accomplish the majority of the control functions can be divided into five distinct control systems. These five control systems consist of rotor blade pitch control, yaw control, microprocessor control, the safety

ORIGINAL PAGE IS
OF POOR QUALITY

system, and the remote control and monitoring system. A block diagram depicting the interactions of the control systems is shown in Figure 4-18. The five systems operate nearly independently and are interfaced through the microprocessor.

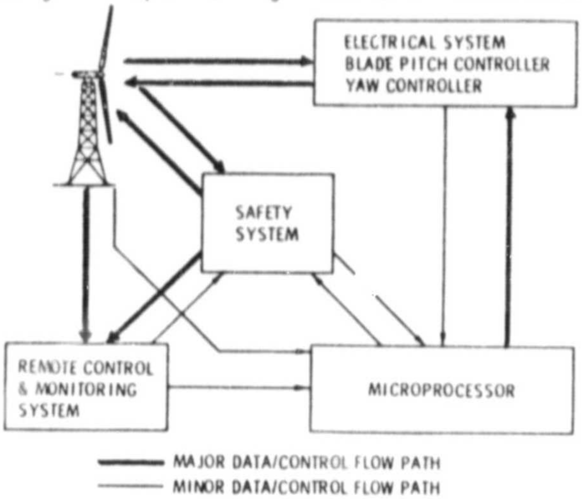


Figure 4-18. Control System Interfaces

Wind turbine rotor power is a function of wind speed and blade pitch angle. As a result, either rotor speed or rotor power at a given rotor speed can be controlled by adjusting blade pitch angle. The blade pitch controller for the MOD-OA machine operates in three distinct modes. Position control is used during initial rotor startup and shutdown. Speed control is used in the intermediate phase of startup between five rpm and forty rpm until the machine is synchronized with the utility network. Closed loop power control is utilized whenever the machine is synchronized with the utility network. The blade pitch angle is driven toward zero degrees when the wind speed is below that required to produce 200 kW of power. The pitch angle is varied to spill wind when the wind speed is in excess of that required to maintain a 200 kW power level. To shut the machine down, the blade pitch angle is reduced at a uniform rate until the blades are feathered. The blades remain feathered until a command to start up the WTG is received.

The yaw controller senses directional error from the anemometer/windvane mounted on the nacelle which monitors wind direction relative to the nacelle, providing a direct measure of the yaw error. The yaw controller has a $\pm 25°$ deadband which must be exceeded prior to initiating a correction. The yaw drive system rotates the nacelle at a rate of one degree per second. A yaw brake is used to provide nacelle restraint in yaw, both when the yaw motors are on and when they are off. During yaw maneuvers, the brake pressure is reduced. When no yawing is required, the brake pressure is increased and the nacelle is essentially locked to the tower.

The microprocessor is the control unit which permits unattended, automatic operation of the wind turbine. The unit provides the commands to initiate startup, control normal operation, and shut down the wind turbine based on wind conditions. Once the microprocessor has been activated, no other function is required of an operator, unless he wants to shut down the machine and/or disable the microprocessor.

Once the microprocessor is activated, it monitors the wind and initiates a startup sequence when the wind speed exceeds 12 mph (5.4 m/s) at hub height. Once synchronized, the machine continues to operate until a wind speed below eight mph (3.6 m/s) at hub height or above 40 mph (17.9 m/s) at hub height is reached. If either of these conditions exist, the microprocessor initiates a shutdown and waits until the wind speed is within the acceptable range before restarting the machine.

The microprocessor is also programmed to shut down the wind turbine whenever certain abnormalities are detected. The abnormalities include slow startup or synchronization, loss of pitch hydraulic pressure, and loss of synchronization. Each of these abnormalities initiates a shutdown and requires on-site resetting prior to resumption of normal operations.

Unattended operation dictates that a separate independent protective system monitor the wind turbine and effect a safe shutdown if a malfunction or out of tolerance performance is detected. The shutdown system is functionally independent of other control systems and includes a series of primary sensors connected to an interface/annunciator circuit. The annunciator provides an indication of the cause of the shutdown. The output of the interface circuitry controls a relay logic system which effects a safety shutdown by feathering the rotor blades and desynchronizing the generator. The safety system includes a primary and a redundant set of sensors. The redundant sensors operate through an independent path to effect the shutdown and provide a backup to insure safety in the event of a failure in the primary system.

The remote control and monitoring system shown in Figure 4-19 provides an interface between the wind turbine and a remote operator. The system serves as

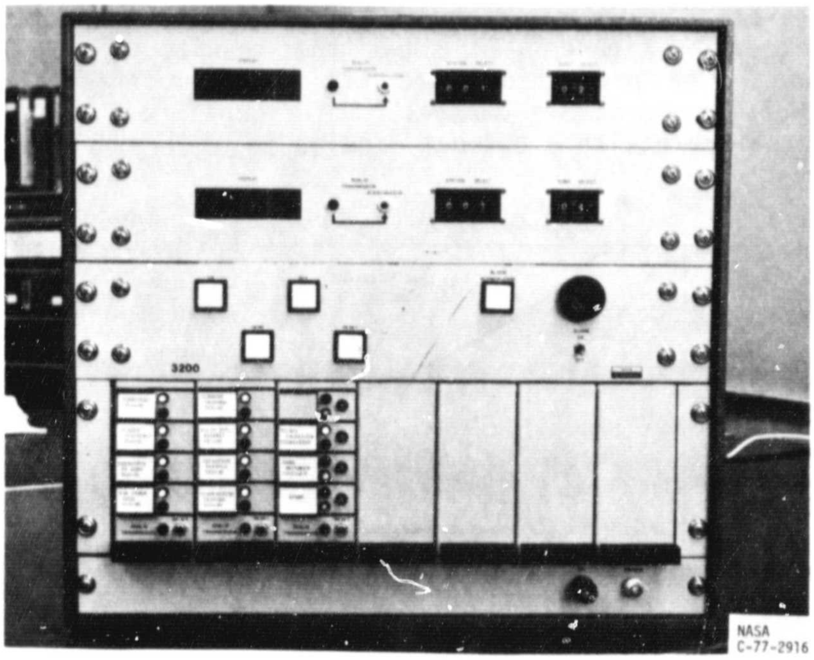


Figure 4-19. Remote Control and Monitoring System

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

a control link, status indicator and performance monitor. The interconnection between the wind turbine and the remote unit is effected by two telephone pairs. The remote system is capable of two control functions: startup and shutdown of the wind turbine through the microprocessor and emergency shutdown through the safety system. Status indications show wind turbine operable or shutdown, microprocessor status, and error conditions from the safety system. Performance of the wind turbine can be monitored by any two of eight channels of analog data which are digitally displayed in engineering units.

4.8 SYSTEMS ANALYSES

This section discusses the MOD-0A dynamic analyses, the analysis results, and the component fatigue evaluations performed using these results.

DYNAMIC LOADS

A fixed rotor axis computer program was utilized to determine the steady state and cyclic loads acting on the WTG blades. This computer program performs a fully coupled aeroelastic blade loads analysis consisting of an aerodynamic performance/trim analysis of a rotor system that is coupled with the dynamic response of the blades. The structural model utilizes a finite element description that permits a detail definition of the rotor blade system. The loads at five key interfaces in the WTG were tabulated and distributed for use in fatigue analyses of the various WTG major components.

FATIGUE

Blade fatigue life prediction entails many uncertainties in both load distribution and in design adequacy. For example, there are many situations that might cause the blade loads to exceed the design values, and untested structural details can cause concern regarding blade life prediction even under known load conditions. Figure 4-20 shows the results of the MOD-0A blade fatigue prediction. The prediction does not consider effects of fretting, corrosion, or other unpredictable damage. The figure shows that a life of 30 years should be attainable with a cut-out wind speed of 41 mph (18.3 m/s).

