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UTILITY OPERATIONAL EXPERIENCE ON THE NASA/DOE MOD-0A 200-kW WIND TURBINE

J. C. Glasgow and W. H. Robbins
National Aeronautics and Space Administration
Lewis Research Center

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Office of Energy Technology
Division of Distributed Solar Technology

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NOTICE

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J. C. Glasgow* and W. H. Robbins**
National Aeronautics and Space Administration
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Cleveland, Ohio 44135

Abstract

The Mod-OA 200 kW Wind Turbine was designed and fabricated by the Lewis Research Center of the NASA under the direction of the U.S. Department of Energy. The project is a part of the Federal Wind Energy Program and is designed to obtain early wind turbine operation and performance data while gaining initial experience in the operation of large, horizontal axis wind turbines in typical utility environments. On March 6, 1978 the Mod-OA wind turbine was turned over to the Town of Clayton Light and Water Plant, Clayton, NM, for utility operation and on December 31, 1978, the machine had completed ten months of utility operation. This paper describes the machine and documents the recent operational experience at Clayton, NM.

Introduction

Large wind turbines for electric power generation have been under development by the U.S. for several years. These wind turbines range in size from 100 kW to multi-MW units. The U.S. Department of Energy (DOE) is responsible for wind turbine development and the management of one phase of the program--large horizontal axis wind turbine development--has been assigned to the Lewis Research Center of the National Aeronautics and Space Administration (NASA). The first of these new developments, called Mod-OA, became operational at a utility site early in 1978. This paper describes the operational experience of that wind turbine.

*Research Engineer
**Manager-Wind Energy Project Office

The overall objective of the Mod-OA project is to obtain early wind turbine operation and performance data while gaining initial experience in the operation of large, horizontal axis wind turbines in typical utility environments. Key issues to be addressed by the demonstration projects include:

- o Compatibility with utility electrical requirements
- o Demonstration of unattended fail-safe operation
- o Reliability of the wind turbine system
- o Required operations and maintenance
- o Public reaction and acceptance

To accomplish these objectives a two machine program was initiated which was later expanded to include four machines. To minimize the time from initiation of the project to first machine rotation it was decided to use the Mod-0 100 kW Experimental Wind Turbine[1] as the basis for the design, making only those changes which were shown to be necessary to achieve a functionally adequate 200 kW machine. The site selected by DOE for the first machine was Clayton, New Mexico. Other sites selected include Culebra Island, Puerto Rico, Block Island, Rhode Island, and Oahu Island, Hawaii. Installation was completed in November 1977 and the wind turbine was turned over to the Town of Clayton Light and Water Plant on

March 6, 1978 for routine operation during the 2 yr experimental period. Photographs of the Mod-OA machines at Clayton, NM, and on Culebra Island, PR, are shown in Figs. 1 & 2.

This report documents the operational experience gained in the initial ten months of utility operation in 1978. A brief description of the Mod-OA design is presented to acquaint the reader with the machine.

Mod-OA Wind Turbine Design

The design of the Mod-OA wind turbine was derived from the Mod-0 wind turbine, an experimental machine designed to assess technology requirements and engineering problems of large wind turbines. The Mod-0 configuration is presented in Refs. 1 and 2 and the Mod-0 configuration is nearly identical to the Mod-OA. The Mod-OA mechanical and control systems are presented briefly below to acquaint the reader with the essential elements of the wind turbine.

Mechanical System

The wind turbine nacelle is depicted in Fig. 3 and consists of a two-bladed rotor, supported by a low speed shaft which drives a generator through a 45 to 1 step up gear box and "V" belts. The rotor is designed to operate at 40 rpm and rotor power is controlled by active control of blade pitch by hydraulic actuators mounted on the hub. Hydraulic power is supplied from a high pressure system mounted in the nacelle and is delivered to the hub through a rotating coupling and the low speed shaft to the hub actuators. The design permits collective pitch changes only. Alignment with the wind is maintained by redundant yaw drive motors driving dual double reduction self-locking worm drives engaging a bull gear attached to the nacelle. A yaw brake which locks the nacelle to the tower is provided to reduce yawing oscillations of the nacelle which are excited by the two bladed rigid downwind rotor. Details of the mechanical systems are summarized in Table I, 200 kW Wind Turbine Specifications.

Control Systems

The Mod-OA wind turbine was designed to be fully automatic power production equipment for use on a utility grid. To satisfy this requirement the wind turbine control system is capable of monitoring wind conditions, maintaining alignment with the wind, controlling rotor speed and power level, starting, synchronizing and stopping the wind turbine safely, monitoring key parameters throughout to assure that critical items are operating within specified tolerances, and providing a power dispatcher or remote operator with the capability of starting and stopping the machine. Five control systems are provided to accomplish these tasks:

1. The rotor blade pitch controller adjusts blade pitch to control rotor speed or generator power output.

2. The yaw controller keeps the wind turbine aligned with the wind.

3. The microprocessor controls the automatic operation of the machine including startup synchronization and shutdown.

4. The safety system monitors system operation and provides a wind turbine shutdown signal when out of tolerance performance is detected.

5. The remote control and monitor system provides a remote operator with the ability to enable the microprocessor to start or stop the wind turbine and to monitor machine performance.

A block diagram depicting the interactions of the control system is shown in Fig. 4. The five systems operate nearly independently and are interfaced with each other through the microprocessor. Each of the elements of the control system is described briefly below and is presented in greater detail in Ref. 2.

Pitch Controller - Wind turbine rotor power is a function of wind speed and blade pitch angle. Therefore, either rotor speed or rotor power at a given rotor speed can be controlled by adjusting blade pitch angle. The relationship between rotor power and blade pitch angle at 40 rpm is given in Fig. 5. The pitch controller operates in one of three modes: position control used during the initial phase of rotor startup and during shutdown, speed control used in the intermediate phase of startup until electrical synchronization is achieved (i.e., from 5 rpm to 40 rpm), and closed loop power control used whenever the machine is synchronized to the utility grid. As indicated in Fig. 5 the blade pitch angle is driven to zero degrees when the wind speed is below that required to produce 200 kW of power and the pitch angle is varied to spill wind when the wind speed is above this value 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 at a pitch angle of -90° and the blades remain in feather position, with the rotor free to rotate, until a command to start is received.

Yaw Controller - The yaw controller senses directional error from the anemometer/wind vane mounted on the nacelle (Fig. 3) which measures wind direction relative to the nacelle, a direct measure of yaw error. The error signal is filtered by a 30 second time constant filter to eliminate noise and smooth out transient wind shifts. The controller has a ± 25° dead band which must be exceeded before a correction is initiated. The yaw drive moves the nacelle at a constant rate of 1° 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 yawing operations the yaw brake pressure is reduced and when no yawing is taking place, the brake pressure is increased and the nacelle is essentially locked to the tower.

The Microprocessor - The microprocessor is the control unit which permits unattended automatic operation of the wind turbine to take place. 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 wind turbine and/or disable the microprocessor.

Once activated the microprocessor monitors the wind and initiates a startup sequence (Fig. 6) when the wind speed, measured on the nacelle, exceeds 5.3 m/sec (12 mph). Once synchronized, the machine continues to operate until a wind speed below 4.5 m/sec (10 mph) or above 17.9 m/s (40 mph) is reached. When either of these conditions is encountered the microprocessor initiates the shutdown sequence (Fig. 7) and waits until the wind speed either increases to the 5.3 m/sec low wind value or drops to the 15.7 m/sec (35 mph) high wind value required for a restart.

The microprocessor is also programmed to shut the wind turbine down whenever it detects certain abnormalities. These include slow startup or synchronization, loss of pitch hydraulic pressure, and loss of synchronization. Each of these abnormal conditions initiates the shutdown sequence and requires an on-site reset before normal operations can continue. A detailed description of the microprocessor and its adaptation to wind turbine control is contained in Ref. 3.

The Safety System - 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 system used on the Mod-OA wind turbine was developed on the Mod-0 experimental wind turbine and is described in Ref. 2. A schematic of the system presently in use on the Mod-OA is shown in Fig. 8. The system is functionally independent of other control systems and includes a series or 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, interconnected with the wind turbine electrical system, which effects the shutdown by feathering the rotor blades and desynchronizing the generator. The 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. Additional sensors have been added recently to monitor blade loads and ice buildups on the blades.

The Remote Control and Monitor System - The Remote Control and Monitor System (RCMS) provides an interface between the wind turbine and the power disptacher's control room about 2 km from the wind turbine. The system serves as a control link, status indicator and performance monitor, and is connected to the wind turbine by a pair of telephone wires. A single unit (Fig. 9) is capable of controlling a number of wind turbines.

The RCMS 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 operating or standby, microprocessor on or off, and error conditions from the safety system. Performance of the machine can be monitored by any two of eight channels of analog data which are digitally displayed in engineering units. These include wind speed, rotor speed, generator power and reactive power, current, voltage and nacelle direction. The functions of the RCMS are summarized in Fig. 10.

Utility Operation Experience

The City of Clayton, New Mexico is located in the extreme northeastern corner of the state near the Texas Panhandle area of the Great Plains. The region represents a large geographic area with excellent wind potential. The wind speed at Clayton, NM at hub height is above 3.8 m/sec (8 mph), 90% of the time and the mean wind speed at the hub is 7.2 m/sec (16.1 mph). The city has a population of approximately 3000 residents and a small municipally owned electric utility system which is capable of operation on natural gas or diesel fuel. The system is independent and interconnection with existing systems is impossible because of existing REA loads. Additional power can only be obtained by negotiation with commercial utility companies and subsequent construction of transmission lines, probably in excess of 100 km in length. Fig. 11 is a photograph of the city of Clayton showing the wind turbine in the center foreground. Table II summarizes the general characteristics of the city's power useage.

