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Mod-2 Wind Turbine System Development Final Report

Volume I—Executive Summary

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Boeing Engineering and Construction Company
(Division of The Boeing Company)

September 1982

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-2

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

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Volume II—Detailed Report

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Seattle, Washington 98124

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1.0 INTRODUCTION

This report, Volume I, is the Executive Summary of work performed by Boeing Engineering and Construction, (a division of The Boeing Company), under NASA Contract DEN3-2, of the MOD-2 wind turbine project. Volume II of this documentation is the detailed report of this activity.

Contract DEN3-2, the MOD-2 WTS project, is a continuation of the United States Department of Energy programs to develop and achieve early commercialization of wind energy. The MOD-2 project and its predecessors MOD-0, MOD-0A and MOD-1 are the current DOE programs under the technical management of the NASA Lewis Research Center (LeRC).

The MOD-2 wind turbine system is design optimized for commercial production rates which, in multi-unit installations, will be integrated into a utility power grid and achieve a cost of electricity at less than 4¢ per kilowatt hour in 1977 dollars. Three machines were built under this contract. On site assembly, checkout and acceptance testing have been completed. The machines are currently being placed in unattended operation at the Goldendale, Washington test site as modifications to various subsystems are completed.

2.0 PROJECT BACKGROUND

The MOD-2 wind turbine program was initiated in August 1977 when Boeing Engineering and Construction was awarded the contract for development of a multi-megawatt wind turbine system. This project was a continuation of the U.S. Department of Energy programs which had previously funded development of the experimental MOD-0 machine at the NASA LeRC Test Center at Plum Brook, Ohio; four of the 200 kW MOD-0A machines installed and operated in New Mexico, Rhode Island, Puerto Rico, and Hawaii; and the 2000 kW MOD-1 machine installed in North Carolina. These earlier machines were invaluable in developing the technology required to harness the abundant and renewable energy from winds and provided a database for use in development of the MOD-2. The contract requirements established for the MOD-2 machine were structured to achieve a significant advancement towards early commercial realization of cost competitive electrical energy from wind power.

2.1 PROJECT GOALS AND REQUIREMENTS

Stated in general terms, the DOE/NASA goals for the MOD-2 program were as follows:

- o Provide an economically viable alternative electrical energy system (cost competitive with some conventional fueled power plants) which could reduce the nation's dependency on non-renewable fossil fuel electrical generation systems.
- o Demonstrate feasibility of wind turbines operating in a utility network. The machine must be compatible with utility interface requirements and general utility operations and maintenance practices.
- o Stimulate a wide industry involvement in the development of a commercial business base.

The primary design requirements established by the MOD-2 contract Statement of Work were:

(1) The machine shall produce multi-megawatts at rated power.

(2) The cost of electricity for the 100th production unit, when operated at a site with a mean wind speed of 14 mph, shall not exceed 4 cents per kilowatt hour, based on 1977 dollars.

(3) The machine shall be of the horizontal axis type.

(4) The rotor diameter shall be no less than 300 feet.

(5) The machine shall be compatible with integration into a utility network (including integration of multi-units in a farm concept).

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(6) Design for safe and reliable operation over a period of 30 years.

(7) Design for unattended operation with automatic control for sequencing its operation.

2.2 PROGRAM APPROACH

The generalized program approach was structured as illustrated in Figure 2-1. As shown, this was a phased program with several DOE and NASA reviews and approvals a prerequisite to entering the subsequent phase. In addition to the DOE/NASA review, several utilities were periodically briefed and contributed to the requirements for the interface to the grid and requirements for operations and maintenance.

The most significant phases in terms of establishing the configuration were the Concept and Preliminary Design Phases. The most significant activities in these phases were the trade studies which evaluated design variations and system performance to obtain least cost of electricity. These trade studies, as well as other activities during the Concept and Preliminary Design Phase are detailed in the MOD-2 Concept and Preliminary Design Report. This Final Report focuses on the remainder of the program to the current Operations & Maintenance phase.

The Detail Design Phase developed the production design drawings and all procurement specifications. During this phase, competitive proposals were solicited and evaluated for the selection of major hardware suppliers. Long lead procurement of selected hardware was authorized by NASA prior to completion of the Detail Design Phase.

With NASA approval to enter the Fabrication Phase for three prototype machines, the remaining subcontracts were awarded for major components and procurement of all hardware was initiated.

Following evaluation by NASA of utility proposals, the Bonneville Power Administration (BPA) was chosen to be the operator of the three unit cluster of MOD-2 machines. The machines are installed at the BPA site located in the Goodnoe Hills near the Columbia River Gorge. This site is located near Goldendale, Washington and generated power is fed to the Klickitat PUD utility grid. On site assembly, checkout, and acceptance testing of the three machines have been completed.

The program is currently in the Operations and Maintenance (O&M) phase. This O&M phase has been invaluable in providing engineering data to allow tuning the system for reducing dynamic loads and improving system performance. Component reliability and system maintenance problems are being discovered, evaluated, and improvements incorporated. The system availability is showing marked improvement as initial operational problems are being solved.

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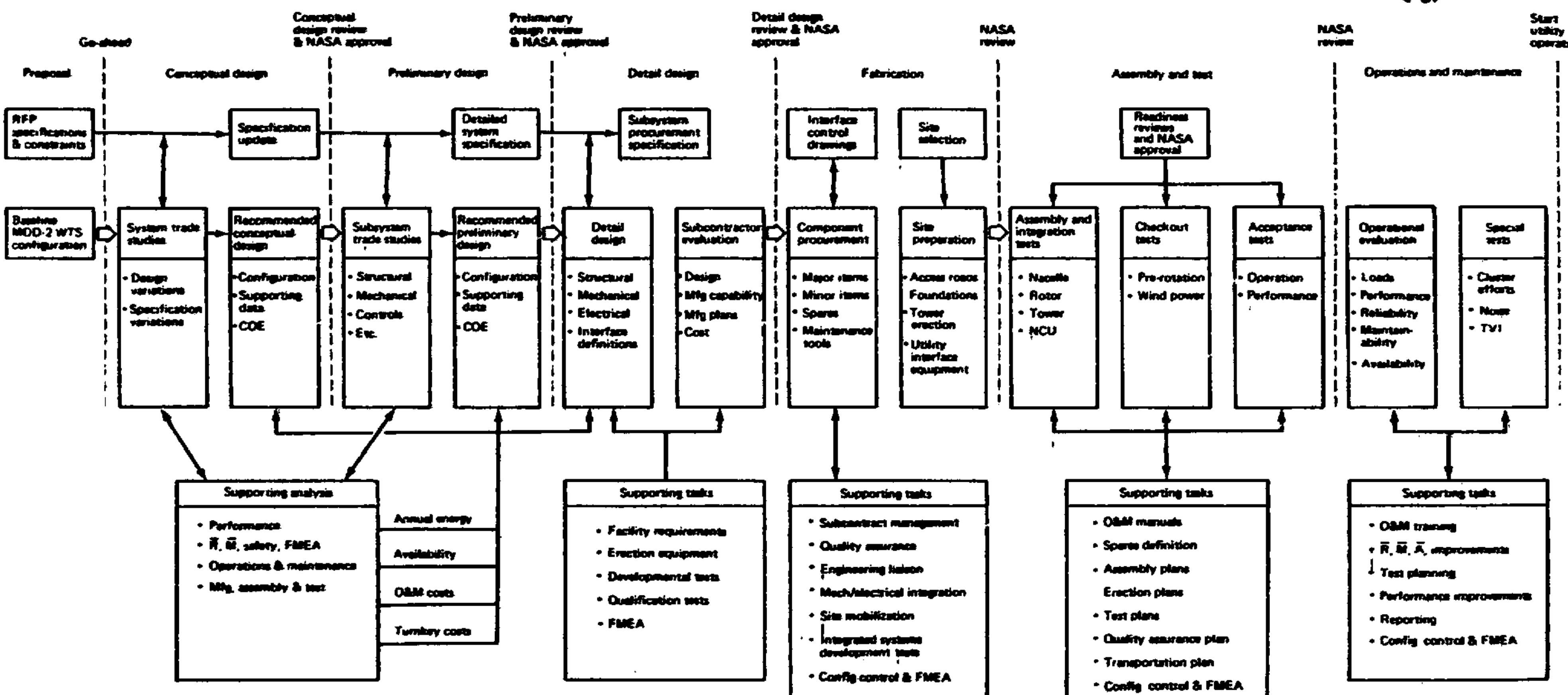

Figure 2-1. Project Approach

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2.3 PROGRAM SCHEDULE

Planned contract schedule milestones were achieved from contract award in August 1977 through the completion of detail design in May 1978.