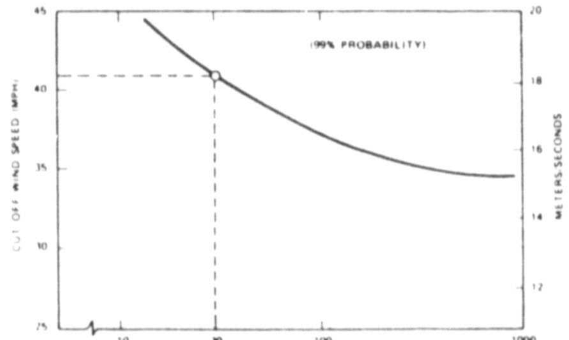


Figure 4-20. Result of Fatigue Analysis of MOD-0A Blades Assuming Structure Quality Comparable to Airplane Wing Structure

ORIGINAL PAGE IS
OF POOR QUALITY

The low speed shaft diameter is set by the bearings that were selected. The critical stress point is the fillet on the rotor side of the downwind bearing. Analysis indicates that the shaft is adequate under normal operation. Off design and transient conditions, however, were not evaluated. The loads at the low speed shaft bearings were calculated and compared to the bearing load ratings. These bearings should have a near infinite life under the computed MOD-OA loadings. A detailed analysis of the bearing caps was performed using a NASTRAN model. The critical location is at a hole through the cap. The bearing caps should also have near infinite life.

The most highly stressed part of the bedplate occurs where the downwind section is welded to the center section. The bedplate cyclic stress is well within that required for infinite life.

The original design and fatigue analysis review of the MOD-OA wind turbine yaw drive system established two basic areas of concern. These areas of concern were marginal or deficient fatigue life in certain components and inadequate design for adverse environments, such as high temperature, sand storms, and salt laden atmosphere. Recommendations to correct these problems were made, accepted, and incorporated into the design.

The tower was modeled with NASTRAN to determine the range of stress produced in each tower member by the operating loads. Both quasi-static and dynamic analyses of the tower were performed. The quasi-static analysis was found to be conservative. The highest stress ranges were found in the horizontal members at the top of the tower and were mainly due to bending stresses near the end connections. It was concluded that the tower should have near infinite life.

ORIGINAL PAGE IS
OF POOR QUALITY

5.0 SYSTEM TESTS AND INSTALLATION

The in plant tests performed on the Clayton WTG are summarized in Section 5.1. These tests were conducted during various phases of the assembly of the wind turbine at the NASA LeRC. Shown in Figure 5-1 is a flow chart for these assembly operations. Section 5.2 summarizes the site tests and installation completed at Clayton, NM. These tests and installation were performed in conjunction with the flow chart for the final assembly of the wind turbine given in Figure 5-2. Further details on these system tests and the installation are presented in the MOD-OA design report.[1]

5.1 IN PLANT TESTS

Several tests were performed at the NASA LeRC during the assembly and checkout of the Clayton MOD-OA WTG. These in plant tests were completed on the drive train, nacelle equipment, rotor, and pitch change mechanism, and included a system checkout test. In addition, a product assurance plan was implemented to establish the reliability and quality assurance aspects of the Clayton WTG.

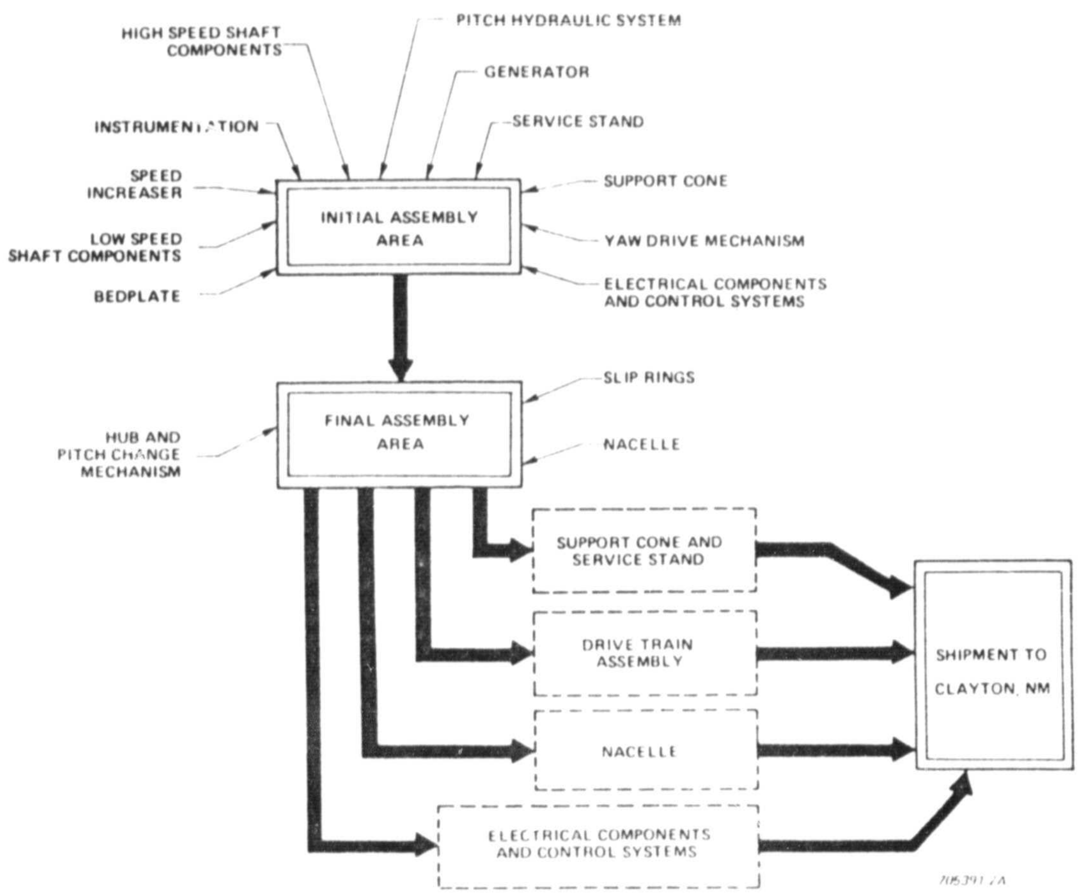


Figure 5-1. Flow Chart for Assembly of MOD-OA WTG at NASA Lewis Research Center

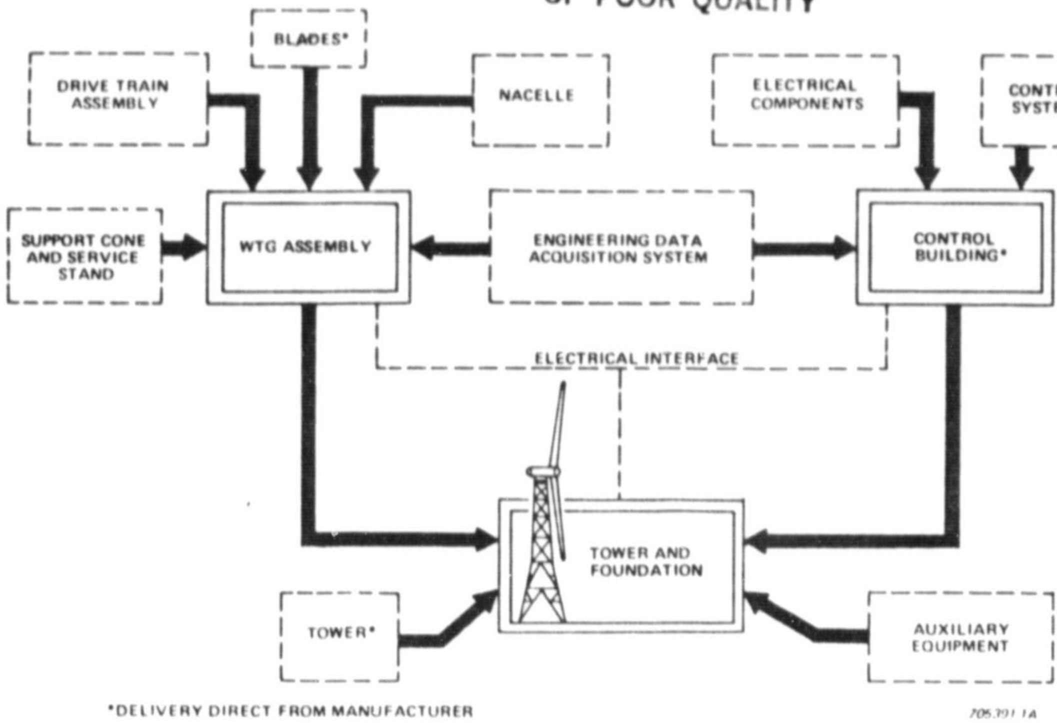


Figure 5-2. Flow Chart for Assembly of MOD-OA WTG at Clayton, NM

DRIVE TRAIN AND NACELLE EQUIPMENT

The assembly and testing of the drive train and nacelle equipment included rotational checkout tests, dynamic balancing, and drive train run-in tests. The drive train was tested without the blades, hub, pitch change mechanism, and pitch hydraulic system. Shown in Figure 5-3 is a sketch of the setup for testing of the drive train assembly. This setup included the use of a dynamometer and a speed reducer to simulate the torque at the rotor hub.