The Clayton, NM site has been an excellent choice for the first utility operated wind turbine. The machine has received a great deal of acceptance from the residents of the community and its proximity to the municipal power plant has made it convenient for service personnel when on-site presence is required. Also, the size of the utility is such that the wind turbine can make a small but measurable contribution to the power output of the municipal system. During the period of its operation the wind turbine has produced 2-1/2% of the total energy used by the community and has produced over 20% of the total power requirements of the community on occasion during the early morning hours.

Operational History

The Clayton, NM, Mod-OA wind turbine operational history is presented in Table III. This table summarizes the major milestones of the program from first rotor rotation until the end of the reporting period. As indicated in the table, during this time the wind turbine generated 260,240 kW hours of power and experienced three shutdown periods which took the machine out of service for a period of 50 days. Two of the shutdown periods were attributed to rotor blade changes and the third shutdown was caused by a generator bearing failure. These situations along with other operational issues are discussed in succeeding sections.

Figs. 12 and 13 show a running total of wind turbine power output and operating time for the period of utility operation through December 31, 1978. As indicated in Fig. 12 the average power generated when the machine was operating was 91.8 kW and the plant factor for the period was 0.202 (Plant factor is defined as the power generated divided by the power that would be generated if the generator operated at rated capacity 100% of the time). The wind turbine operated 44.2% of the time throughout the period (Fig. 13). For both the plant factor and the average operating time calculations, the 50 days of wind turbine shutdown were omitted. Both the plant factor (.202) and the average power output (91.8 kW) were excellent for the first operational unit.

The Mod-OA wind turbine weekly availability is shown in Fig. 14. The time period covered is the period of utility operation, March 6 through December 31, 1978. As expected, the weekly availability was initially low (approx. 70%) and approached the project goal of 90% as the year progressed. The average availability over the reporting period excluding the two blade change periods was 77%. This is an excellent record for the first wind turbine in utility service.

The various symbols on the availability plot (Fig. 14) identify weeks when certain repairs were necessary or unique conditions existed and serve as an explanation for the reduced availability. The circles indicate routine operation over the weekly period. Each of these conditions will be discussed in the section devoted to operational issues, with the exception of the circuit breaker repair which was attributed to a defective part.

Wind turbine availability in percent is defined as the ratio of the hours of synchronous operation divided by the hours that the wind speed is between cutin and cutout wind speed, multiplied by 100. The term is a comparison of the actual machine operating time to the time that winds were available to operate the machine and is a convenient measure of overall machine reliability for long-term wind turbine evaluation.

Aerodynamic and Structural Performance

The aerodynamic performance of the Mod-OA wind turbine was measured and reported in Ref. 4. The results of this study indicated that the machine was performing aerodynamically as predicted and is shown in Fig. 15. However, as expected, the power generated over monthly periods was found to be less than that which would be predicted based on the measured wind data (i.e., from the meteorological tower) for the month. Performance losses are thought to be caused primarily by the operational startup and shutdown logic in the microprocessor and the time required for startup and shutdown of the wind turbine. The predicted energy will always be higher than the actual energy since momentary excursions in wind speed, above cutout or below cutin wind speed, will initiate a shutdown cycle even though the wind returns to proper operating speeds. These shutdown cycles naturally reduce total power output. Investigations are underway to modify the wind turbine operations to maximize energy capture while not reducing the 30 year operational life of the machine.

The machine blade loads and structural dynamic response have been shown to be generally within the predicted values as reported in Refs. 5 and 6. The agreement between predicted and measured loads on the Mod-OA rotor blade is shown in Fig. 16. Loads encountered in winds near the cutout wind speed 17.9 m/sec (40 mph) do occasionally exceed predicted values; however, analysis of these load conditions are under review.

Utility/Wind Turbine Interface

The Clayton municipal electric system is set out in a radial configuration with a central power plant consisting of seven diesel powered generating units. These units serve the community load through six distribution feeders that operate at 2400 volts. All generating units are located in one power plant and produce power at the distribution level of 2400 volts which is fed into a common bus. The Mod-OA wind turbine is placed near the end of one of the residential-commercial distribution feeders about one kilometer from the power plant. The wind turbine produces power at 480 volts which is stepped up through a transformer to the system voltage.

The Clayton generators produce power with a normal oscillation at 3 Hz. The wind turbine produces oscillations at first and second multiples of the rotor frequency 0.67 and 1.33 Hz, and at a lower frequency, approximately .02 to .05 Hz, which is attributed to the interaction of the power control system with wind turbulence or gustiness. In each case the power oscillations were found to be too fast for the reaction of the governor controls on the lead diesel and system frequency deviations were unaffected by the wind turbine. Also, the wind turbine has not experienced any difficulty in maintaining synchronism with the Clayton system throughout its operation. The power plant operator appears to maintain more spinning reserve when the wind turbine is operating during off-peak hours indicating an effort on the part of the operator to provide extra margin for the variable nature of the wind.

The wind turbine has been used primarily as a fuel saver due to the variable nature of the wind and while operating in this mode has produced 260 MWhrs of electric energy. Operation and routine maintenance have been handled satisfactorily by utility personnel and the machine has experienced a great deal of public acceptance in the community. The Clayton electrical system, without the wind turbine, produces 60 Hz power with normal frequency variations of ±0.5 Hz. The system also experiences ±2.5% power swings with a characteristic frequency of 3 Hz. When the wind turbine was added to the system, no difficulty in maintaining synchronism was experienced and no adverse electrical effects were noted on the Clayton system which could be attributed to the wind turbine. A more detailed treatment of the utility/wind turbine interface is contained in Ref. 7.

Operational Issues

As stated in the introduction, the primary objective of the Mod-OA program is to gain early operating experience with wind turbines at utility sites. In keeping with this objective, the main thrust of the program has been to maximize machine availability, operating time and power output. Throughout the period of time from the first rotation in November 1977 through December 1978, a number of operational shutdowns have occurred; problems which are normal with the startup of any new facility or in prototype development of a new piece of machinery. These interruptions have been associated with adjustment and tolerance setting of the control and safety system parameters and design defects in some of the mechanical systems.

The Mod-OA experienced many startup and adjustment problems in the early phases of the program and large wind turbines can be expected to experience a number of these with each new installation. The Clayton wind turbine experienced particular difficulties with electrical noise and heat buildup in the microprocessor and a number of false safety system shutdowns before proper adjustments and settings were determined. Minor lubricant and hydraulic/pneumatic leaks were encountered and dealt with. These problems were minor and corrected by the addition of a different gasket material, etc., and are not enumerated in this report. Design defects have also been manifested. Structural modification of the blades, redesign of the rotating hydraulic coupling and the upgrading of generator bearings fall into this category.

Operational problems which had a significant impact on machine operating time and availability are discussed below in some detail. Environmental problems encountered on the Mod-OA program are also discussed.

Rotor Blades

Throughout the program at Clayton, NM, periodic inspections of various subsystems were routinely conducted by NASA personnel. On one of these inspections, in March 1978, a fastener was found missing on one of the blades near the blade root. The blades had experienced about 500 hours of operation at this point. A later inspection in May 1978 revealed that more fasteners in the area of the root had worked loose and reports of loud creaking noises were received from Clayton Light and Water personnel. On June 2, 1978, the wind turbine was removed from the tower and lowered to ground level for detailed inspection. This inspection revealed several cracks in the aluminum skins of both blades and it was decided to ship the blades back to the Lewis Research Center for repair.

At Lewis, access holes were made to allow removal of the shank of the root section. Detailed inspection indicated that almost all of the damage occurred in the inboard 2 meters of the 19 m blade as indicated in Fig. 17. In this area the load from the wing-like structure is transferred to the shank or root section as indicated in Fig. 18. The shank is attached to the rib at station 81 and to the shear web just inboard of station 81. The shank is not attached to the station 48 rib but is designed to bear against the rib at this station. The blade bending loads are resisted by means of a force couple at the station 48 and 81 ribs.

Damage to the blades consisted of cracks in the station 81 ribs and stringers near the root end, loosening of external rivets, skin cracks, and excessive wear of the station 48 ribs at the free floating joint. The internal damage was repaired and a set of doublers was added to the exterior surfaces of the blade centered over the station 81 rib. These doublers are shown in Figs. 19 and 20. Also, a sacrificial bearing material which can be inspected easily and replaced as required was installed at the station 48 rib.

After these structural modifications were incorporated, the blades were reinstalled and the wind turbine was returned to service on September 25, 1978. Since that time the blades have operated successfully over 1000 hours without any problems and the structural modifications are being incorporated in the three follow-on Mod-OA wind turbines.

The blade problems have been attributed to two causes. First, the blade design in the area of the root was deficient in not providing adequate strength at the joint between the wing-like structure and the steel root shank. Stress concentrations and wear in this area caused the fatigue cracks after only 1000 hours of service. Second, blade loads higher than predicted were encountered in service at Clayton. These high loads occurred at wind speeds near the cutout wind speed of 17.9 m/sec, during safety system shutdowns where a high feather rate is used to stop the rotor, and in some periods when the yaw brake did not supply normal restraint during yaw corrections.

Adjustments have been made to eliminate these problems in the future. The blade root area has been redesigned to provide the additional strength and better load paths for load transfer to the root fitting; a blade load monitor has been added to the safety system which will shut the machine down if high loads are encountered; and the high feather rate used in safety system shutdowns is being reduced. We feel that these modifications will eliminate blade structural problems throughout the life of the Mod-OA program.