Following detail design, there were five particularly significant events which led to major program phasing changes. These were:

(1) Site selection and site access delay (1979)

(2) Rotor fabrication slides (mid 1980)

(3) Boilermaker union strike (1980-1981)

(4) Winter weather and low winds (1980-1981)

(5) Major equipment failure of unit No. 1 (1981)

The achieved program schedule is shown in Figure 2.2.

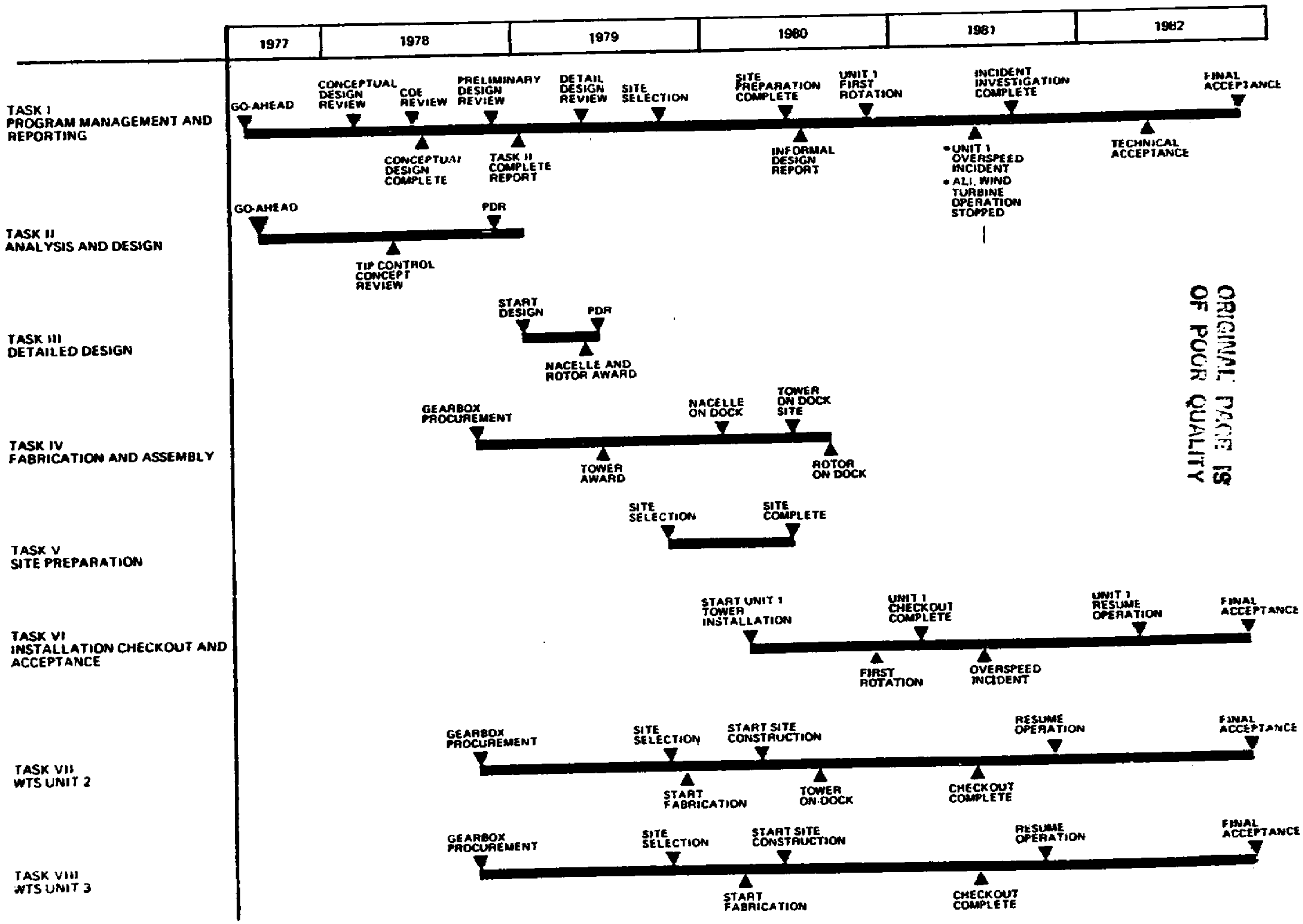


Figure 2-2. As Completed MOD-2 Contract Schedule

3.0 SYSTEM DESCRIPTION

A photo of the Goldendale site is shown in Figure 3-1. The general arrangement and characteristics of the current WTS configuration are shown in Figure 3-2. It is designed for operation at sites where the annual average wind speed is 14 mph measured at 30 feet (20 mph @ hub height). The system generates electricity when the wind speed at hub height (200 feet) exceeds 14 mph. At 27.5 mph and higher (at hub height), the system is designed to produce its rated power of 2500 kW. Above 45 mph (at hub height), the system is shut down to avoid high operating load conditions. The annual energy output at a site with a 14 mph average wind speed is nearly 10 million kWh. This energy output combined with an estimated 100th production unit turnkey cost of $1,710,000 (in 1977 dollars) results in a predicted cost of electricity of 3.3¢/kWh at the bus bar. During operation, the wind turbine is tied to the utility's power grid through standard transmission lines.

The WTS is a horizontal axis machine utilizing a 300 foot diameter partial span control, upwind rotor. The rotor's center of rotation is 200 feet above ground level. It is coupled to the low speed shaft through an elastomeric teeter bearing. A 2500 kW synchronous generator is driven via a step-up planetary gearbox and "soft" quill shaft. The generator, gearbox, hydraulic systems, electronic controls and other support equipment are enclosed in a nacelle mounted atop a cylindrical steel tower. The nacelle can be yawed (rotated) to keep the rotor oriented correctly into the wind as the wind direction changes. A hydraulic pitch control system is used to control the position of the movable rotor tips. The movable rotor tips are used to obtain a constant rotational speed of 17.5 rpm, and to maintain the proper power output at wind speeds above rated wind speed (27.5 mph @ hub), and to provide for shutdown by feathering of the rotor tips.

The WTS is controlled by an electronic microprocessor. The microprocessor is designed to allow unattended operation of the WTS at a remote site by monitoring wind conditions and the operational status of the wind turbine. Equipment failures result in automatic safe shutdown of the WTS. The system status is monitored at the utility substation, from which maintenance crews are dispatched as needed.