Rotational checkout tests were completed on portions of the drive train as various components were added to the bedplate. The purpose of these tests was to detect any misalignments or defects in the rotating components. Initially, the low speed shaft and speed increaser were mounted on the bedplate and tested in the Engine Research Building of the NASA LeRC. Subsequent tests were performed after the high speed shaft, its associated components, belt drive, and generator were assembled. Various instrumentation sensors were monitored and other parameters investigated. Satisfactory results were obtained from the tests.

Dynamic balancing of the drive train was performed at 1800 rpm. After the balancing, vibration amplitude readings were monitored on the low speed and high speed shaft bearings and acceptable results were obtained.

A series of eight hour drive train run-in tests was completed. These tests were accomplished by operating the dynamometer and varying a resistance load bank to obtain a generator power output of no load, 50-60 kW, 90-100 kW, and

140-150 kW. The instrumentation monitored included the accelerometers, temperatures, rotational speeds, and generator output. Satisfactory performance was demonstrated from the results.

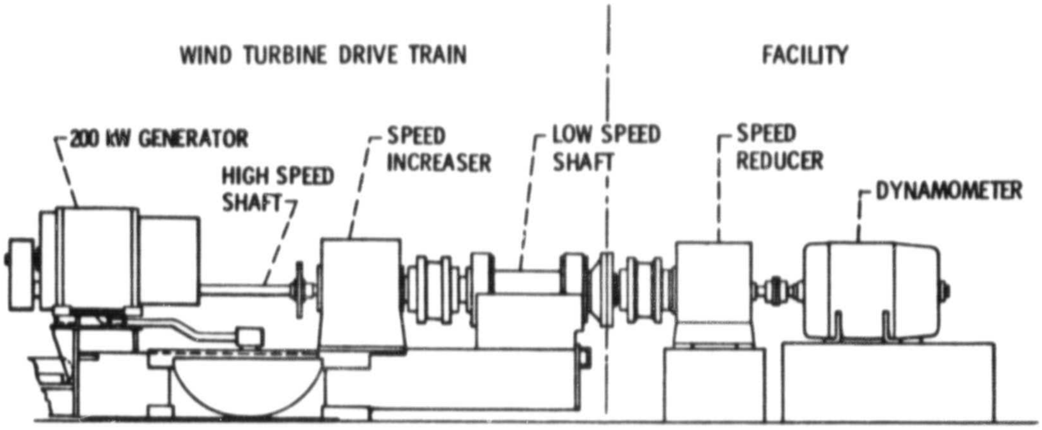


Figure 5-3. Sketch of Setup for In-Plant Testing of Drive Train Assembly

ROTOR

The in plant tests on part of the rotor assembly (without the blades) consisted of strain gage calibration tests and balancing of the hub assembly. The strain gage calibration testing was performed at the NASA LeRC Fabrication Shop. Strain gages were installed on the bedplate to measure bending loads and on the low speed shaft to measure bending loads and torque. The calibration tests were done in three steps: bending loads, shaft torque, and combined loads tests. Six strain gages on the low speed shaft and two on the bedplate required calibration. The tests involved the use of a "spider" type loading fixture attached to the low speed shaft. Shown in Figure 5-4 is a photograph of the loading fixture and test setup.

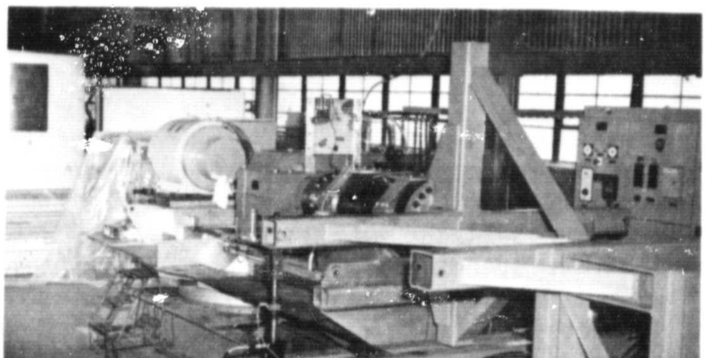


Figure 5-4. Photograph of Loading Fixture and Test Setup Used During Strain Gage Calibrations (Looking Upwind)

The bending loads tests were conducted by applying a bending moment to the shaft as a force couple to the loading fixture. Shown in Figure 5-5 are the results for one of the strain gages during the bending moment tests. Comparable data were obtained for the other strain gages during these tests, during the shaft torque tests, and during the combined bending moment and torque tests. The strain gage calibrations were satisfactorily completed.

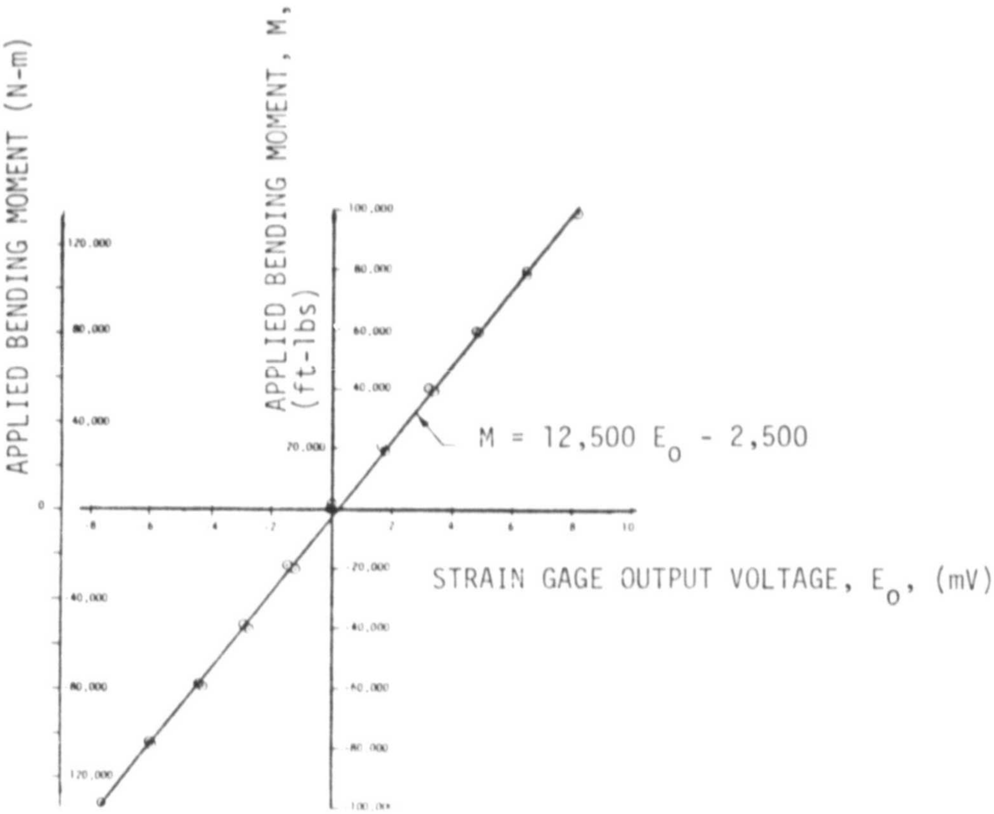


Figure 5-5. Strain Gage Calibration Results for Bending Moments on the Low Speed Shaft

Prior to balancing the hub, the strain gage fixture was removed. Then, the hub (without the blades) was attached to the low speed shaft, and the pitch change mechanism and its hydraulic system were installed. Both static and dynamic (hub rotating at 40 rpm) balancing operations were completed. The generator was run as a synchronous motor and various instrumentation sensors were monitored during the dynamic tests. Dynamic balancing was accomplished by adding or adjusting weights to the exterior surface of the hub. The hub was considered balanced when the acceleration readings on the low speed shaft bearings were no greater than those previously recorded after balancing the drive train.