Rotating Hydraulic Coupling

The rotating hydraulic coupling provides power to the pitch control actuators mounted on the rotating hub. The hydraulic system operates at 1.03 MN/m^2 (1500 psi) and several leaks have developed during the 2800 hours of operation, about 7×10^6 cycles. Failures have been traced to bearings in the coupling. The third modification which incorporated uprated bearings and regular lubrication has completed over 1000 hours of operation at this point and is undergoing accelerated life tests at Lewis. The results thus far are promising on this current coupling design.

Advanced wind turbines such as Mod-1 and Mod-2 have avoided this potential problem area either by accomplishing blade pitch changes with mechanical linkages or by mounting the hydraulic power supply on the rotating hub-shaft system.

Safety System

The Mod-OA safety system has had an excellent record in performing its assigned function of protecting the machine from damage. Blade overload and a blade ice detector have been added to the safety system as a result of operational experience. However, in providing for safety in unattended operation, the safety system has caused a number of unnecessary shutdowns which have resulted in some loss of operating time and have caused blade overloads. Improvements have been made in the system by re-designing some channels and adding filtering to others to eliminate noise. Also, a redesign of the system is underway to reduce the blade pitch feather rate to eliminate blade overload during emergency shutdowns initiated by the safety system.

Ice Buildup

Early operation of the Mod-OA at Clayton, NM, demonstrated the problems associated with ice buildup on the rotor blades. Reports from the Smith-Putnam wind turbine (circa 1940) indicated that blade flexing would shed ice before buildup became a problem; and the Clayton experience essentially demonstrated this. However, the ice that was thrown from the blades was a significant safety hazard. Blade tip speed is 79 m/sec (260 ft/sec) and pieces of ice of up to 20 cm in length were found on the ground around the machine after operation during icing conditions. To prevent the recurrence of this hazardous condition, an ice detector was installed on the rotor blade (Fig. 21). The ice detector is a highly reliable standard item developed for use on aircraft which provides a signal which indicates the onset of ice buildup. The signal is sent to the safety system which effects a shutdown. Tests were conducted in the Lewis icing tunnel to demonstrate the suitability of the detector for this application and installation was completed in the Fall of 1978. The system has been effective in preventing operation during icing conditions but has resulted in reduced wind turbine availability during the Fall as indicated in Fig. 14.

Generator Bearing

After 2500 hours of synchronous operation the rotor bearing at the drive end of the generator failed. Analysis of the failed parts indicated that the design bearing was not adequate for a side drive and had failed due to overload. Bearings are being replaced with an uprated bearing.

Environmental Issues

In addition to being an excellent wind site Clayton, NM, subjects the wind turbine to some hostile environmental conditions. Temperature extremes of 38° C to -17° C (100° F to 0° F) are common and the area is subject to ice and dust storms. A fan to remove heat generated by the electronics and filtered air in the control building have been adequate to handle heat and dust problems at Clayton and early operation at Culebra, PR, have not indicated any problems at this time.

There have been no reported bird kills attributable to the wind turbine and interference with television has not been a problem since the town of Clayton is serviced by cable T.V. The wind turbine is essentially noise free and the Light and Water Company has not received any complaints from the residents about noise. Public acceptance of the wind turbine has been excellent.

Concluding Remarks

During 1978, the Mod-OA 200 kW wind turbine successfully completed nearly ten months of operation by the Town of Clayton Power and Water Plant on their utility network. This limited experience has demonstrated that a large automatic horizontal axis wind turbine can be successfully operated and maintained by a small electric utility and the power generated can be integrated into the utility network without difficulty. Minor operational problems have been encountered and corrected during the first year's operation but no major issues have been identified which would invalidate the basic system design. The Mod-OA operational experience to date has:

1. Provided verification of the basic design and systems analysis of the Mod-OA wind turbine.

2. Demonstrated satisfactory operation and electrical compatability on a small utility.

3. Demonstrated excellent public acceptance in a highly visible location.

The data generated and the experience gained on the program have been a valuable source of information for the continued development of the technology base for the Large Horizontal Axis Wind Turbine Program. Analysis of the results thus far has indicated three areas requiring additional effort. These include:

1. Improved description of the wind which characterizes the factors affecting aerodynamic performance and rotor loads.

2. A sustained systematic effort to optimize Mod-OA power output.

3. Incorporation of design improvements to reduce down time for maintenance and increase wind turbine availability.

As the end of the first year of utility operation approaches, the Mod-OA experience has served as a confirmation of our original belief that a large horizontal axis wind turbine can be operated practically on a utility network as a fuel conservation device.

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Rotor

Number of blades	2
Diameter, ft.	125
Speed, rpm	40
Direction of rotation	CCW (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable Pitch
Cone angle, deg	7
Tilt angle, deg	0

Blade

Length, ft.	59.9
Material	Aluminum
Weight, lb/blade	2300
Airfoil	NACA 23000
Twist, deg	26.5
Solidity, percent	3
Tip chord, ft.	1.5
Root chord, ft.	4
Chord taper	Linear

Tower

Type	Pipe truss
Height, ft.	93
Ground clearance, ft.	37
Hub height, ft.	100
Access	Hoist

Transmission

Type	Three-stage conventional
Ratic	45:1
Rating, hp.	460

Generator

Type	Synchronous ac
Rating, kVA	250
Power factor	0.8
Voltage, V	480 (three phase)
Speed, rpm	1800
Frequency, Hz	60

Orientation drive

Type	Ring gear
Yaw rate, rpm	1/6
Yaw drive	Electric motors

Control system

Supervisory	Microprocessor
Pitch actuator	Hydraulic

Performance

Rated power, kW	200
Wind speed at 30 ft, mph (at hub):	
Cut-in	6.9 (10.8)
Rated	18.3.(21.4)
Cut-out	34.2 (40)
Maximum design	125 (150)

Weight (klb)

Rotor (including blades)	12.2
Above tower	44.9
Tower	44.0
Total	88.9

System Life

All components, yr	30

TABLE I - MOD-OA 200 kW WIND TURBINE SPECIFICATIONS

Population	3,000
Annual Energy Consumption (1978)	15,100 MW hr
Peak Demand	3.8 MW
Average Daytime Demand	2.8 MW
Mean Annual Wind Speed @ 9.1m	5.82m/sec (13.0 mph)
Hub Height 30m	7.2m/sec (16.1 mph)

Table II Clayton, New Mexico - General Characteristics

November 30, 1977	First Rotation
January 19, 1978	First 100 hrs of Operation
March 6, 1978	Turn Over to Utility
May 24, 1978	1000 hrs of Operation, 94,000 kW-hr
June 2, 1978	Shutdown to Inspect and Replace Blades
June 28, 1978	Returned to Service
September 11, 1978	Shutdown to Install Modified Blades
September 25, 1978	Returned to Service
October 12, 1978	2000 hrs of Operation 181,000 kW-hr
December 1, 1978	Shutdown - Generator Bearing Failure
December 11, 1978	Returned to Service
January 1, 1979	2810 hrs of Operation 260,240 kW-hr

Table III Operational History, Mod-0A 200 kW Wind Turbine
Clayton, New Mexico

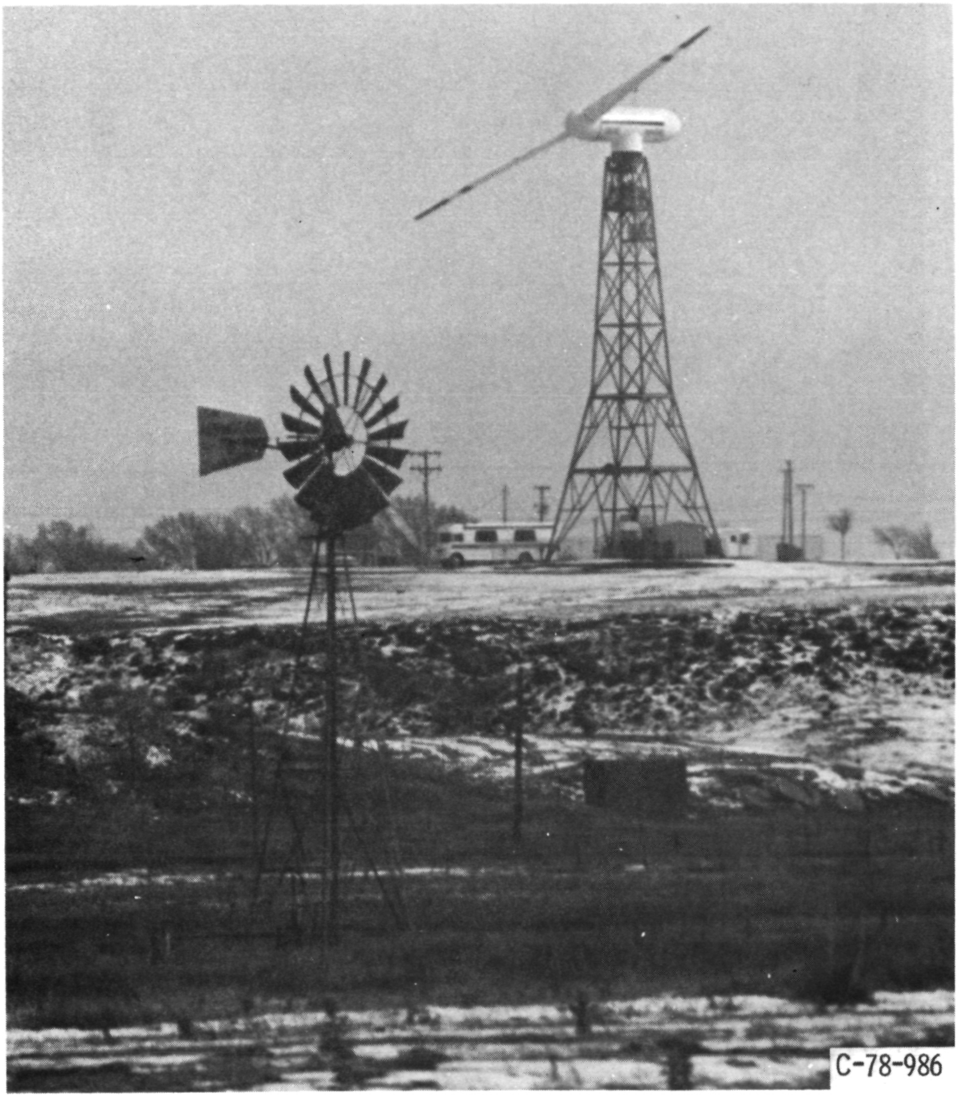


Figure 1. - DOE/NASA 200 kW experimental wind turbine, Clayton, New Mexico.