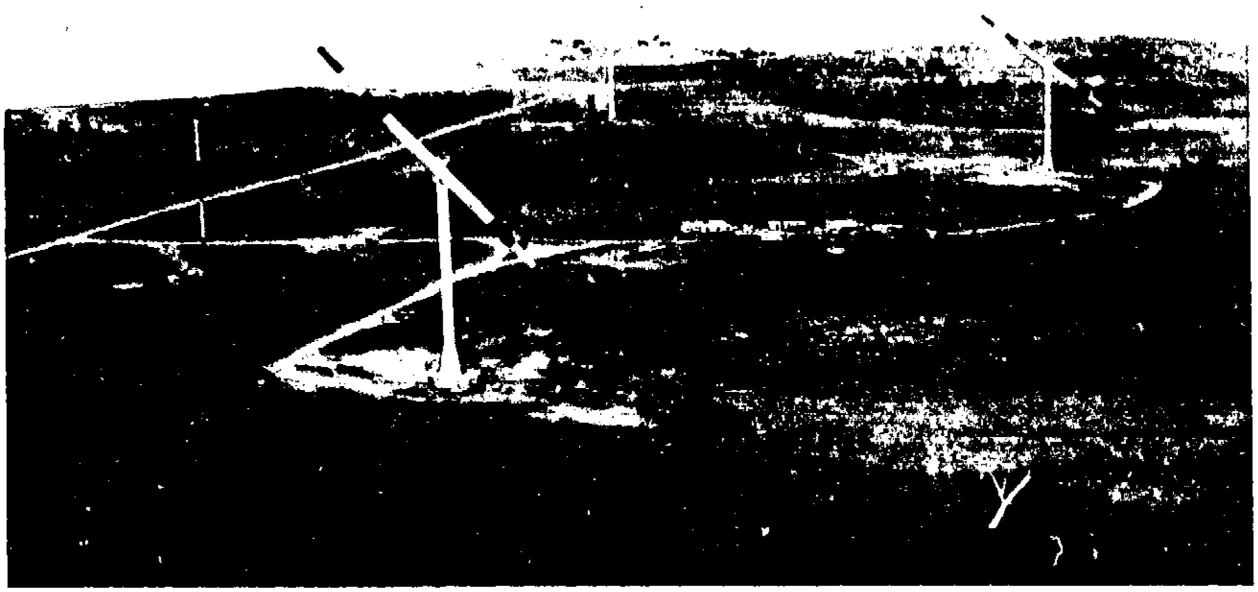
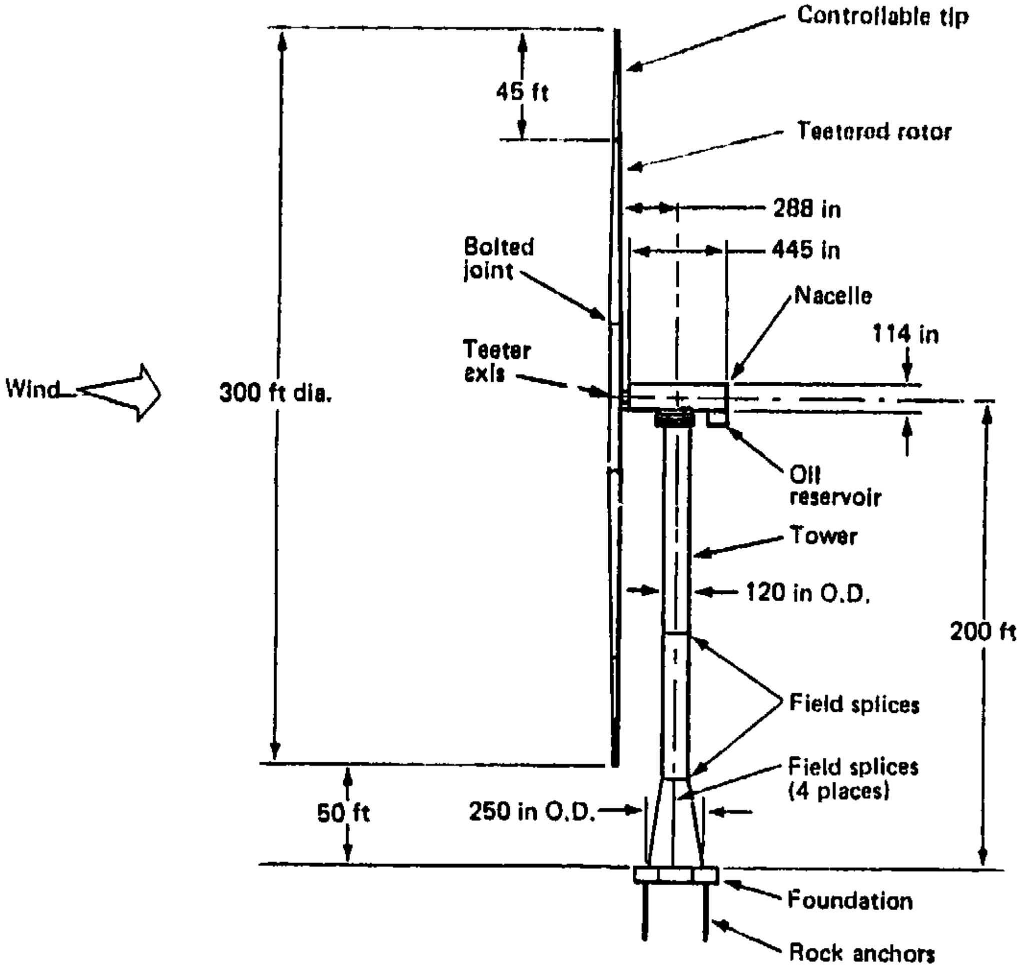


Figure 3-1. Goldendale Site



Rated power	2,500 KW
Rotor diameter	300 ft
Rotor type	Teetered - tip control
Rotor orientation	Upwind - 2.5° tilt
Rotor airfoil	NACA 230XX
Rated wind @ hub	27.5 mph
Cut-off wind speed @ hub	45 mph
Rotor tip speed	275 ft/sec
Rotor rpm	17.5
Generator rpm	1,800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height	200 ft
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient (max)	0.382

Figure 3-2. Configurations Features and Characteristics

4.0 Test Program

Development and fielding of the MOD-2 WTS has required considerable testing to establish design criteria, provide data for checkout and acceptance, and establish turbine performance. The following paragraphs provide a summary of the testing completed during the MOD-2 program.

4.1 Developmental Tests

Developmental tests were conducted to verify strength, fatigue capability, and operational characteristics of components to verify they would perform in the wind turbine design environment and meet the 30 year time between failure requirements. Development tests conducted, their purpose and results are summarized in Table 4-1.

4.2 Integration, Checkout and Acceptance Tests

A flow chart of the testing completed on the MOD-2 to verify system integrity determine system performance and compliance with contract requirements is shown in Figure 4-1.

4.2.1 Integration Testing

Integration testing is that system and subsystem testing conducted on each wind turbine prior to initial wind powered rotation. As shown in Figure 4-1 integration tests were performed on main subassemblies prior to installation on the WTS to ensure all components within the subassembly were functional. After the WTS was completely assembled the system was tested to verify proper interconnection of the subassemblies.

4.2.2 Checkout and Acceptance Testing

After integration testing was complete a test readiness review was held to assure all necessary tests had been completed prior to initial wind-powered operation. Following this review, the system was operated under wind power and the system checkout test completed to verify all subsystems were functioning properly. At the completion of checkout testing, a configuration review was held to review data obtained and changes made to the system during the checkout tests. The turbine then entered the acceptance test phase where system compliance with contract requirements was verified.

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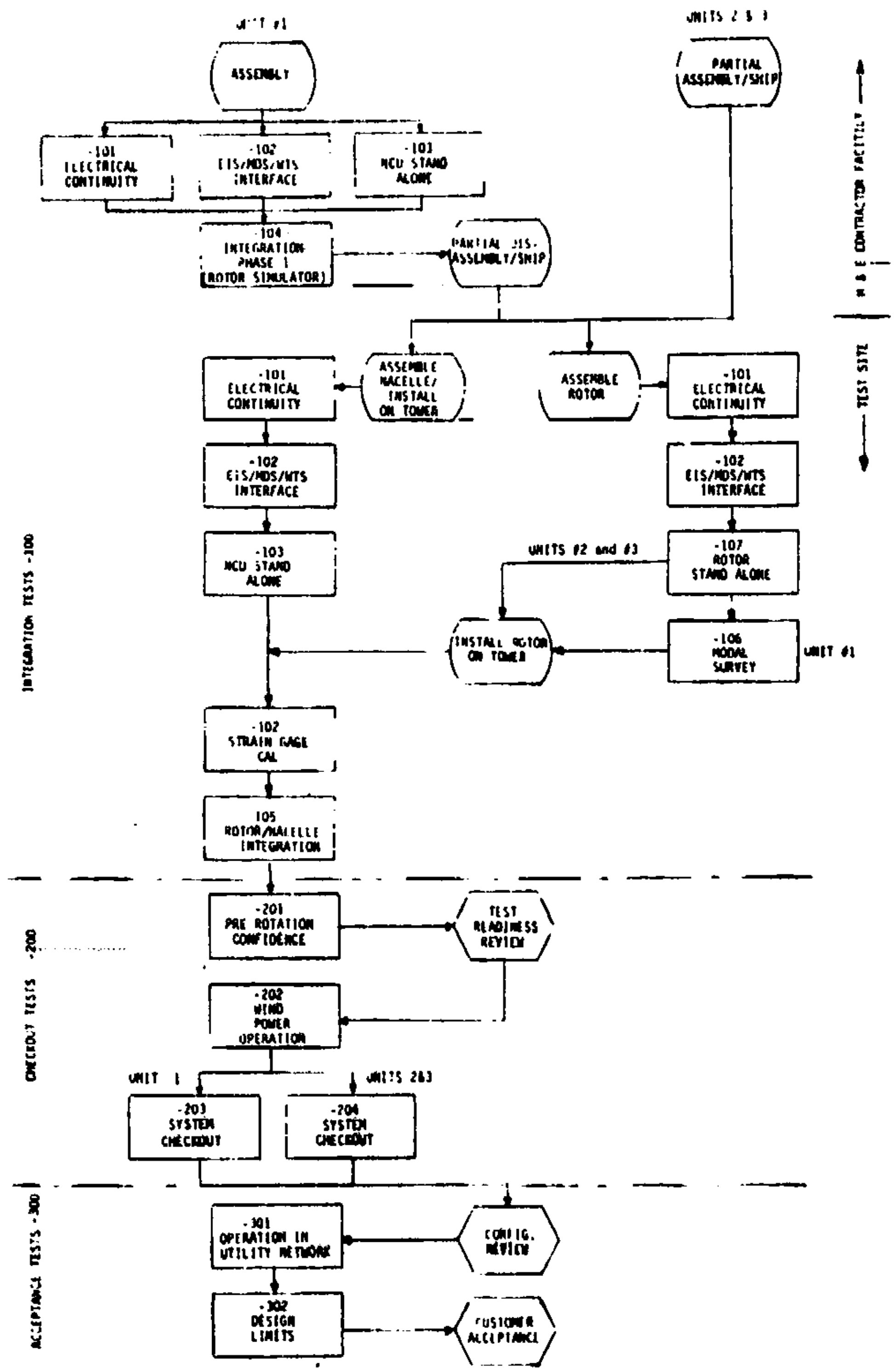