ORIGINAL PAGE IS
OF POOR QUALITY

PITCH CHANGE MECHANISM

Tests on the pitch change mechanism and its control system were performed both statically and dynamically. Shown in Figure 5-6 is a sketch of the in plant test setup. The objective of these tests was to evaluate the performance characteristics.

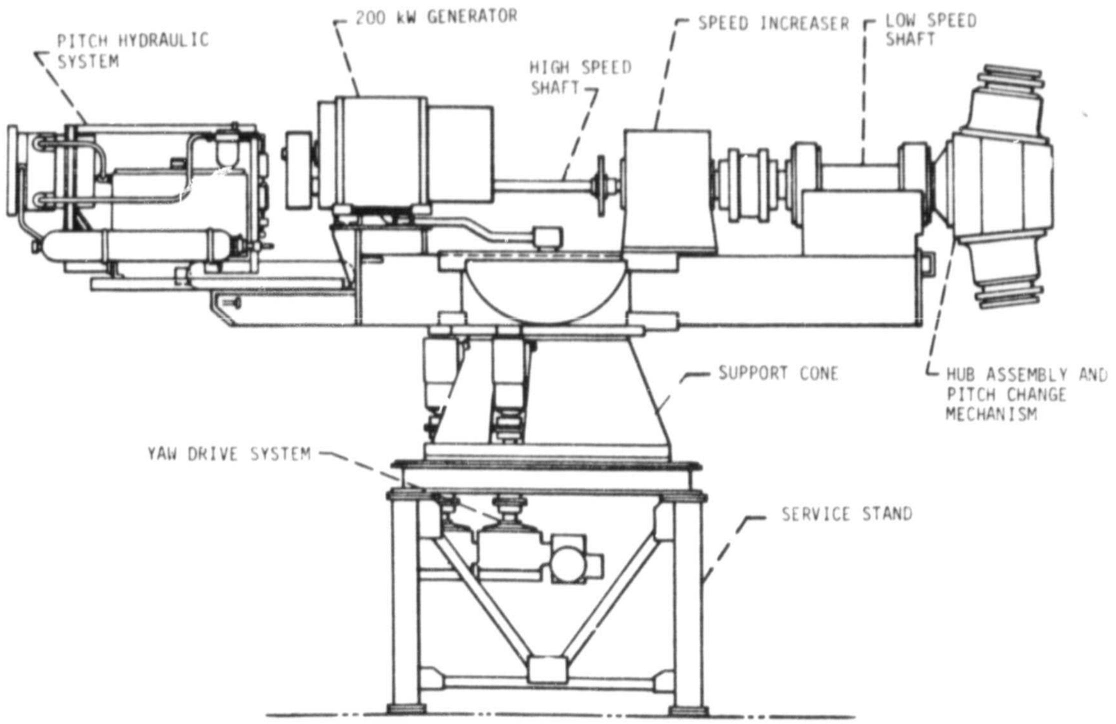


Figure 5-6. Sketch of In-Plant Test Setup for Final Acceptance Testing

The static tests were accomplished with the drive train not operating and the blade simulators installed (i.e., dummy weights were used to simulate the pitch change inertia of the blades). This testing included control calibration and resolution, slow and fast pitch operation, fail-safe mechanism confirmation and frequency response, acceleration, and deceleration tests. Extensive data were recorded during the tests. The pitch hydraulic system was operating and the pneumatic spring pressure was set at its normal pressure. The dynamic tests completed on the pitch change mechanism and pitch control system were a slow pitch rate, a fail-safe speed control, and maximum speed tests. These tests were performed with the blade simulators removed and the drive train operating at 40 rpm. The results obtained from the static and dynamic tests conducted on the pitch change mechanism were deemed satisfactory and similar to the MOD-0 (100 kW) wind turbine performance.

SYSTEM CHECKOUT

The checkout of the WTG system consisted of yaw drive system tests and a sensor installation and wiring verification test. For these tests, the yaw drive system and yaw brake (see Figure 5-6) were assembled and the electrical, hydraulic, and data acquisition components were connected. The switchgear and most of the control systems were operational. Shown in Figure 5-7 is a photograph of the MOD-OA WTG prior to the in plant system checkout tests. The testing of the yaw drive system involved the following operations and tests: setting and checking the dual yaw preload, verifying the operation of the hydraulic power unit, calibrating the time delay relay, evaluating nacelle response, deadband tests, yaw drive rate tests, and verifying system deactiviation. Various instrumentation was monitored during the testing. From the tests on the yaw drive system, acceptable results were obtained and proper operation was demonstrated.

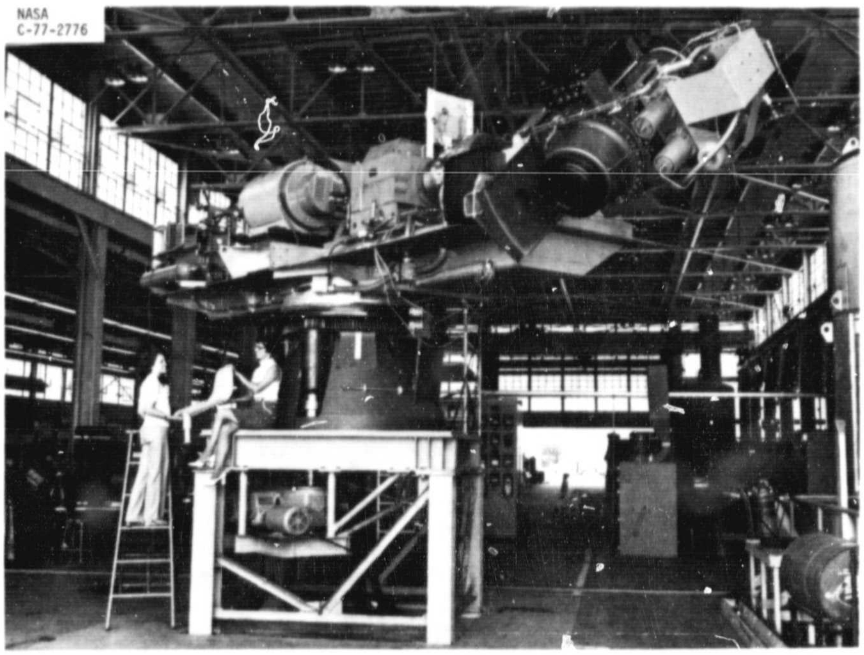


Figure 5-7. Photograph of MOD-OA WTG Prior to In-Plant System Checkout Tests

The in plant, overall system checkout tests included sensor installation and wiring verifications. Continuity tests were completed to verify that the data acquisition system and the power and control circuits were installed correctly. These tests involved the use of the Mobile Data System. Various sensors for the data system are located on the rotor, drive train, nacelle/bedplate, and tower, and in the control building. These sensors measure the temperatures, accelerations, pressures, strains, generator speed, low speed shaft position, and the current, voltage, output power (kW), VARS, and frequency for the generator. From the test results derived, proper installation, wiring, calibration, and accuracy capability were confirmed.

ORIGINAL PAGE IS
OF POOR QUALITY

5.2 SITE TESTS AND INSTALLATION

Several operations and tests were performed at Clayton, NM during the final assembly and checkout of the WTG. These tests and operations included a check on rotor performance, a systems checkout, testing of the drive train and nacelle equipment, and the installation experience. In conjunction with these tests, a NASA LeRC review team was assembled to verify the operational readiness of the Clayton WTG before it was released for utility operation. This team reviewed the as-built hardware, system checkout procedures and results, instrumentation requirements, and safety procedures.

ROTOR

The site tests and activities on the rotor included the installation of the blades and an instrumentation checkout. The rotor instrumentation which was checked at the site included the strain gages located on the blades. These gages had been calibrated previously at the Lockheed plant. Additional results on the pitch change mechanism, its control system, and dynamic balancing of the rotor are summarized below.