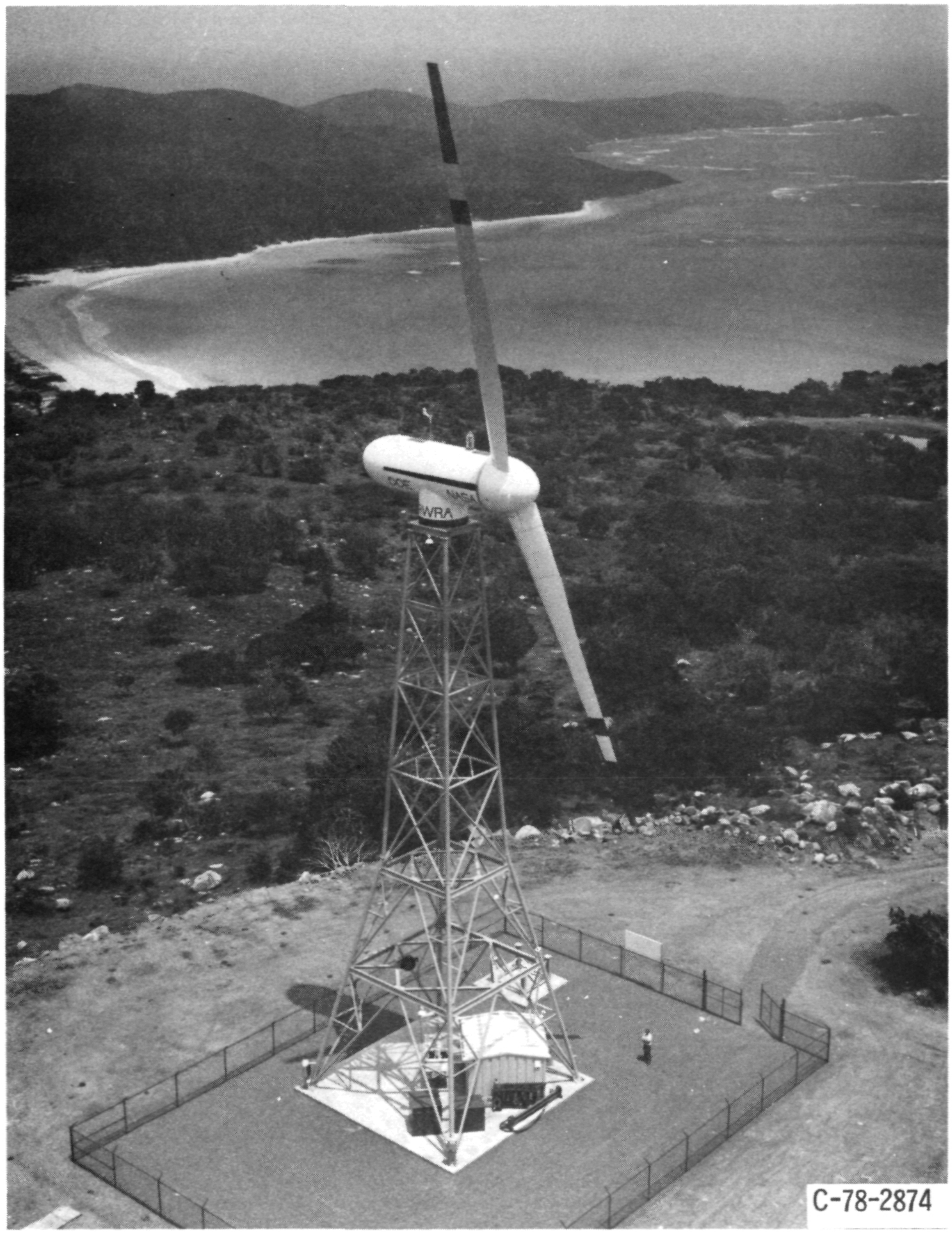


Figure 2. - DOE/NASA/PRWRA 200 kW experimental wind turbine, Culebra Island, Puerto Rico.

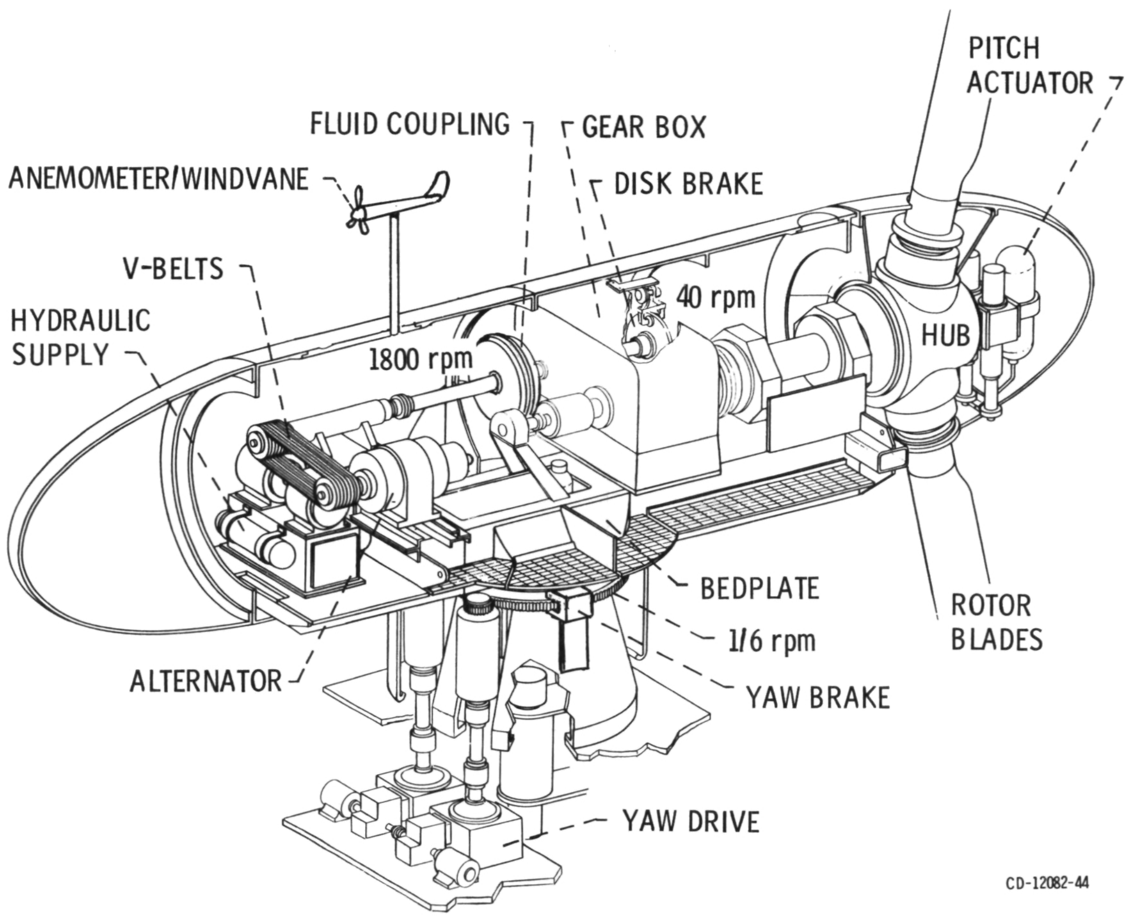


Figure 3. - Mod-0A 200 kW wind turbine - schematic of nacelle interior.