Figure 4-1. MOD-2 WTS Test Flow

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Table 4-1. Development Test Summary

TEST	PURPOSE	RESULTS
Crack Detection System	Verify crack detection system could reliably detect cracks prior to their reaching critical length.	Design verified after minor improvements.
Rotor Field Joint	Validate joint design for highly stressed fatigue loading.	Good correlation between predictions and results, joint design validated.
Rotor Spindle	Substantiate structural integrity of rotor blade spindle and supporting structure.	Good correlation between predicted and measured loads. Design life of 30 years demonstrated by accelerated life testing.
Pitch Control	Functional test of hydraulic swivel and frequency response of hydraulic system.	Design verified and frequency response data obtained.
Teeter Bearing	Qualification of bearing design and verification of fatigue capability.	Qualification of bearing for 30 year life. (200×10^6 cycles).
Back to Back Gearbox	Verify predicticted capabilities of gearbox.	Minor rework of some gear lead correction angles and substantiation of fatigue capabilities up to 155% of rated torque.
Materials Testing	Develop fatigue allowables for materials at 2×10^8 cycles.	Fatigue allowables developed.
Modal Survey	Verify predicted system design frequencies.	Good correlation between actual and predicted data.

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5.0 INITIAL OPERATION

This section discusses the performance of the MOD-2 WTS during its initial operating period. Information presented on system performance and loads is based on data gathered from January 1981 through mid May 1982. Availability and maintenance experience data covers the period January 1981 through early June 1982.

5.1 System Performance

The typical power variation with wind speed for Unit #3 is shown in Figure 5-1. This is typical for the three MOD-2 units at Goldendale, Washington. The power shown in Figure 5-1 was measured at the generator output terminals and the wind speed was measured at the 195 ft. level of the BPA meterological tower on the site.

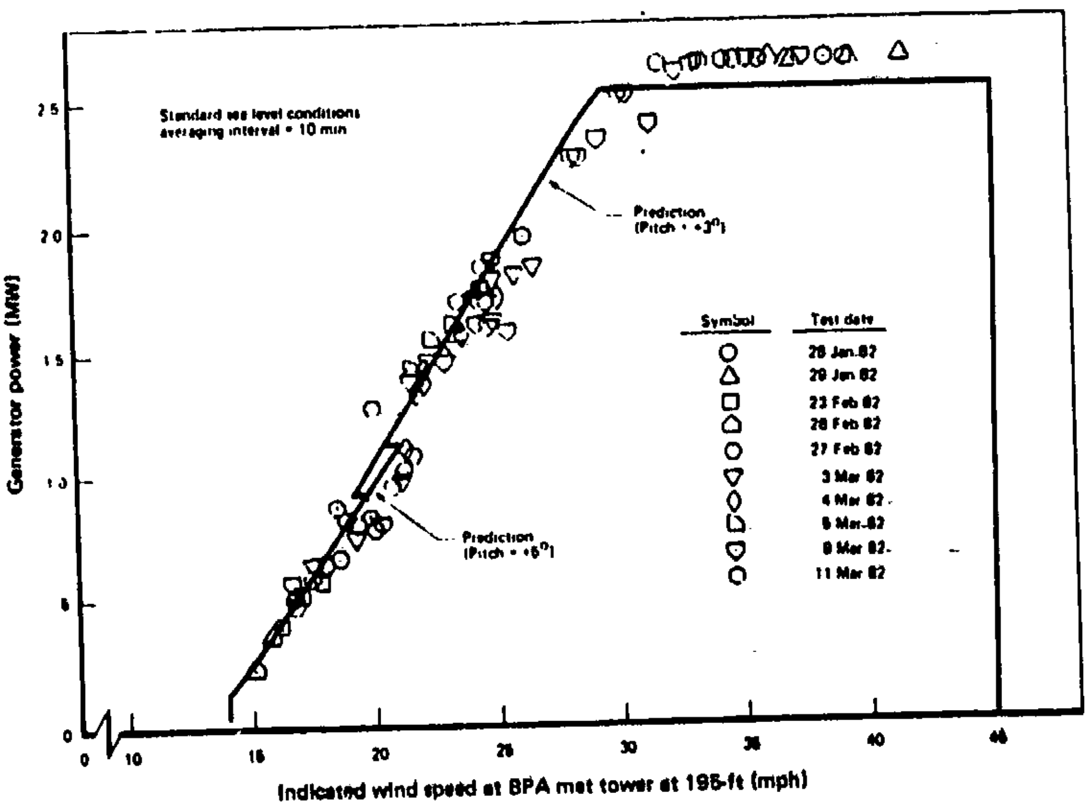

Figure 5-1. Performance Curve for MOD-2 (WTS Number 3)

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The drive train losses for the MOD-2 wind turbine are shown in Figure 5-2. This data was obtained by comparing the power transmitted through the quill shaft with the power delivered at the generator terminals.

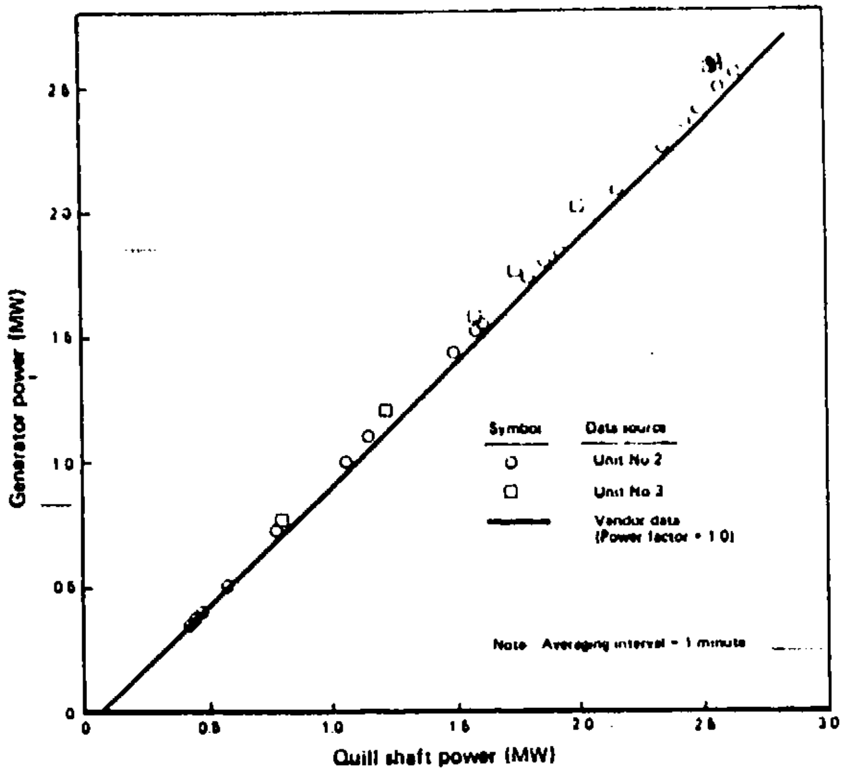

Figure 5-2. MOD-2 Electrical/Mechanical Losses Between Rotor and Generator

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The time during startup for the rotor to reach 17.5 rpm after the rotor brake is released is shown versus wind speed in Figure 5-3. The data shows considerable scatter because of the difficulty in accurately measuring average wind speed during the startup period. However, the average of the data is better than predictions.