SYSTEMS CHECKOUT

The systems checkout tests at the site involved the yaw drive system, the completion of the electrical terminations, the safety shutdown system, the pitch control system, and system shutdown tests. During the verification tests on the yaw drive system, checkout operations of the two drive motors, the yaw brake hydraulic pump circuit, the yaw brake, and the yaw control system were conducted. Satisfactory operation and performance was demonstrated from the tests. After the WTG assembly was mounted on top of the tower, final electrical, control, and instrumentation terminations were completed.

A series of checkout tests of the safety shutdown system was performed. These verifications included a checkout of the appropriate shutdown parameters to achieve a critical, an emergency, or a redundant shutdown. Checkout operations on the performance of the disk brake were also completed. During these tests, various parameters were monitored and the data reviewed to ensure that the red line values were not exceeded. Satisfactory results were obtained from these checkout tests. Both manual and automatic checkout operations on the pitch control system were accomplished to verify that the blades could be feathered as designed. Proper operation of the pitch control system was confirmed. In addition to a safety shutdown, two other shutdown modes were tested: manual and fully automatic (microprocessor). From the results derived, the manual and microprocessor shutdown capabilities were verified.

DRIVE TRAIN AND NACELLE EQUIPMENT

Several tests and operations were performed on the drive train and on the equipment located within the nacelle. Rotating tests were completed, including a final checkout on dynamic balancing. The final peak-to-peak vibration amplitude results from the balancing operations were comparable to the results derived during the in plant tests.

ORIGINAL PAGE IS
OF POOR QUALITY

A series of tests was performed for manual and automatic startup and operation. A pre-startup verification and checkout procedure was completed to ensure that all components and systems were operational. Tests on pitch, speed, and load control modes of manual operation were done and satisfactory results were obtained. Automatic startup and operation tests, with the use of the microprocessor, were also conducted. Satisfactory performance of the microprocessor was demonstrated.

INSTALLATION EXPERIENCE

The installation of the MOD-0A at the Clayton site involved the following operations: site preparation, pouring of foundations, tower erection, assembly of control building and equipment, installation of the personnel and equipment hoist, reassembly of drive train, blade installation, lifting of the WTG to the top of the tower, and power, control, and instrumentation hookup. Site preparation activities included providing an access road, a security fence, and the electrical interface equipment. Excavations were made and concrete foundations were poured to support the tower, assembly stand, control building, transformer, and oil circuit recloser. The installation of the MOD-0A tower was completed at the Clayton site, as shown in Figure 5-8.

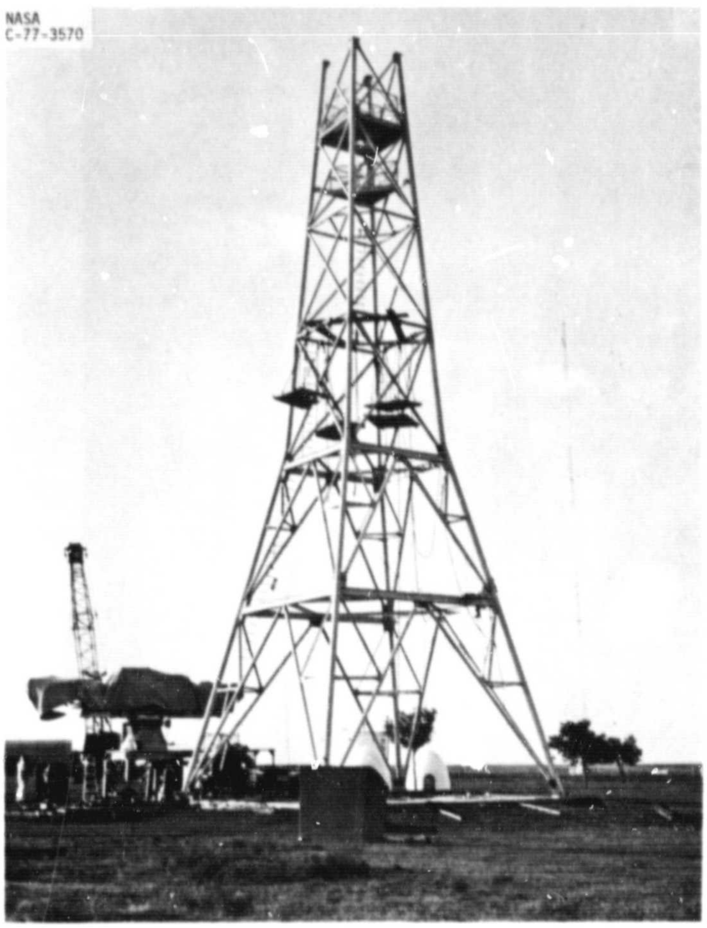


Figure 5-8. Installation of MOD-0A Tower at Clayton

The control building was assembled and the power, control, and instrumentation components located within the building were installed. Installation of the oil circuit recloser, transformer, and the remote control and monitoring system were completed. The equipment and personnel hoist was installed to permit access from ground level to the top of the tower. The reassembly of the drive train to the support cone, the assembly of the blades to the rotor, and the assembly of the nacelle enclosure were accomplished with the WTG mounted on the service stand.

Lifting of the complete WTG assembly (rotor, blades, drive train, bedplate, support cone, nacelle, and mounting frame) to the top of the tower was performed with the use of a crane. A photograph of the final stage of this lifting operation and the installation to the tower is shown in Figure 5-9. The mechanical attachment and the electrical, control, and instrumentation terminations were completed. Final checkout of all of the mechanical, electrical, control, instrumentation, and safety systems was performed. The installation of the Clayton WTG was satisfactorily completed and the wind turbine was dedicated on January 28, 1978. On March 6, 1978, the WTG was released to the Town of Clayton Light and Water Plant for operation.

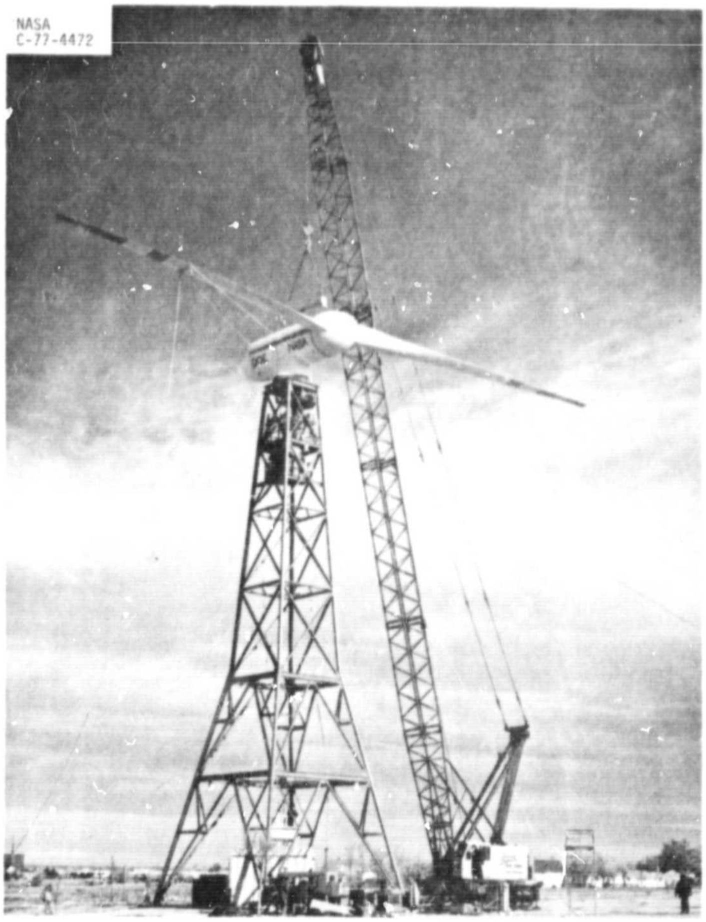


Figure 5-9. Final Stage of WTG Lifting Operation and Installation to the Tower

6.0 SAFETY CONSIDERATIONS

Safety considerations for the MOD-OA wind turbine included the safety philosophy used in the design, construction, and operation; the normal and emergency operating procedures; the identification of hazards and an evaluation of their probability and predicted consequences; and the safety related physical features and administrative controls.