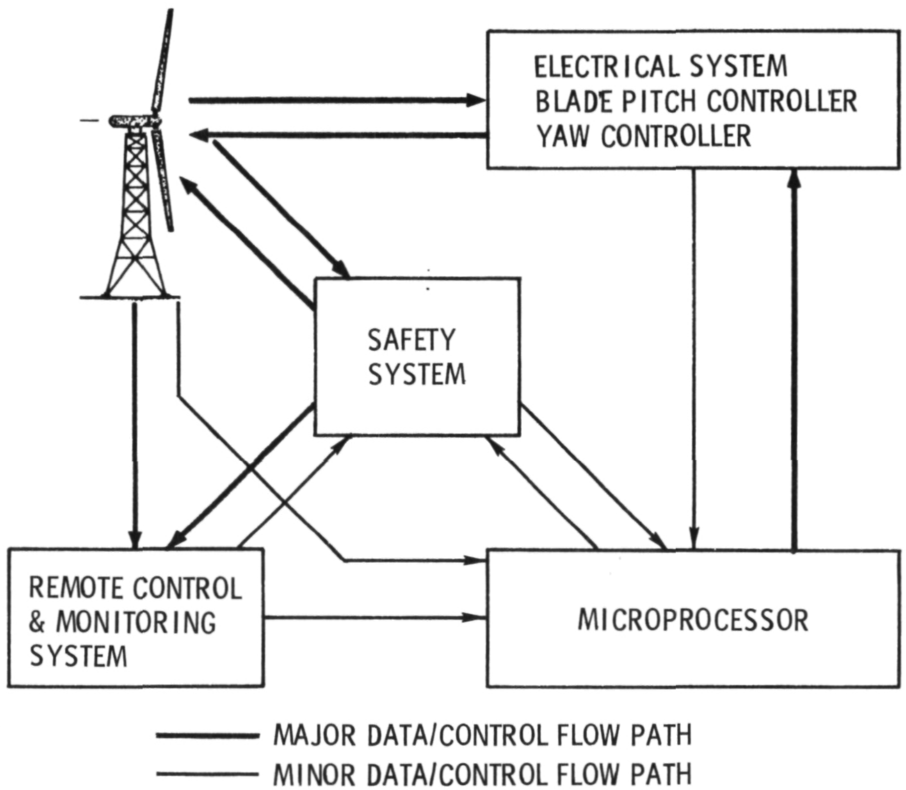


Figure 4. - Wind turbine control system interfaces.

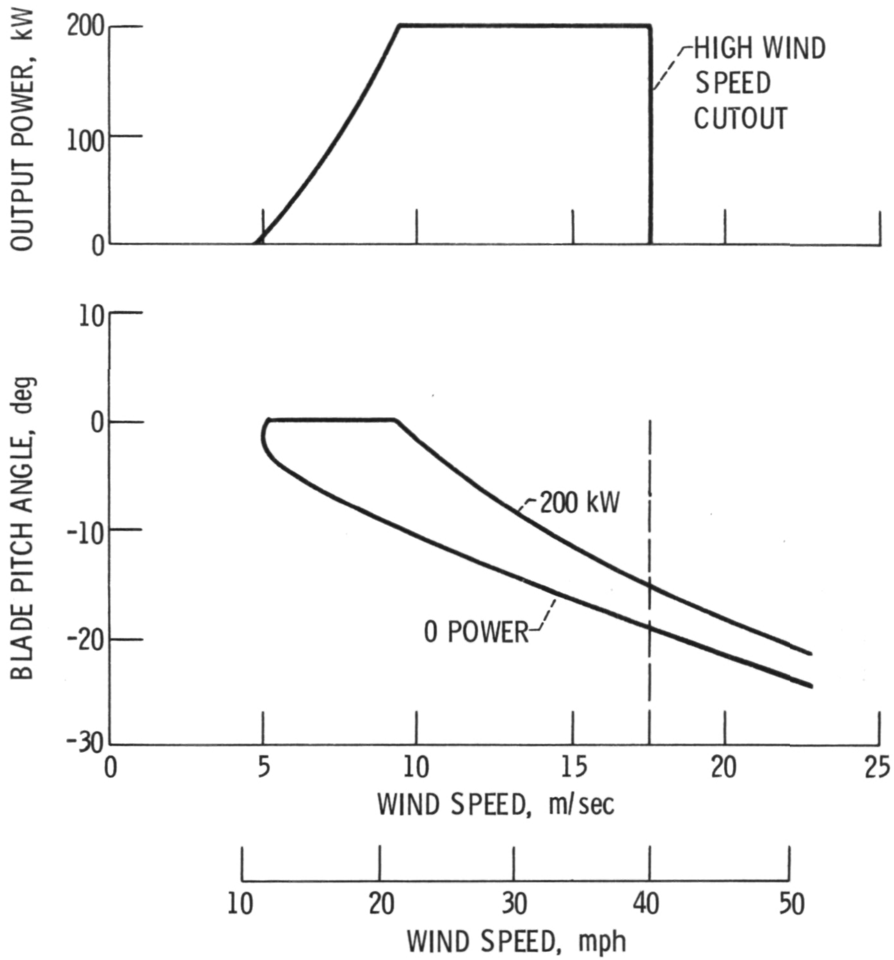


Figure 5. - Mod-0A 200 kW wind turbine power control-output power and blade pitch angle vs wind speed.

START PITCH HYDRAULIC PUMP

RELEASE EMERGENCY FEATHER

INCREASE BLADE PITCH TO START ROTATION

SWITCH TO SPEED CONTROL

INCREASE ROTOR SPEED TO 40 rpm

TURN ON FIELD

SYNCHRONIZE

SWITCH TO POWER CONTROL

INCREASE POWER SET POINT TO 200 kW

Figure 6. - Mod-0A 200 kW wind turbine startup sequence - microprocessor control.

TRANSFER TO PITCH CONTROL

DECREASE BLADE PITCH ANGLE

DESYNCHRONIZE WHEN POWER GOES TO ZERO

TURN OFF FIELD

DECREASE PITCH TO FEATHER POSITION

OPEN EMERGENCY FEATHER VALVE

TURN OFF HYDRAULIC PUMP

Figure 7. - Mod-0A 200 kW wind turbine shutdown sequence - microprocessor control.

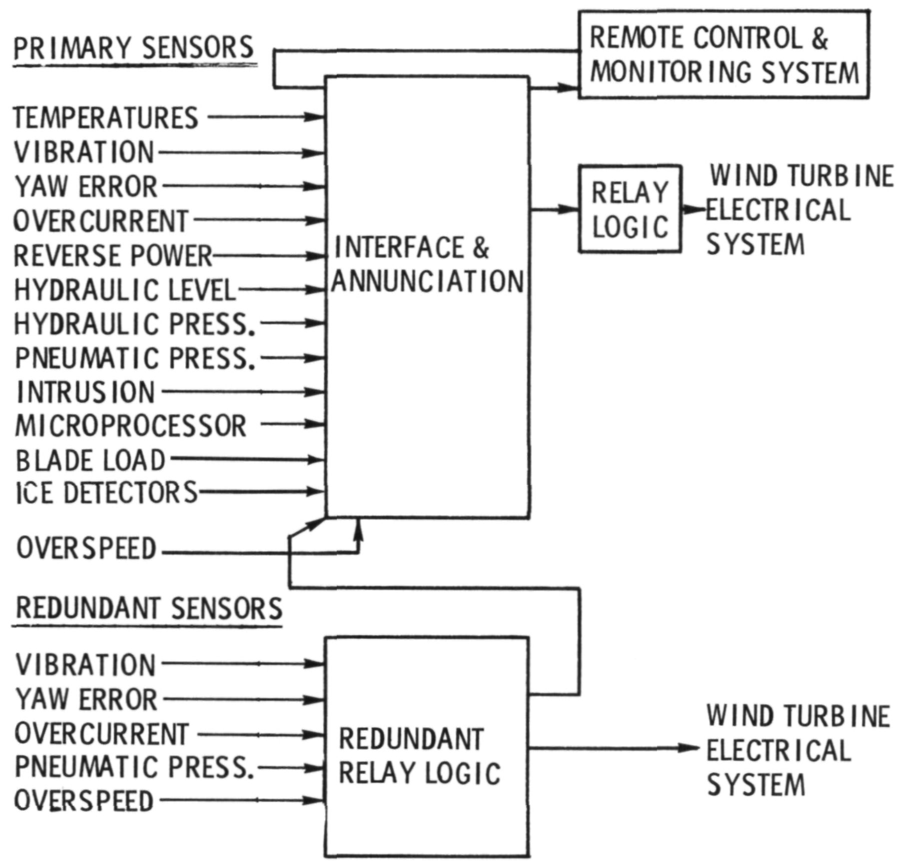


Figure 8. - Safety system block diagram.

Figure 9. - Remote control and monitoring system.

CONTROL LINK

- a) STARTUP & SHUTDOWN THROUGH MICROPROCESSOR
- b) INITIATION OF EMERGENCY SHUTDOWN THROUGH THE SAFETY SYSTEM.

STATUS INDICATOR

- a) WIND TURBINE OPERATING OR SHUTDOWN
- b) SAFETY SYSTEM ERROR CONDITIONS
- c) MICROPROCESSOR OPERATING OR STANDBY.

PERFORMANCE MONITOR

- a) ROTOR SPEED
- b) WIND SPEED
- c) POWER OUTPUT

Figure 10. - Remote control and monitoring system functions.