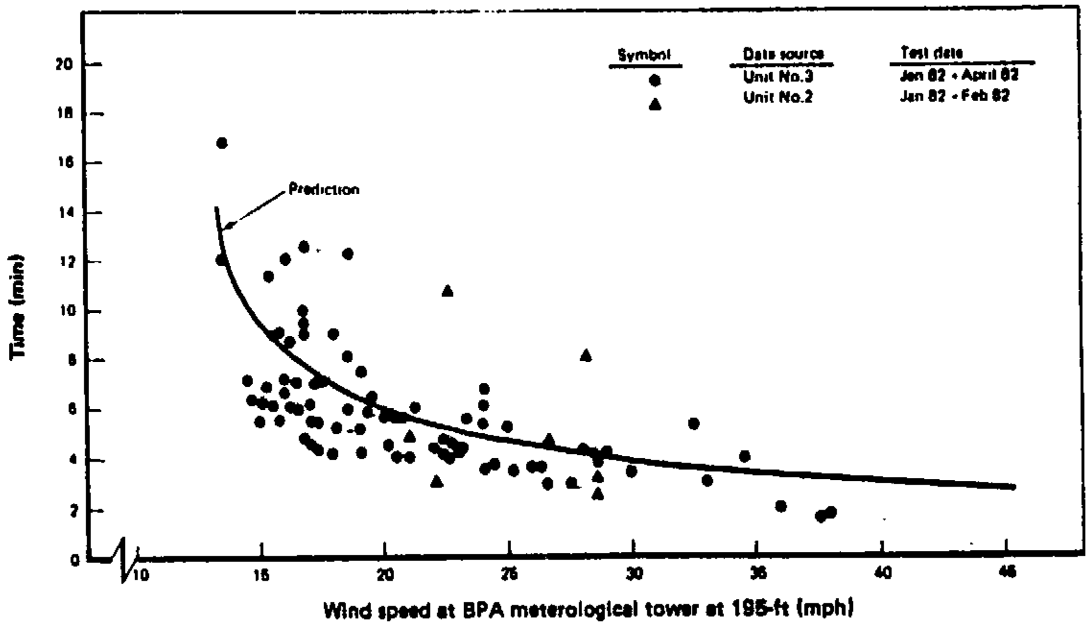

Figure 5-3. Time from Breakaway to Synch, Enable

5.2 Loads and Fatigue Analyses

A primary goal of the MOD-2 acceptance test program was to gather sufficient data for determination of the loads on critical WTS structures and their structure fatigue life. The term fatigue life when applied to the rotor and tower structure is actually the mean time between repairs. When a fatigue crack develops in either of these structures, it can be repaired and the structure returned to service. This section summarizes the results of this effort.

5.2.1 Rotor Analysis

After intial operation of the units at Goldendale, it became apparent that the mean flapwise and chordwise bending moments on the rotor were close to their predicted values. However, the cyclic flapwise bending moments were more severe than predicted.

The measured mean flapwise bending moments at station 370 and 1164 on unit #3 are compared with design loads in Figure 5-4 and 5-5 respectively. The design loads were based on the MOSTAB computer program developed by NASA. Loads predictions of the GEM computer program are shown for reference. Similar data was collected for units #1 and #2.

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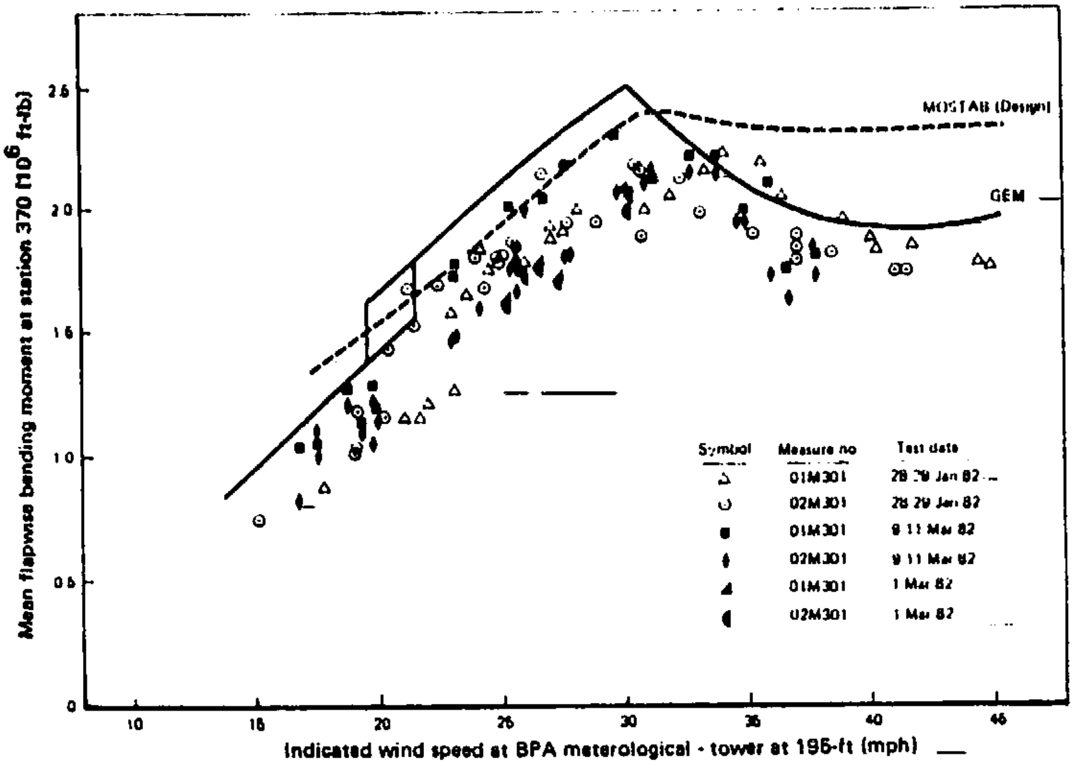

Figure 5-4. Mean Flapwise Bending Moment at Station 370 (WTS Number 3)

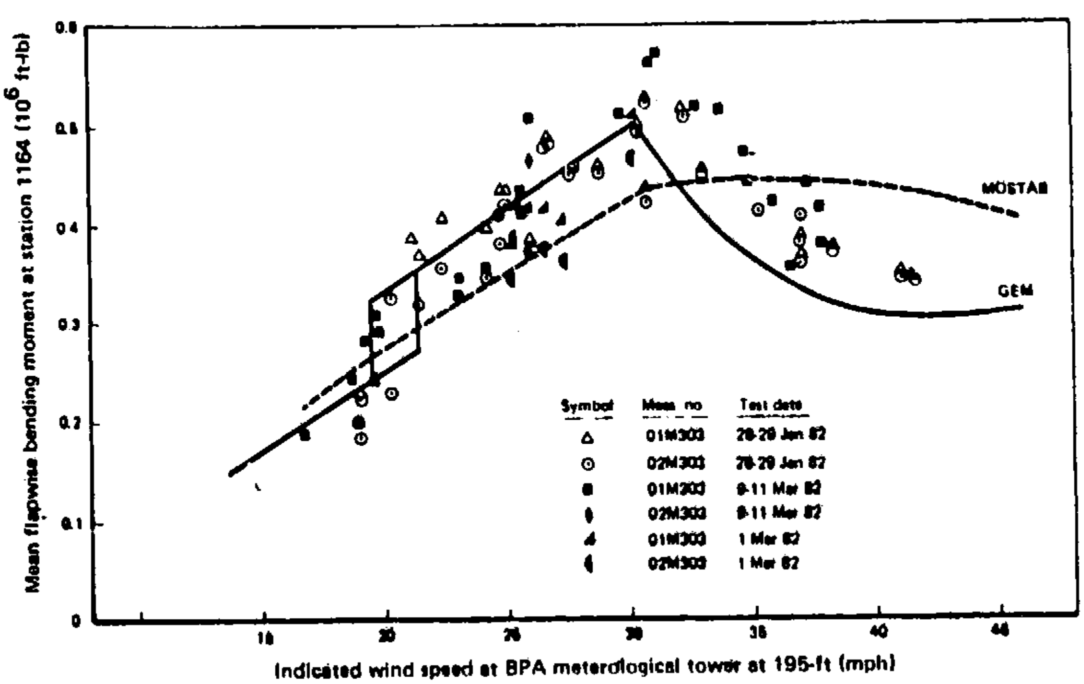

Figure 5-5. Mean Flapwise Bending Moment at Station 1164 (WTS Number 3)

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The cyclic flapwise bending moments at stations 370 and 1164 for unit #3 are shown in Figure 5-6 and 5-7 respectively.