6.1 SAFETY PHILOSOPHY

The MOD-OA safety program identified, evaluated, and either eliminated or controlled all undesirable hazards with potential to cause personal injury, damage the system or support equipment and facilities, or cause loss of program objectives. These objectives of the safety program were accomplished by: a) identifying the equipment, functions, and operations that possibly could result in hazards, b) assessing those hazards for impact and probability, c) instituting methods to eliminate hazards or reduce them to an acceptable risk level, and d) verifying the implementation of control measures in design, operating controls, and procedures for installation, test, and maintenance.

The safety design philosophy was that no major damage should occur during the service life of the machine because of a single-point failure or a single failure following an undetected failure. The fail-safe approach was employed. All major safety related systems were provided with redundant and diverse backup systems.

All appropriate standards were satisfied during the design and construction of the Clayton wind turbine. As examples, the support tower and foundation were designed to American Concrete Institute and American Institute of Steel Construction codes, the electrical system was designed to the National Electrical code, and the generator was purchased according to NEMA standard MG1. During construction and operation, all Occupational Safety and Health Administration (OSHA) requirements were satisfied.

6.2 NORMAL AND EMERGENCY OPERATING PROCEDURES

Normal operation of the wind turbine generator is performed via the remote control and monitoring system from the master control station within the utility dispatcher's office. However, prior to the start of operation, preliminary operational checks are made at the wind turbine site. When entering the wind turbine site, definite entrance procedures are followed to ensure the safety of all operating and maintenance personnel. The major areas of concern are the control building and the nacelle. After verifying that personnel are away from the tower and out of the nacelle, a detailed electrical and mechanical checklist is followed before operation can be performed by the utility dispatcher. With the dispatcher in control, the turbine is started using microprocessor control. The dispatcher then maintains control and shuts down the machine when appropriate.

All of these operations are governed by the detailed Normal and Emergency Operating Procedures Manual which reflects the NASA Safety Permit and the City of Clayton Safety Plan.

6.3 IDENTIFICATION OF HAZARDS, PROBABILITY OF OCCURENCE, AND PREDICTED CONSEQUENCES

Several obvious hazards exist for the Clayton wind turbine. These are tower collapse or component blow-off, blade failure, ice thrown from the blades, aircraft collision, and injury due to unauthorized access. A systematic identification of hazards is part of the FMEA in Section 7.0.

The probability of occurrence and the predicted consequences have been summarized below for the obvious hazards. The FMEA in Section 7.0 is a systematic discussion of the consequences of failures of all significant systems and components.

1) Tower Collapse or Component Blow-Off

   The risk to personnel or visitors near the wind turbine is not expected to be high in the event of tower collapse or component blow-off, due to the extreme severity of conditions which would precipitate the risk. It is highly unlikely that people would be in exposed areas near the wind turbine during periods when winds approached or exceeded 125 mph (55.9 m/s) or during a tornado warning period. During an earthquake, the turbine would pose less risk than many other structures due to its high structural integrity, relatively low mass, and absence of loosely attached overhangs or facades.

2) Blade Failure

   Safety features and precautions instituted to identify structural problems and decrease the risk of blade failure include: a) automatic monitoring of the turbine's operational performance and structural dynamics, b) automatic shutdown and required manual restart in the event a structural imbalance becomes evident, and c) regular inspections and maintenance. As an additional precaution, and to protect the machine structure, the blades are feathered and braked by redundant systems when the wind speed exceeds 40 mph (17.9 m/s). The rotor has been designed to withstand wind speeds in excess of 125 mph (55.9 m/s) at 30 ft. (9.1 m) in a feathered position. An additional factor limiting the potential for injury is that it is not probable that people (particularly visitors) will be in exposed areas within or near the exclusion radius during high wind or storm conditions. Analysis indicated the maximum range of a thrown blade is 630 ft. (192 m) when thrown at the expected 55 rpm blade attachment bolt failure speed.

3) Thrown Ice

   The safety feature that precludes problems with significant quantities of thrown ice is the vibration monitor located on the low speed shaft bearing housing which will cause shutdown at uneven loads. Even if the icing is the same for both blades, ice thrown from one blade would create an imbalance and the vibration sensor would shutdown the system.*

4) Aircraft Collision

The wind turbine nacelle and blades are painted orange and white for high visibility during daylight hours. The turbine is located 762 feet (232 m) away from the much taller KLMX radio tower; thus, the aircraft warnings for this tower also give some protection for the turbine.

5) Unauthorized Access

Safety risks associated with unauthorized accesses to the wind turbine are controlled by a fence around the site, elimination of footholds to discourage climbing of the tower, and positioning the cable-hung hoist sufficiently high to make it inaccessible from ground level. All ground level electrical equipment is shielded in compliance with OSHA regulations.

6.4 SAFETY RELATED PHYSICAL DESIGN FEATURES AND ADMINISTRATIVE CONTROLS

The major safety related physical design feature is the safety shutdown system which can operate independently from all other control systems. A set of sensors monitor potential problems and these sensors are typically redundant to protect the machine from catastropic failure. These sensors monitor over-speed, overcurrent or reverse power, vibration, yaw error, pitch system hydraulic fluid level and pressure, bottle pressures, temperatures, and microprocessor failure. The microprocessor control system is fail-safe in that failure of any critical component will automatically shut down the wind turbine.

The major administrative controls applied to this project were through a Safety Committee and quality assurance procedures.

The safety committee met regularly to review all phases of the project from a safety viewpoint. It was composed of senior technical and management personnel with expertise in all areas related to wind turbine generators. A safety permit issued by this committee was required before each phase of the project: construction, testing, and operation.

* In March, 1978, operating personnel first observed large pieces of ice, scattered on the ground, adjacent to the wind turbine. It was then observed that ice was shedding from the blades, while the blades were rotating at 40 rpm. This situation posed a safety hazard for personnel and equipment. Therefore, an ice detector system was installed on the blades to sense ice formation and initiate shutdown of the wind turbine generator. An aircraft type ice detector was tested satisfactorily in the NASA LeRC Icing Research Tunnel. After the ice detector was installed in the blades during November 1978, it performed as expected and no further instances were observed of ice thrown from the blades.

Strict quality assurance procedures controlled the NASA LeRC in-house design and construction effort, the field construction work, and the site operation. The quality assurance procedures were a blend of those used at NASA LeRC for launch vehicles, spacecraft, and aircraft engines and those normally used for electromechanical industrial components. Their objective was to achieve a safety level close to that of aerospace projects at the low cost of normal industrial practice.

6.5 CONCLUSIONS

The MOD-OA wind turbine generator at Clayton does not impose any appreciable risks to the general public, operating personnel, or equipment and facilities.

The safety design criterion was that no major damage should occur during the service life of the machine because of a single-point failure or a single failure following an undetected failure. The fail-safe approach was employed. All major safety related systems were provided with redundant and diverse backup systems.

The only part of the wind turbine generator that does not comply with the above criterion and approach is the blade and its attachment structure. The probability of a blade separation is so small that the risk from this event is acceptably small. The low probability resulted from the analysis of the blade and its mounting, the design verifications of the test program, the inspections and checks of the quality program, the redundancy built into the overspeed shutdown circuits, and the extensive inspection program during operation.

7.0 FAILURE MODES AND EFFECTS ANALYSIS

The failure modes and effects analysis (FMEA) was primarily directed at identifying those critical modes that would be hazardous to life or would result in major damage to the system. As a result, the analysis was conducted from the "top down," minimizing the extent of analysis that would lead to trivial conclusions, had the analysis been approached from the "bottom up". The criterion used for system evaluation was that no major damage should occur because of a single-point failure or a single failure following an undetected failure.

The results of the FMEA indicated the failure criterion was satisfied, except for the blade and its attachment structure. The probability of a blade separation is acceptably small as discussed in Section 6.0. The analysis of the blade and its mounting, the design verifications of the test program, the inspections and checks of the quality program, the redundancy built into the overspeed shutdown circuits, and the inspection program during operation all combine to assure safe operation.