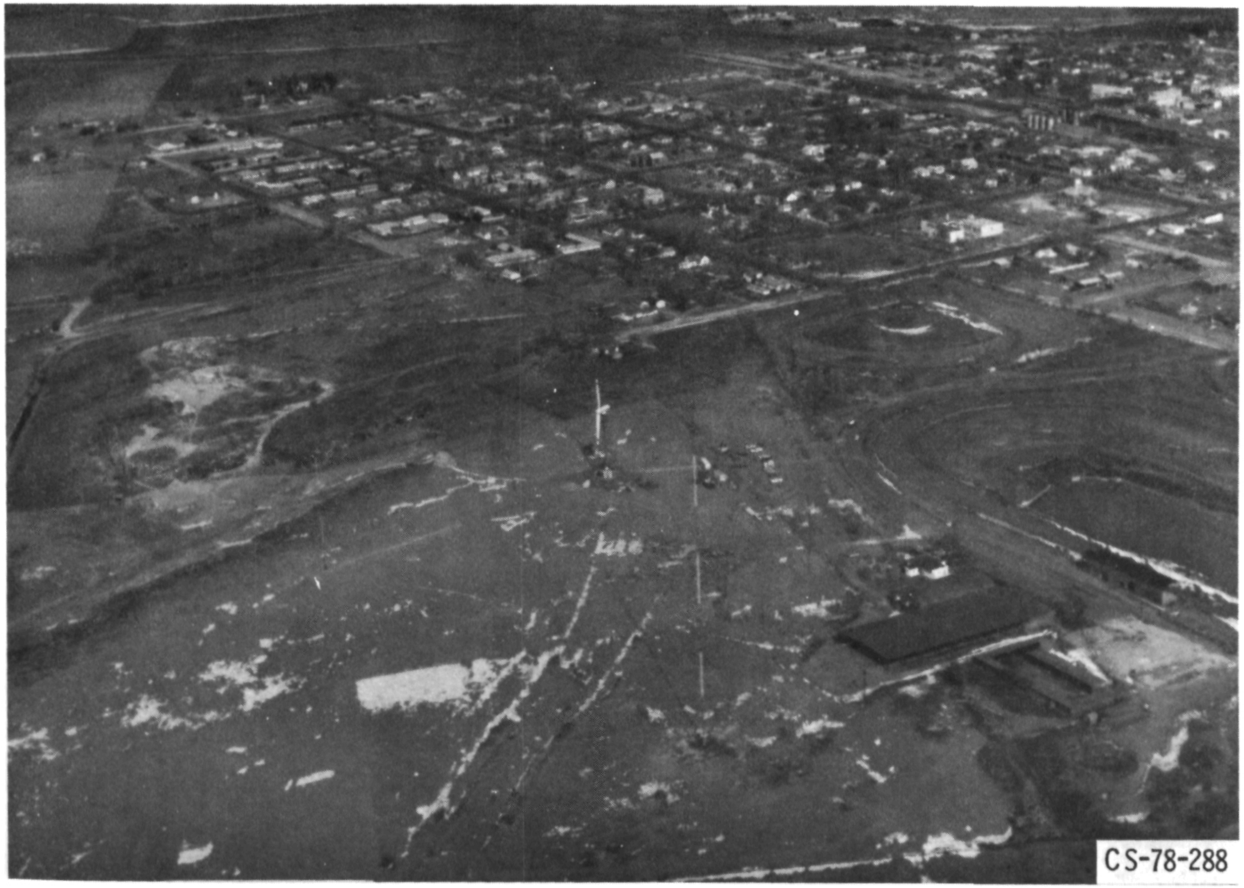


Figure 11. - Clayton, New Mexico with MOD-OA 200 kW wind turbine - center foreground.

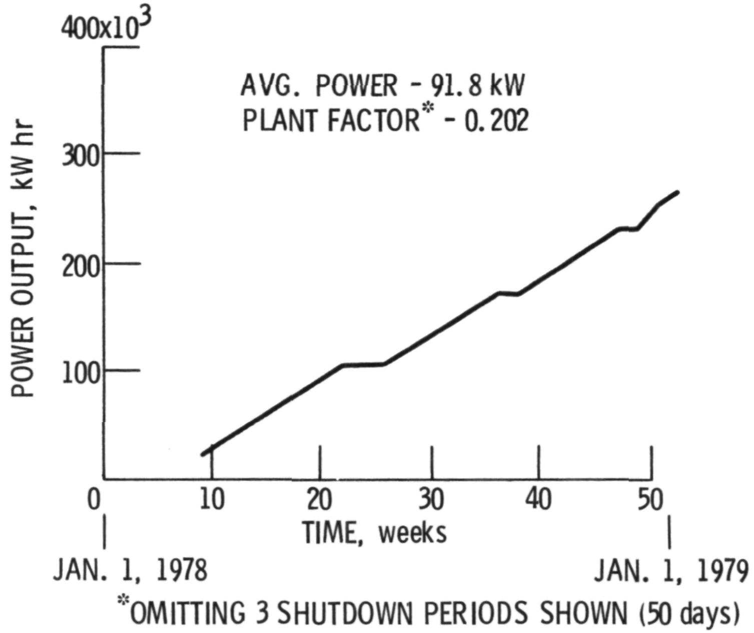


Figure 12. - Mod-0A 200 kW wind turbine power output March 6 - December 31, 1978.

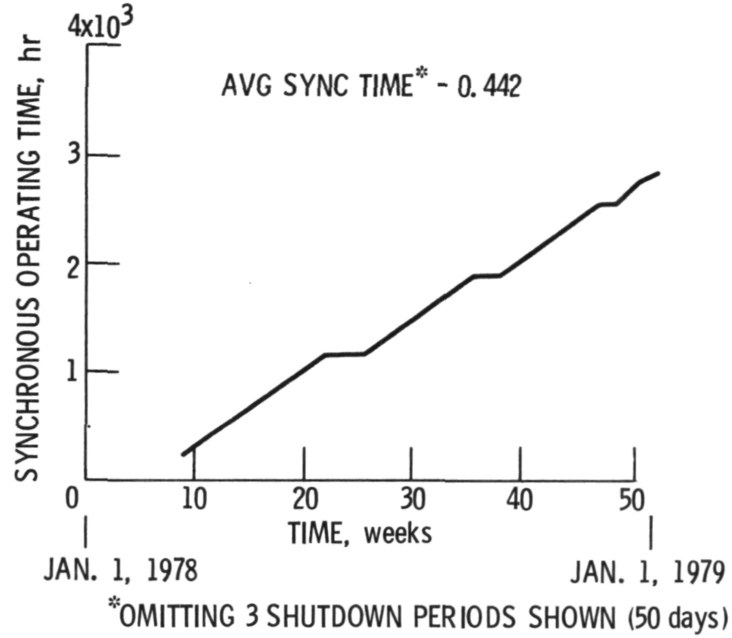
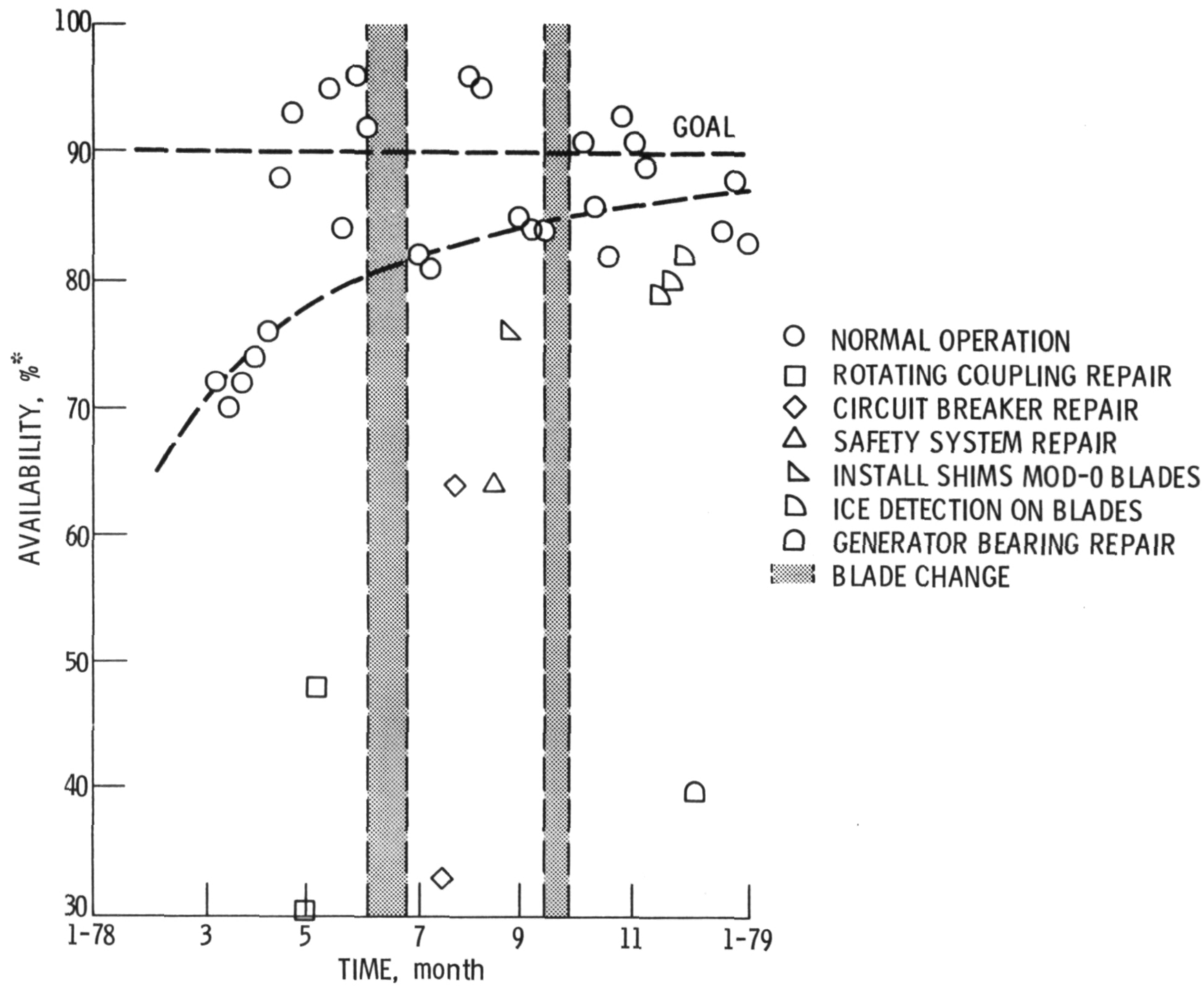


Figure 13. - Mod-0A 200 kW wind turbine synchronous operating time.



$$^{*}\text{AVAILABILITY} = \frac{\text{hr OF SYNCHRONOUS OPERATION}}{\text{hr BETWEEN CUT-IN AND CUT-OUT WIND SPEED}} \times 100$$

Figure 14. - Mod-0A 200 kW wind turbine - 1978 availability, Clayton, New Mexico.