To determine the cumulative probability of cyclic flapwise moments, the above test data was combined with the Weibull wind speed frequency distribution shown in Figure 5-8. These cumulative probabilities are shown in Figure 5-9 and 5-10 for stations 370 and 1164 respectively. Based on these data, a summary of the fatigue life analysis is shown in Table 5-1. This analysis is based on a flaw size-of 0.05 inches deep by 0.25 inches long. Actually the weld inspection criteria was to detect and repair all flaws greater than 0.05 in. deep by 0.125 in. long. Table 5-1 indicates that most critical areas of the rotor achieve 30 year life for flaws which should have been detected and repaired during inspection.

As shown in Figure 5-8, the Goldendale wind frequency distribution is considerably less severe than the specified Weibull distribution. Table 5-2 summarizes the fatigue life in this Goldendale environment.

The less severe environment at Goldendale dramatically reduces the number of rotor areas with negative margins. For the worst area (Station 363), the 30 year flaw size is 0.030 in. deep by 0.150 in. long. If the inspection/acceptance criteria was successful in detecting and repairing defects greater than 0.125 in. the rotor should have a 30 year life at Goldendale if the "out-of-contour" stresses are low. If the "out-of-contour" stresses are high and defects are present in the high stress area, or if defects larger than 0.125 inches were missed, then there will be inservice repairs. Repairs can be made before the crack grows to critical length because the rotor crack detection system will initiate a shutdown and indicate the presense of a crack. The rotor is therefore a failsafe structure and the fatigue life predicted is actually time between anticipated repairs.

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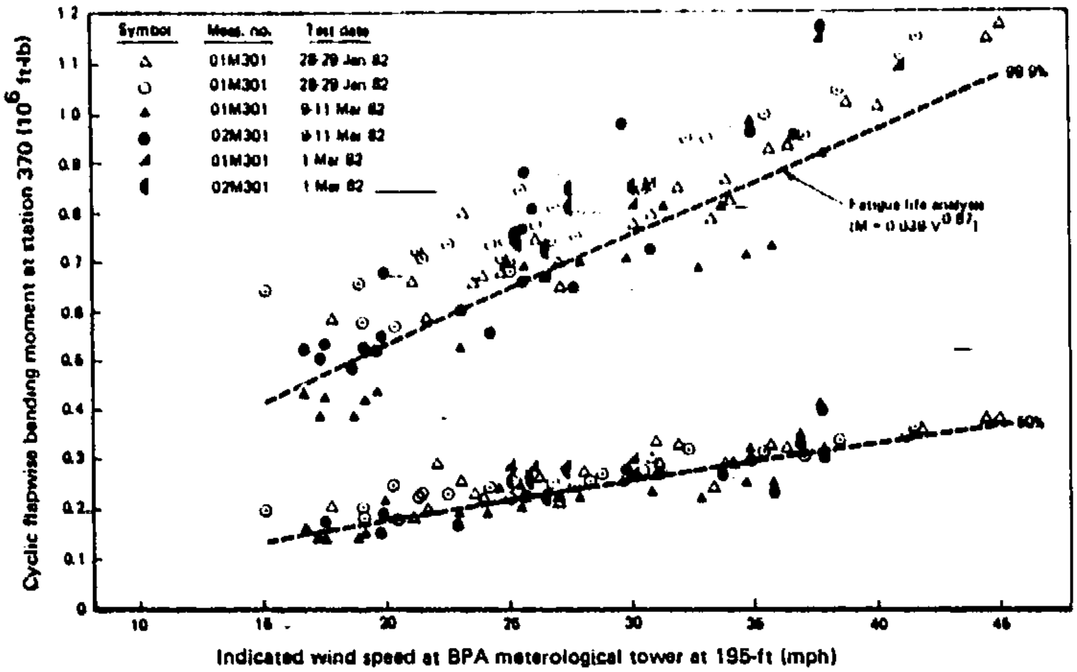

Figure 5-6. Cyclic Flapwise Bending Moment At Station 370 (WTS Number3)

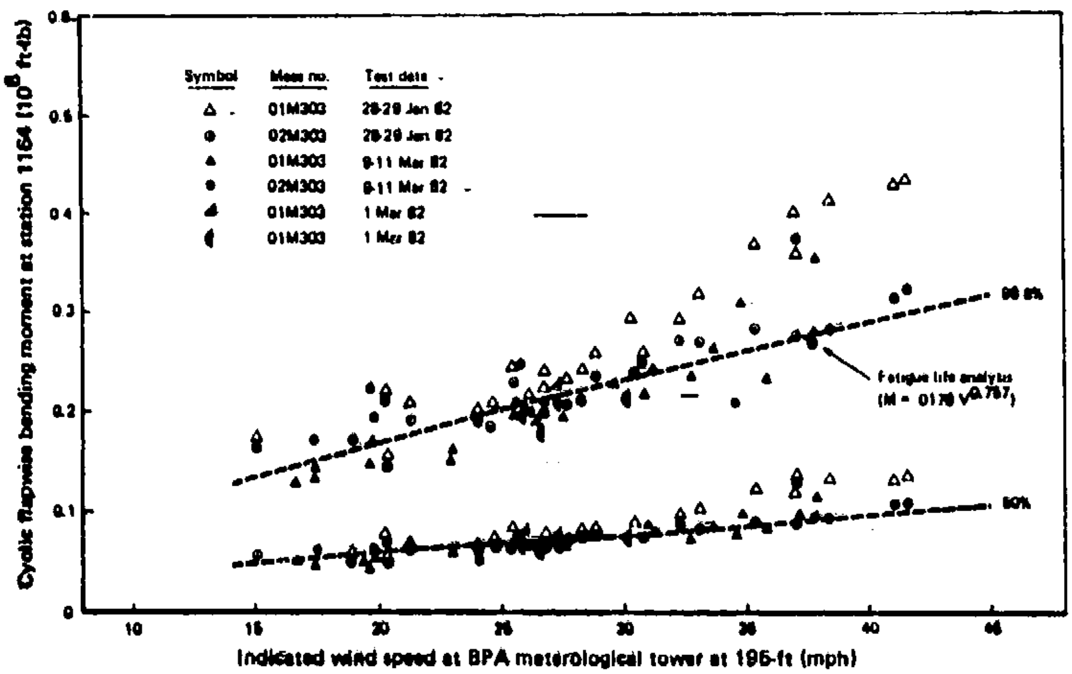

Figure 5-7. Cyclic Flapwise Bending Moment at Station 1164 (WTS Number 3)