As a result of the FMEA, several deficiencies were found in the design. To eliminate these deficiencies, the following modifications were made:

1) The rotor brake system was made fail-safe.

2) Safety related sensors, primary devices, and interconnecting circuitry were placed entirely within the nacelle so they were not dependent on tower slip rings.

3) Two independent high yaw error signals cause a shutdown.

4) Intrusion alarms on the control building and nacelle cause a shutdown, an audible alarm in the control room, and a warning on the dispatcher's console.

5) The reliability of the safety related systems and components was increased through redundancy, minimum electrical path, component quality, and periodic verification of system operation.

6) The yaw motor high temperature shutdowns were removed.

8.0 ENGINEERING DATA ACQUISITION

The instrumentation and data acquisition system collects the data required for evaluating the operation and performance of the MOD-OA wind turbine. The system consists of sensors located in the nacelle, in the control building, and on the meteorological tower; three remote multiplexing units; a mobile data system; and a stand alone instrument recorder.

The sensors associated with the data system are segregated according to their specific locations. The outputs of the sensors provide input to three remote multiplex units (RMUs) where the signals are multiplexed and sent to the mobile data system for processing.

The remote multiplexing units are located on the hub, on the bedplate, and in the control building. Each RMU contains the electronics required for signal conditioning and multiplexing data signals (FM technique) for transmission to the mobile data system. Each RMU can accommodate up to 32 data channels. All channels can be individually configured to signal condition data from resistance outputs or voltage sources. In addition, 20 of the 32 channels have the capability to signal condition inputs from type "T" copper/constantan thermocouples.

The mobile data system provides the equipment necessary to process data at the wind turbine site. This self-propelled instrument vehicle is constructed to a) permit movement from site to site over public roadways without special permits or approvals and b) provide a controlled environment for the equipment contained within the vehicle. An overview of the flow of data within the mobile data system is illustrated in Figure 8-1.

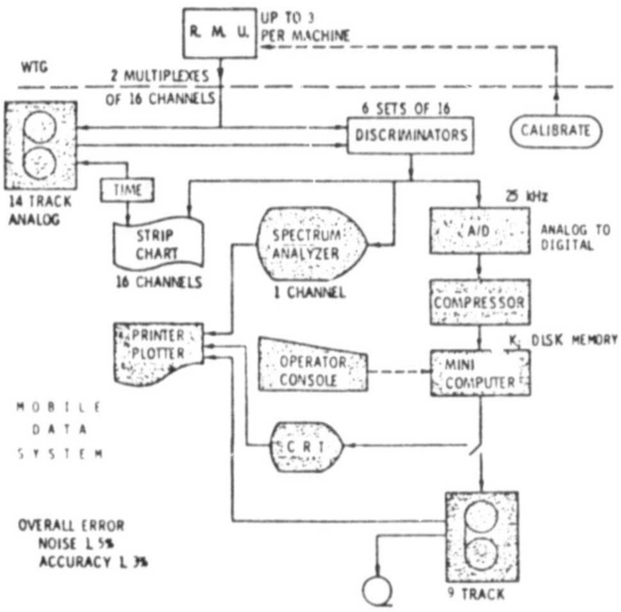


Figure 8-1. Data System Overview

The stand alone instrument recorder (SAIR) recorded data when the mobile data system was not at the site. The SAIR provided for continuous, 24 hours per day, recording of four tracks of data. Three of the data tracks supported the three RMU's and the fourth track supported an internally generated time of day time code signal. The tape consisted of a continuous loop which provided a stored record of the previous thirty minutes of data.

ORIGINAL PAGE IS
OF POOR QUALITY

9.0 INITIAL OPERATING PERFORMANCE

First rotation of the Clayton MOD-0A WTG was accomplished on November 30, 1977. In January 1978, the machine completed its first 100 hours of operation, and in March 1978, the wind turbine was released for utility operation. The following sections document the operational experience gained in the initial four months, from November 30, 1977 through March 1978, and summarize the aerodynamic, structural, and control system performance; the utility interface aspects; and the ice detector system added to the blades.

9.1 AERODYNAMIC PERFORMANCE

Of primary importance in the design of any wind turbine is the accurate prediction of the machine's performance characteristics. Data from the Clayton wind turbine have been analyzed to enable correlation of the predicted and actual performance. This section contains results of this analysis for alternator power output and drive train performance. Power oscillations data are also presented.

The performance predictions for the MOD-0A wind turbine were calculated using the aerodynamic performance code PROP. This analysis is based on the blade element/momentum theory of rotor performance. The comparison in Figure 9-1 shows general agreement between the theory (shown as the solid line) and measured performance of the MOD-0A wind turbine. The

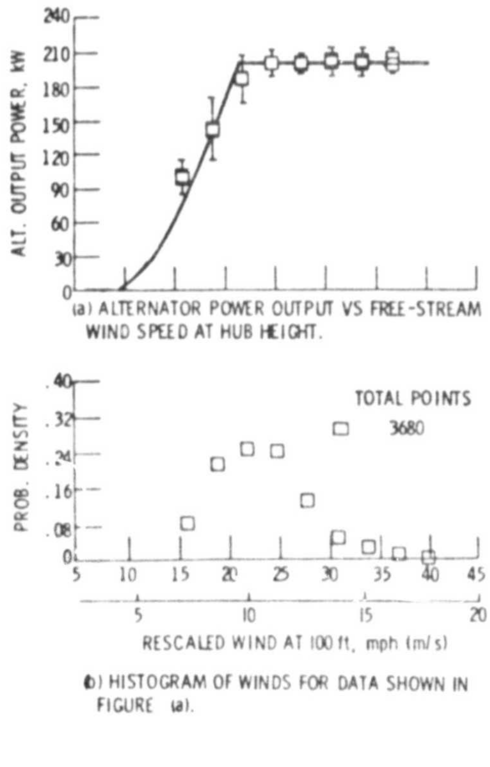


Figure 9-1. Clayton, New Mexico: Power Versus Rescaled Wind at 100 Feet

ORIGINAL PAGE IS
OF POOR QUALITY

deviation from theory (based on steady-state winds) near rated wind speed, that is, at the "sharp corner" of the curve, is well understood and has been discussed fully by Golding[3]. It is due to the fluctuation of the wind about its "steady" value which is equivalent to the wind turbine retaining an averaging on the two sides of the "corner".

Figure 9-2 shows a comparison of the constant design value for drive train efficiency, η_d, of 0.75 and the measured values which range from 0.0 to 0.86. The design value for the drive train efficiency represents a conservative average value which has been calculated by estimating the efficiencies of the various components from the rotor to the generator (at rated power). In practice, these component efficiencies vary with rotor power. In particular, the generator efficiency increases sharply with increasing rotor power. Therefore, as alternator power approaches a significant fraction of rated output, the measured drive train efficiency coincides with the design value of 0.75 and in fact exceeds this value as the rated power of 200 kW is achieved.

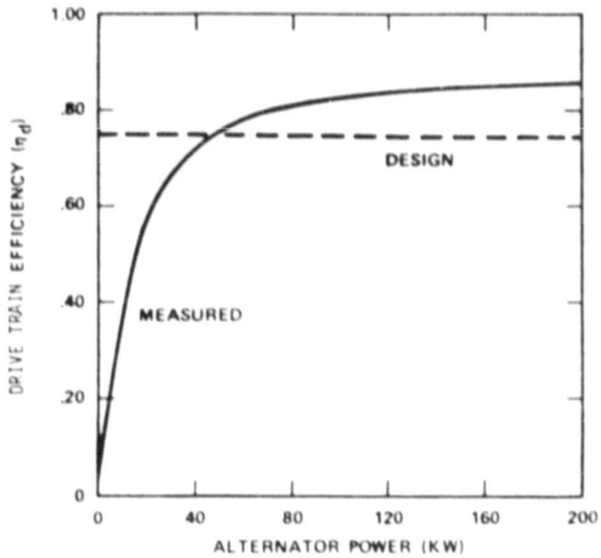


Figure 9-2. Comparison of the Design Value of Drive Train Efficiency with Measured Values at Various Alternator Powers

Cyclic power [(maximum-minimum)/2 per revolution] is caused by both tower shadow and wind shear effects. The tower shadow effect is caused by the blades passing through the region of reduced wind speed downwind of the tower. The wind shear effect is caused by the blades passing through the variation in wind speed with height. The magnitude of the cyclic power was, on the average, less than ± 20 kW.