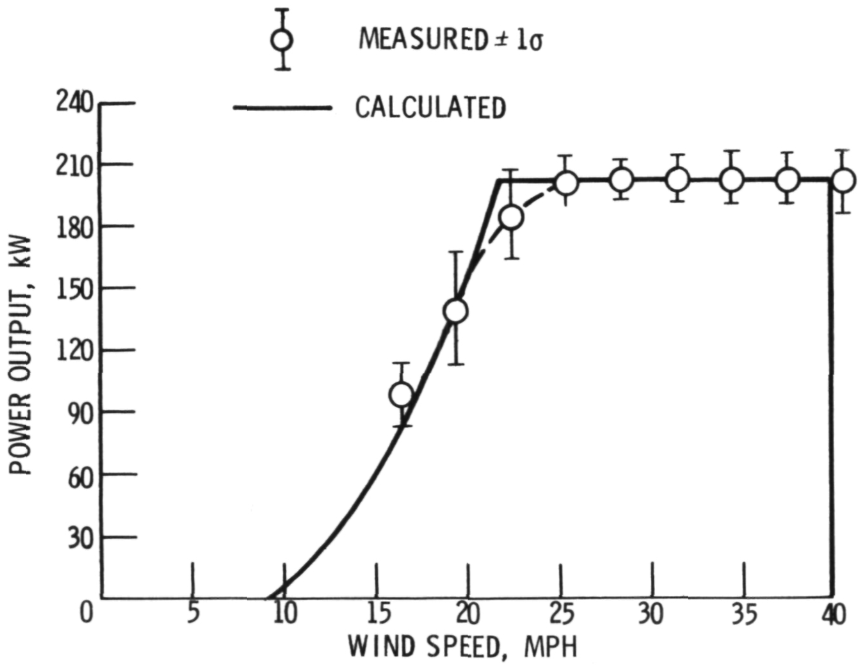


Figure 15. - Comparison of measured and predicted power - Mod-OA 200 kW Wind Turbine, Clayton, NM.

CS-79-588

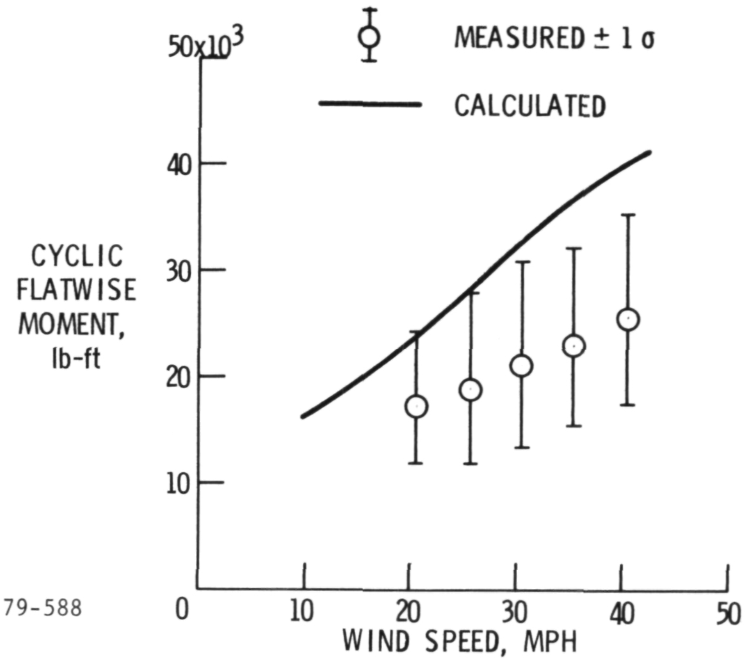


Figure 16. - Comparison of measured and calculated blade loads - Mod-OA 200 kW Wind Turbine, Clayton, NM.

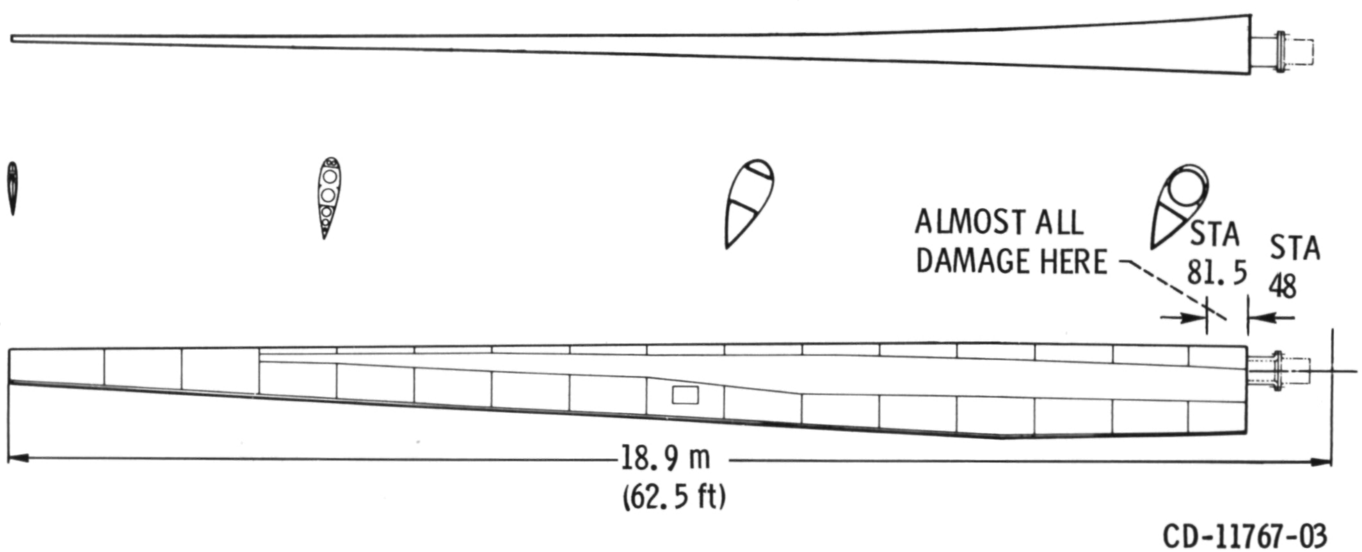


Figure 17. - Rotor blade - 200 kW experimental wind turbine.

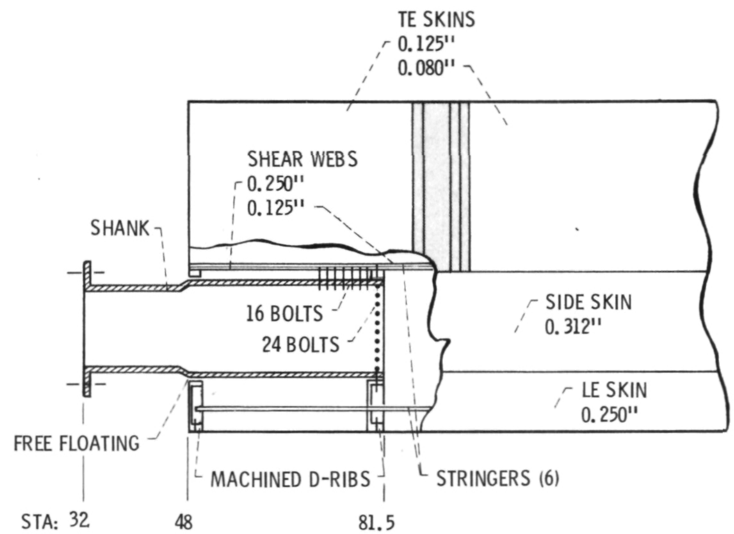


Figure 18. - Mod-0A blade root end.