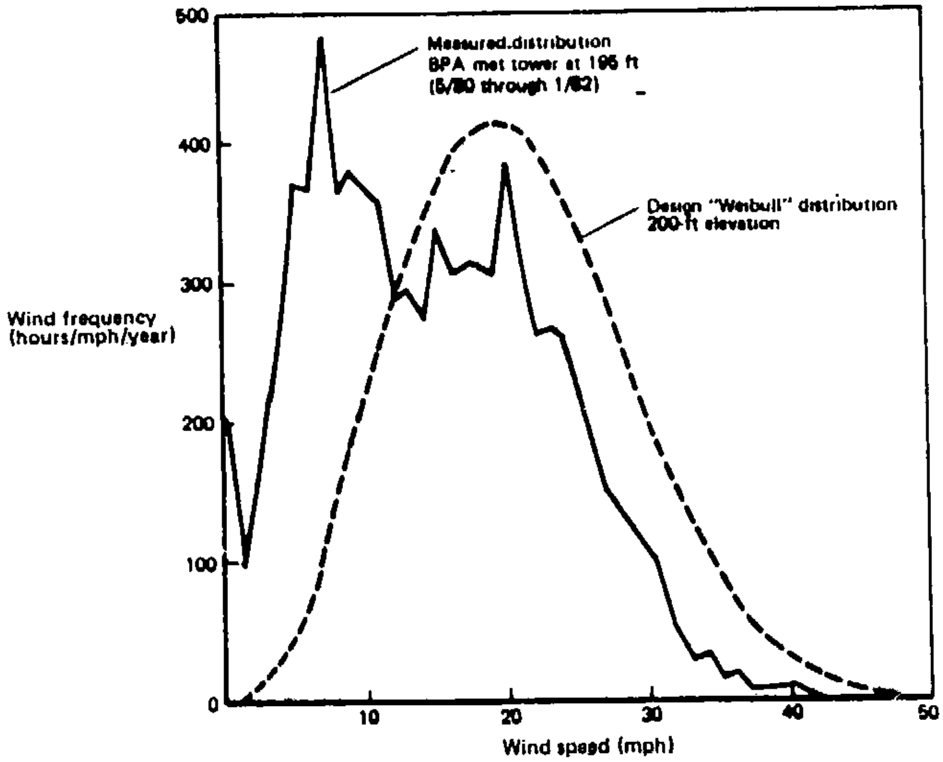

Figure 5-8. MOD-2 Wind Speed Frequency Distribution

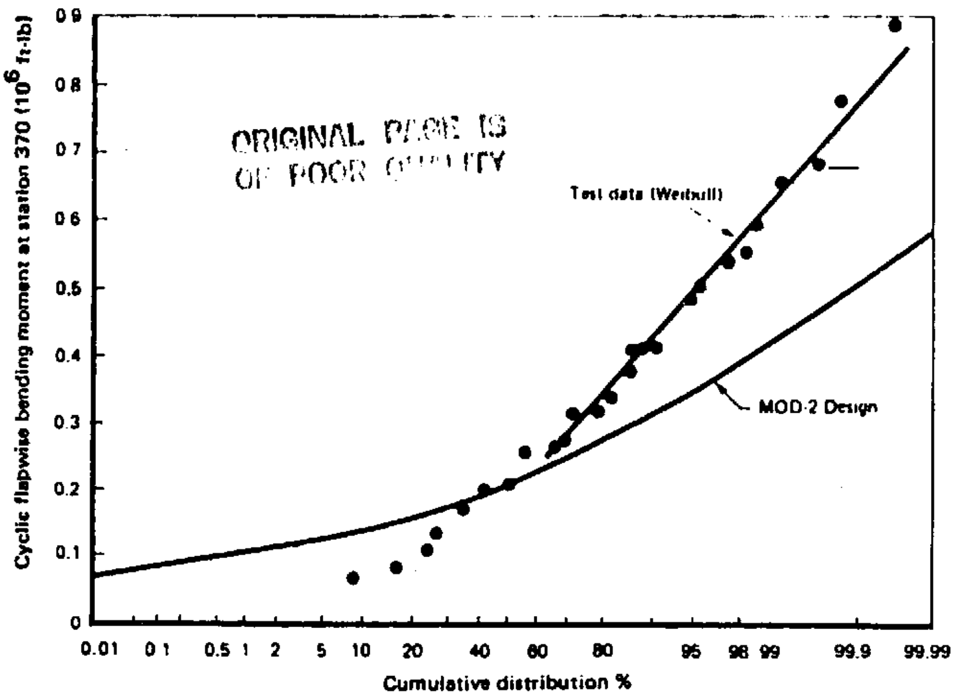

Figure 5-9. Cumulative Probability of Cyclic Flapwise Moments at Station 370

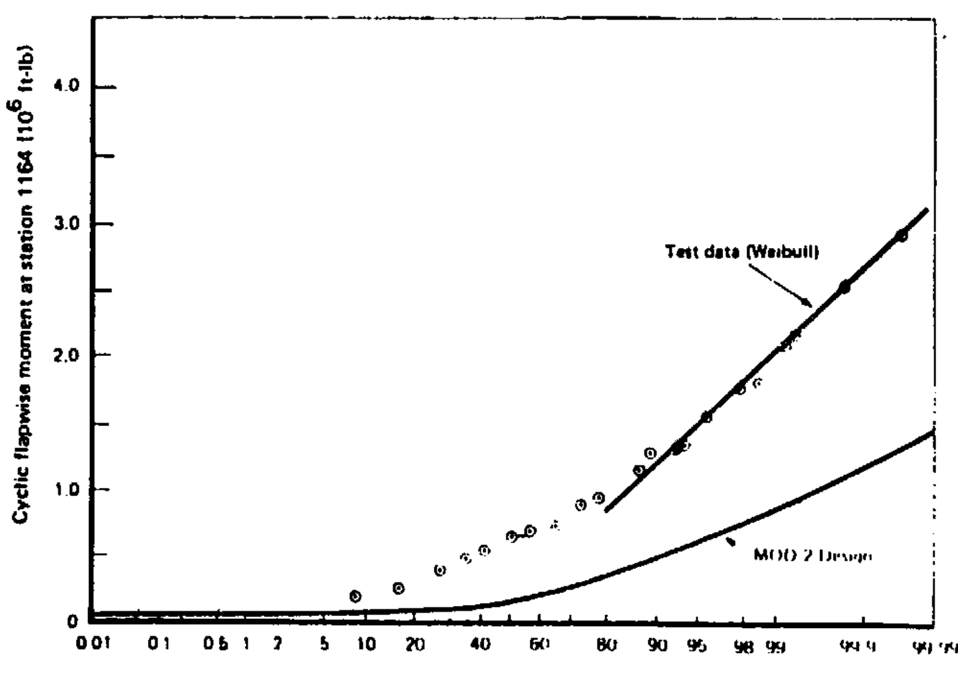

Figure 5-10. Cumulative Probability of Cyclic Flapwise Moments at Station 1164

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Table 5-1. Summary Rotor Fatigue Status - Weibull Wind Speed Distribution

ROTOR STATION	ESTIMATED LIFE BASED ON ORIGINAL CRITERIA [1]	LENGTH OF CHORDWISE WELD WITH < 30-YEAR LIFE	FLAW SIZE FOR 30-YEAR LIFE DEPTH X LENGTH	COMMENTS
0	12,000 HRS. (1.7 YRS.)	20 IN.	.039 X .195 IN.	FILLET WELDS AT AFT SPAR < 30-YEAR LIFE (28,000 HRS)
91	18,800 HRS. (2.7 YRS.)	35 IN.	.040 X .200 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (25,000 HRS)
224	23,500 HRS. (3.4 YRS.)	56 IN.	.040 X .200 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (120,000 HRS)
357	16,900 HRS. (2.5 YRS.)	42 IN.	.030 X .150 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (75,000 HRS)
363	7,200 HRS. (1.0 YRS.)	121 IN.	.020 X .100 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (33,000 HRS)
492	12,800 HRS. (1.9 YRS.)	72 IN.	.023 X .115 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (70,000 HRS)
620	13,000 HRS. (1.9 YRS.)	96 IN.	.020 X .100 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (80,000 HRS)
750	21,400 HRS. (3.1 YRS.)	67 IN.	.023 X .115 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (85,000 HRS)
880	31,000 HRS. (4.5 YRS.)	44 IN.	.025 X .125 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (85,000 HRS)
1012	51,800 HRS. (7.5 YRS.)	32 IN.	.030 X .150 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (120,000 HRS)
1144	150,000 HRS. (21.8 YRS.)	19 IN.	.045 X .225 IN.	FILLETS O.K.
1360	90,000 HRS. (13.1 YRS.)	40 IN.	.041 X .205 IN.	FILLET WELDS AT FORWARD AND MIDDLE SPAR < 30-YEAR LIFE (100,000 HRS)
SPINDLE	15,000 HRS. (2.2 YRS.)	≈20% OF CIRCUMFERENCE	.021 X .063 IN.	

TOTAL WELD LENGTH WITH < 30-YEAR LIFE — CHORDWISE 106 FT., SPANWISE 330 FT.