9.2 STRUCTURAL PERFORMANCE

The structural performance of the wind turbine during initial operation generally has been within predictions. This section presents comparisons of measured and calculated blade loads and examines the unsteady loads induced by tower shadow and wind shear effects.

ORIGINAL PAGE IS
OF POOR QUALITY

The cyclic loads experienced by the blades of the MOD-OA at Clayton were somewhat lower than MOSTAB-WTE predictions. The mean chordwise and flapwise loads matched the MOSTAB-WTE predictions very closely. Hence, the comparisons between the MOD-OA data and MOSTAB-WTE predictions generally indicated good agreement between measured and predicted blade loads.

Deviations from a pure sinusoidal waveform in the chordwise bending moment and the flapwise bending moment, as shown in the strip chart records in Figure 9-3, were encountered during initial operation of the wind turbine. These were caused by both tower shadow and wind shear effects. Two deviations per revolution were detected. The large deviation is the direct effect on the blade from which the loads are measured. The smaller deviation is a result of the second blade experiencing the tower shadow-wind shear effects and communicating (via vibration, for example) this effect to the other blade.

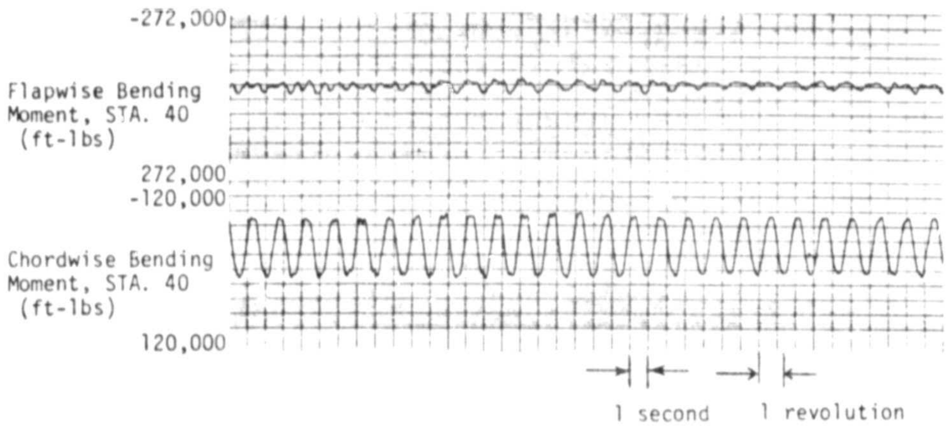


Figure 9-3. Strip Chart Records of Flapwise and Chordwise Bending Moments at Station 40

9.3 CONTROL SYSTEM PERFORMANCE

This section summarizes the performance of the yaw control, pitch control, and microprocessor control systems for the wind turbine.

The results of typical yaw maneuvers indicated that the yaw control system functioned satisfactorily during initial operation of the wind turbine. As the yaw brake pressure is reduced to allow realignment of the nacelle with the wind, the two yaw shaft loads change sharply. When yaw error is again within the ±25° deadband, the brake pressure is increased to the maximum and the nacelle is clamped rigidly to the tower.

Strip chart records of generator power, blade pitch angle, and rotor speed for startup conditions indicated that as the blade pitch angle approached 0°, the wind turbine rotor speed increased properly to 40 rpm. When 40 rpm was achieved, the machine was synchronized to the utility grid and power was produced.

The microprocessor is the control unit which permits unattended automatic operation of the wind turbine. Strip chart records of a low wind startup and shutdown showed that the microprocessor control unit operated satisfactorily.

9.4 UTILITY INTERFACE

Portions of this material have been reproduced, with the permission of the IEEE and the authors.[4]

The wind turbine generator has been placed near the end of one of the town's seven power feeders, about a half mile from the power plant. It produces power at 480 V, which is stepped up through a transformer to 2400 V, the level at which power is distributed. Clayton's municipal electric system has a radial configuration, with seven diesel generators in the central plant. Separate lines supply a hospital, high school, feed lot, and three residential feeders. A seventh line serves the internal needs of the power station. All generators feed into a common bus.

The basic system control philosophy is similar to that of most other utilities: system frequency and time are regulated. System frequency is determined by the lead unit, which corrects frequency errors by a simple reset control that balances total generator load to match the instantaneous demand. The set point units do not contribute directly to frequency regulation except as their output is altered by the droop controls. The droop value for these generators is normally set at a gain of 0.4 per unit to provide a fairly sluggish response to load changes. This value is very different from the ones used in large steam or hydro plants (typically 0.05 per unit), but not uncommon for diesel generators operating on a common bus where excessive fluctuation (hunting) might exist.

VOLTAGE VARIATIONS

Initial operation of the wind turbine indicated normal functioning of the subsystem with no noticeable variations from the 480 volt nominal output.

FREQUENCY VARIATIONS

The Clayton system frequency has a characteristic natural mode of oscillation (Fourier component) at three Hz. However, the presence of the wind turbine does not affect this Fourier component. The system and the wind turbine frequencies were identical. The MOD-OA wind turbine exhibited several natural modes of oscillation - notably at 1.33 Hz, which is twice the blades' rotational speed. Oscillations at this frequency are created by both tower shadow and wind shear effects. Such tower shadow and wind shear oscillations were found in early experiments with the MOD-0 wind turbine at the NASA Lewis Research Center. Because Clayton was to be the first utility demonstration wind turbine of that design, there was concern that the machine might excite natural oscillation modes. Since the dominant mode of oscillation at Clayton is three Hz, no such problems will occur.

When both the wind and system activity are high, the wind turbine generator tracks the system frequency determined by the lead diesel, while the wind power output tracks the wind. Gusting clearly affects the amount of output power, but seems not to accentuate system frequency excursions. The lead machine does spend more effort regulating frequency, but its response capability is adequate to keep frequency variations within typical values. More to the point, pitch control maintains the average power output from the WTG at 200 kW, or at the appropriate power level predicted by Figure 2-4 (Section 2.3).

Because of the high per-unit resistance of the distribution line connecting the wind turbine to the central station, it appears that power oscillations caused by tower shadow and wind shear effects are attenuated to a level where they are too small to be sensed by the diesel generators.

9.5 ICE DETECTOR FOR BLADES

In March 1978, blade icing occurred on the wind turbine generator. At that time, NASA LeRC personnel first observed large pieces of ice, scattered on the ground, adjacent to the wind turbine during operation. It was then observed that ice was shedding from the blades while the blades were rotating at 40 rpm. This situation posed a safety hazard for personnel and equipment in close proximity to the machine.

For personnel safety, NASA LeRC decided to provide an ice detector subsystem on the wind turbine. The control system was modified to monitor the ice detector signal and initiate shutdown of the wind turbine. The ice detector subsystem (Rosemount Inc. Model 871FA-122) was installed and operational at Clayton in November, 1978.

10.0 REFERENCES*

1. Andersen, T.S., Bodenschatz, C.A., Eggers, A.G., Hughes, P.S., Lampe, R.F., Lipner, M.H., and Schornhorst, J.R., "MOD-OA 200 kW Wind Turbine Generator Design and Analysis Report," DOE/NASA/0163-2, NASA CR-165128, and AESD-TME-3052, August 1980.*

2. Andersen, T.S., Bodenschatz, C.A., Eggers, A.G., Hughes, P.S., and Lampe, R.F., "MOD-OA 200 kW Wing Turbine Generator Engineering Drawing Report," DOE/NASA/0163-3, NASA CR-165129, and AESD-TME-3053, August 1980.

3. Golding, E.W., The Generation of Electricity by Wind Power. New York, Philosophical Library, 1955.

4. Reddoch, T.W. and Klein, J.W., "No Ill Winds for New Mexico Utility," IEEE Sprectrum; Vol. 16, No. 3, March 1979, pp. 57-61, © 1979, IEEE.**

---

* A comprehensive list of cited references and a bibliography have been included in the detailed report of Reference 1.

** Portions of this copyrignted article have been reproduced with the permission of the IEEE and the authors.