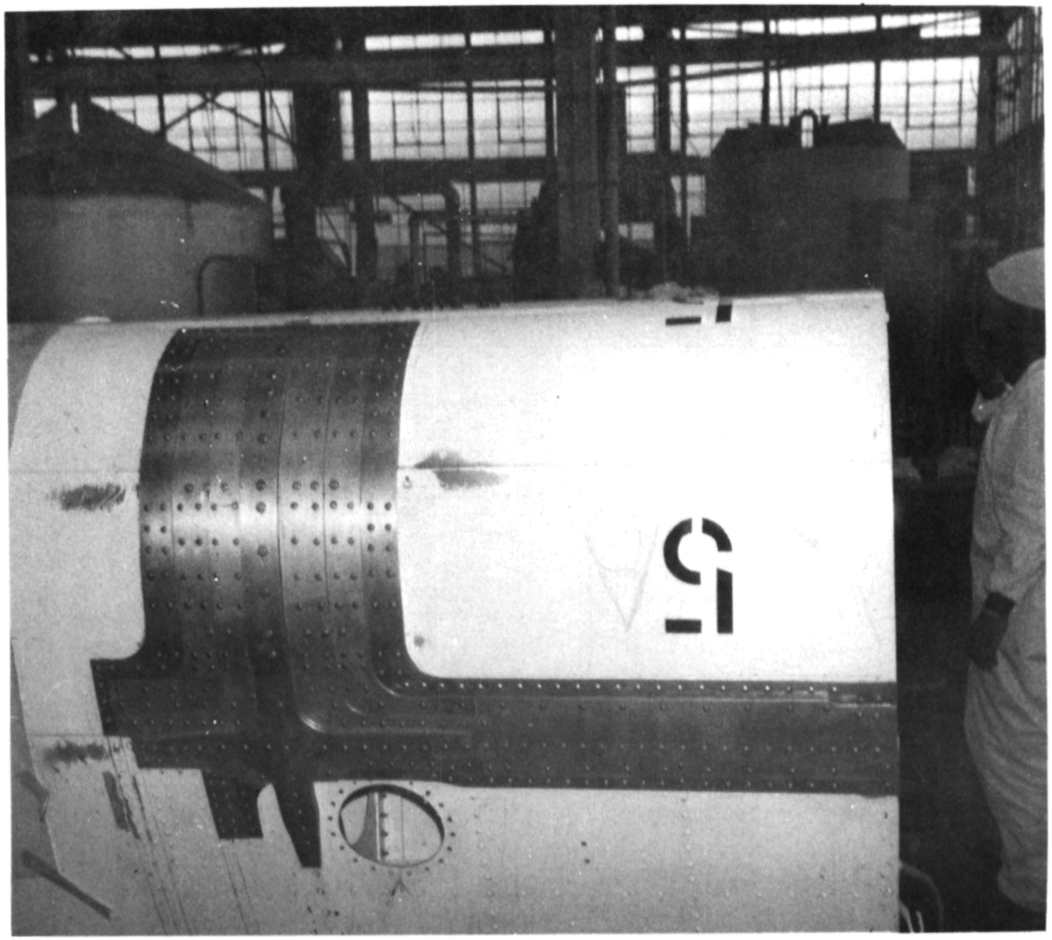


Figure 19. - Final installation of doublers on low pressure side of blade.

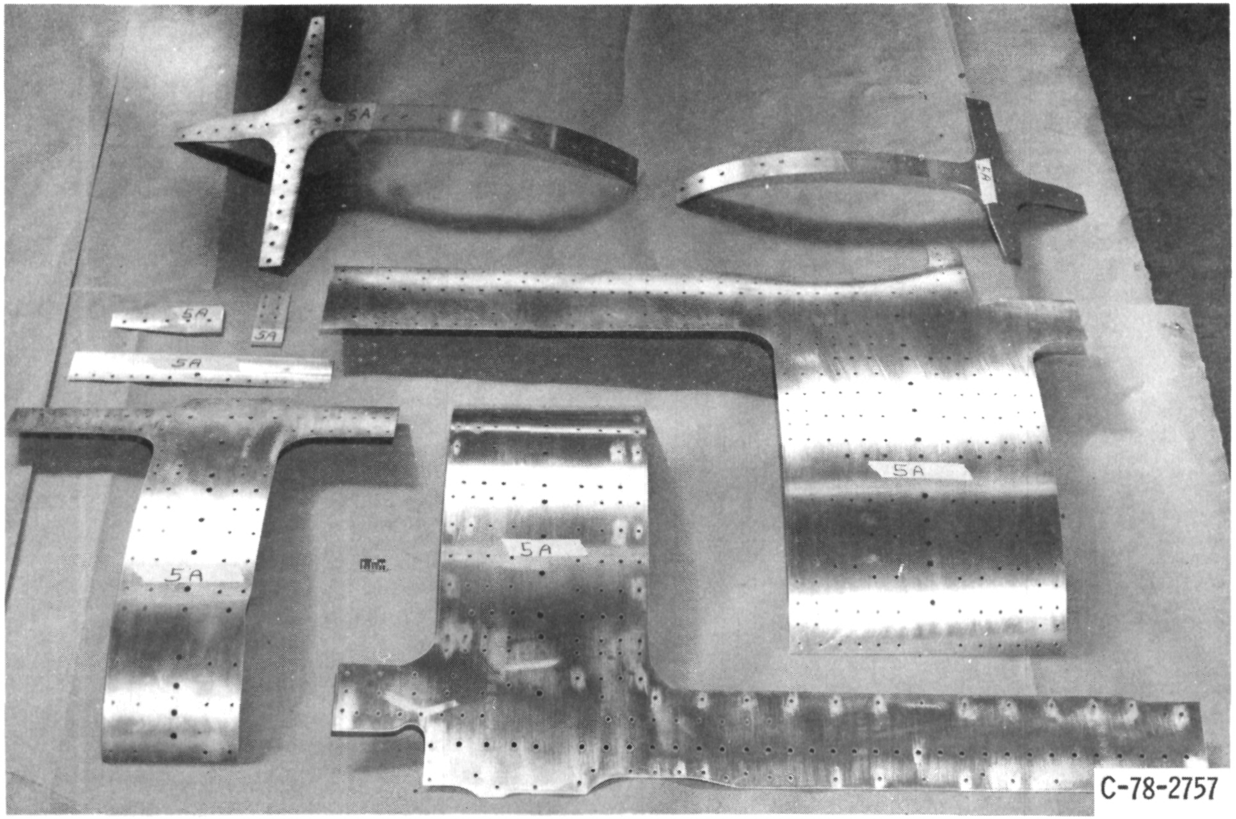


Figure 20. - Doublers before installation on blade.

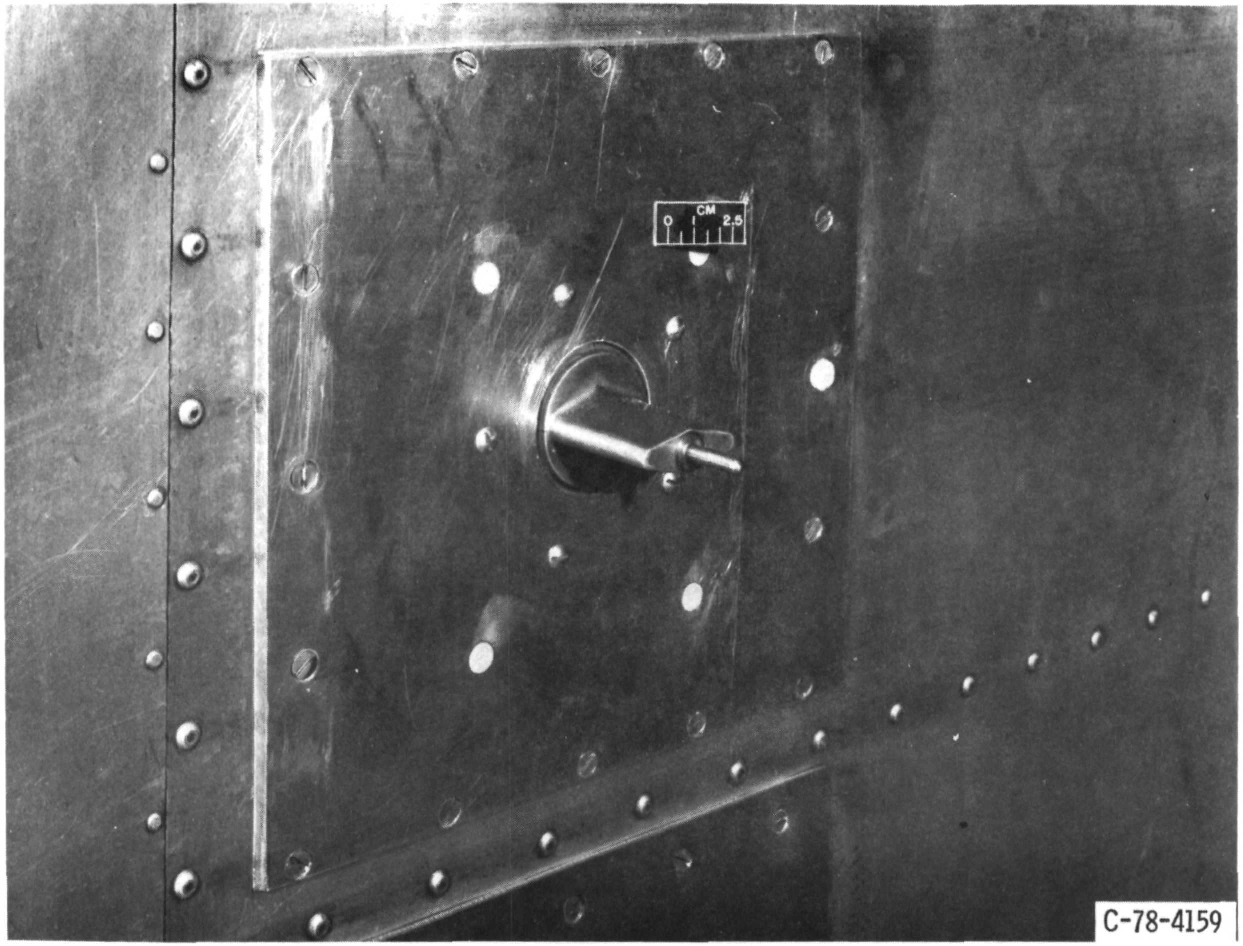


Figure 21. - Ice detector mounted on blade test section.

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16. Abstract

The Mod-0A 200 kW Wind Turbine was designed and fabricated by the Lewis Research Center of the NASA under the direction of the U.S. Department of Energy. The project is a part of the Federal Wind Energy Program and is designed to obtain early wind turbine operation and performance data while gaining initial experience in the operation of large, horizontal axis wind turbines in typical utility environments. On March 6, 1978 the Mod-0A wind turbine was turned over to the Town of Clayton Light and Water Plant, Clayton, NM, for utility operation and on December 31, 1978, the machine had completed ten months of utility operation. This paper describes the machine and documents the recent operational experience at Clayton, NM.

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