[1] **Life = Mean time between repairs**

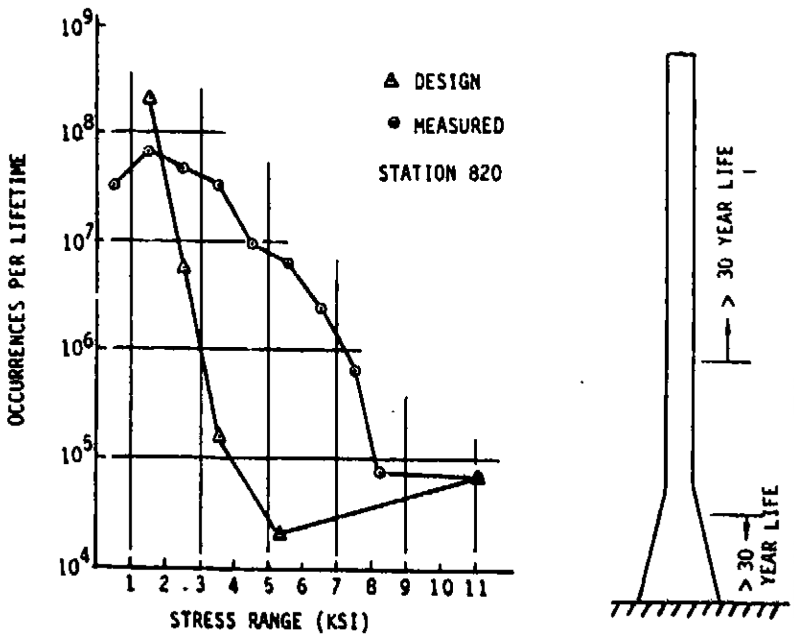
Table 5-2. Summary of Rotor Status - Goldendale Wind Distribution

LOCATION	ESTIMATED FATIGUE LIFE [1]	COMMENTS
STATION 0	3.4 YRS (15,300 HRS)	FILLET WELDS AT AFT SPAR < 30 YEAR LIFE (56,000 HRS)
STATION 91	5.4 YRS (24,600 HRS)	FILLET WELDS AT AFT SPAR < 30 YEAR LIFE (56,000 HRS)
STATION 224	7.0 YRS (32,000 HRS)	FILLET WELDS OK
STATION 357	4.7 YRS (21,400 HRS)	FILLET WELDS AT FORWARD SPAR < 30 YEAR LIFE (140,000 HRS)
STATION 363	1.8 YRS (8,100 HRS)	FILLET WELDS AT FORWARD AND AFT SPAR < 30 YEAR LIFE (60,000 HRS)
STATION 492	3.5 YRS (15,800 HRS)	FILLET WELDS AT FORWARD AND AFT SPAR < 30 YEAR LIFE (130,000 HRS)
STATION 620	3.5 YRS (15,800 HRS)	FILLET WELDS AT FORWARD SPAR < 30 YEAR LIFE (145,000 HRS)
STATION 750	6.4 YRS (29,000 HRS)	FILLET WELDS OK
STATION 880	9.6 YRS (44,000 HRS)	FILLET WELDS OK
STATION 1012	20.0 YRS (90,000 HRS)	FILLET WELDS OK

[1] **Life = Mean time between repairs**

5.2.2 Tower Analysis

Figure 5-11 presents the assessment of tower fatigue life (time between repairs) for both the Weibull and Goldendale wind speed distributions. These analysis are based on the existance of a flaw in a critical area 1.5 times longer than the inspectable flaw size. For the Goldendale wind distribution there are only two weld seams with less than 30 years life. For these two the minimum life is 20 years. However, these areas have 30 year life at Goldendale if the maximum flaw size is 1.45 times the inspectable flaw size. Periodic inspection can be used on the tower to detect incipient crack propagation and repair prior to failure.



WEIBULL WIND SPEED DISTRIBUTION

ELEVATION	ESTIMATED LIFE [1]		INCHES OF WELD WITH < 30 YEAR LIFE
	HRS	YRS	
410	120,000	17.7	65 INCHES
500	72,000	10.5	80 INCHES
600	120,000	17.7	60 INCHES
700	69,000	10.0	80 INCHES
820	82,000	12.0	75 INCHES
940	120,000	17.4	55 INCHES
1060	129,000	18.8	50 INCHES

GOLDENDALE WIND SPEED DISTRIBUTION

ELEVATION	ESTIMATED LIFE [1]		INCHES OF WELD WITH < 30 YEAR LIFE
	HRS	YRS	
500	113,000	25	35
700	90,000	20	45

[1] Life = Mean time between repairs

Figure 5-11. Tower Fatique Status

5.2.3 Other Components

Loads on other critical components within the MOD-2 were within design limits and fatigue life analysis shown they have a 30 year life expectancy. Components examined included the pitch actuator and drive train components. In addition, the vibration environment within the nacelle was evaluated and found to be within the design envelope.

5.3 SUBSYSTEM OPERATION

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5.3.1 Pitch Control Hydraulic System

The rotor pitch control hydraulic system is designed to control blade tip motion during normal WTS operation, and rotate blade tips to the feather position for system shutdown. Few problems have been experienced with this system. However, in June 1981 an incident occurred in which the blade tips failed to feather during a test resulting in an overspeed condition. Investigation revealed that this resulted from contaminated hydraulic fluid causing two spool type start-stop valves to silt-up and stick in the open position. These valves have been replaced with poppet type valves which are less susceptible to silting. In addition, position monitors have been added to the valves to warn of sluggish valve action, and an independent emergency shutdown system has been added providing a means of ensuring system shutdown if the two start-stop valves should fail to operate.

5.3.2 Yaw Control System

The yaw control system has shown itself capable of rotating the nacelle at the required rate of 1/4 degree per second. Problems in the yaw system have been confined to loosening of fasteners securing the yaw drive gearbox and parking brakes. These problems never interferred with yaw system operation and have been resolved with design changes.

5.3.3 Drive Train

The MOD-2 drive train has proven itself capable of operating as designed with very few problems. The measured cyclic loads in the drive train were less than 50% of design, providing assurance of 30 year life. During the overspeed incident the drive train was subjected to torques considerably higher than design values yet only the quill shaft sustained significant damage. The drive train lubrication systems have experienced some leak problems, all of which have been eliminated by improved seal designs. Minor problems in the gearbox lubrication system were resolved by changing pressure switch set points and revising system plumbing.

5.3.4 Electrical Power System

The electrical power system has demonstrated that it is capable of providing power to a utility network while providing electrical protection for the WTS generator. Many of the protective relays have successfully operated to initiate WTS shutdown when electrical conditions exceeded design limits. Automatic synchronization with the utility network has been extremely successful with the average time from reaching synchronous speed to connection with the grid being approximately 2 minutes. The only significant problem with the electrical power system was an inadequate generator bearing lubrication system. The original scoop system design did not provide sufficient lubrication at low rpm and was very susceptible to installation adjustment error. To alleviate this problem, an active pump fed lubrication system was developed and has been retrofitted onto the machines.

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5.3.5 Control System

The MOD-2 control system provides all of the system monitoring and control commands necessary for unattended failsafe operation of the WTS. It has done this successfully, while being continually updated to improve system performance. While many changes have been made to the control algorithms to affect various machine operations, the most significant changes have been in the areas of loads alleviation and stability improvement. The initial control configuration was marginally stable in turbulent wind conditions and contributed to considerably higher than predicted tower and rotor cyclic loads due to the interactions between tip motion and tower and rotor natural frequencies. Table 5-3 summarizes the revision which have been made to the control system in these areas.

Table 5-3. Control System Improvements

	Feb '81 Baseline	June thru Dec '81	Jan '82	Feb '82	April '82	July '82
Configuration	2P Notch filter	−9 db Tower notch filter	Control loop gain changes hysteresis added	−23 bd Tower notch filter revised gains	−15 db Blade notch filter	−23 db Tower notch filter, revised gains, 5° below rated pitch schedule, 0° pitch limit
Stability	Limited stability	Marginal stability	Improved stability above/below rated transition problems	Improved stability above/below rated transition problems	Improved stability above/below rated transition problems	Stable
Power quality	±350 kW	±750 kW	±200 kW	±250 kW	±250 kW	±250 kW

5.3.6 OPERATIONS AND MAINTENANCE EXPERIENCE

Unit #1 was first synchronized to the Bonneville power grid on December 22, 1980. Units #2 and #3 were synchronized on line April 7, 1981, and May 19, 1981, respectively. Since unit #1 was put into service, the three units have produced over 3,000 megawatt hours during approximately 2,700 hours of operation. The performance summaries of the three units are shown in Table 5-4. An operating time history is shown in Figure 5-12. The accumulation of operating time on the machines has been hampered by equipment failures and the need to make modifications and special tests due to the developmental nature of the units. The primary cause of downtime was the unit #1 overspeed incident which resulted in no machine operation between June 8, 1981 and October 20, 1981 when unit #3 was brought back on line. In addition, to minimize the potential for another overspeed incident, operation of the machines was restricted to require an operator at the site during operation.

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Table 5-4. Operating Experience 1/1/83 – 10/3/82

	WTS unit			
	No.1	No.2	No.3	Cumulative
Hours of operation	717	1,089	1,288	3,094
Energy generated (kWh)	747,300	1,278,800	1,401,800	3,427,900
Adjusted availability	0.71	0.79	0.83	0.78
Maximum operating winds (mph)	50	50	50	

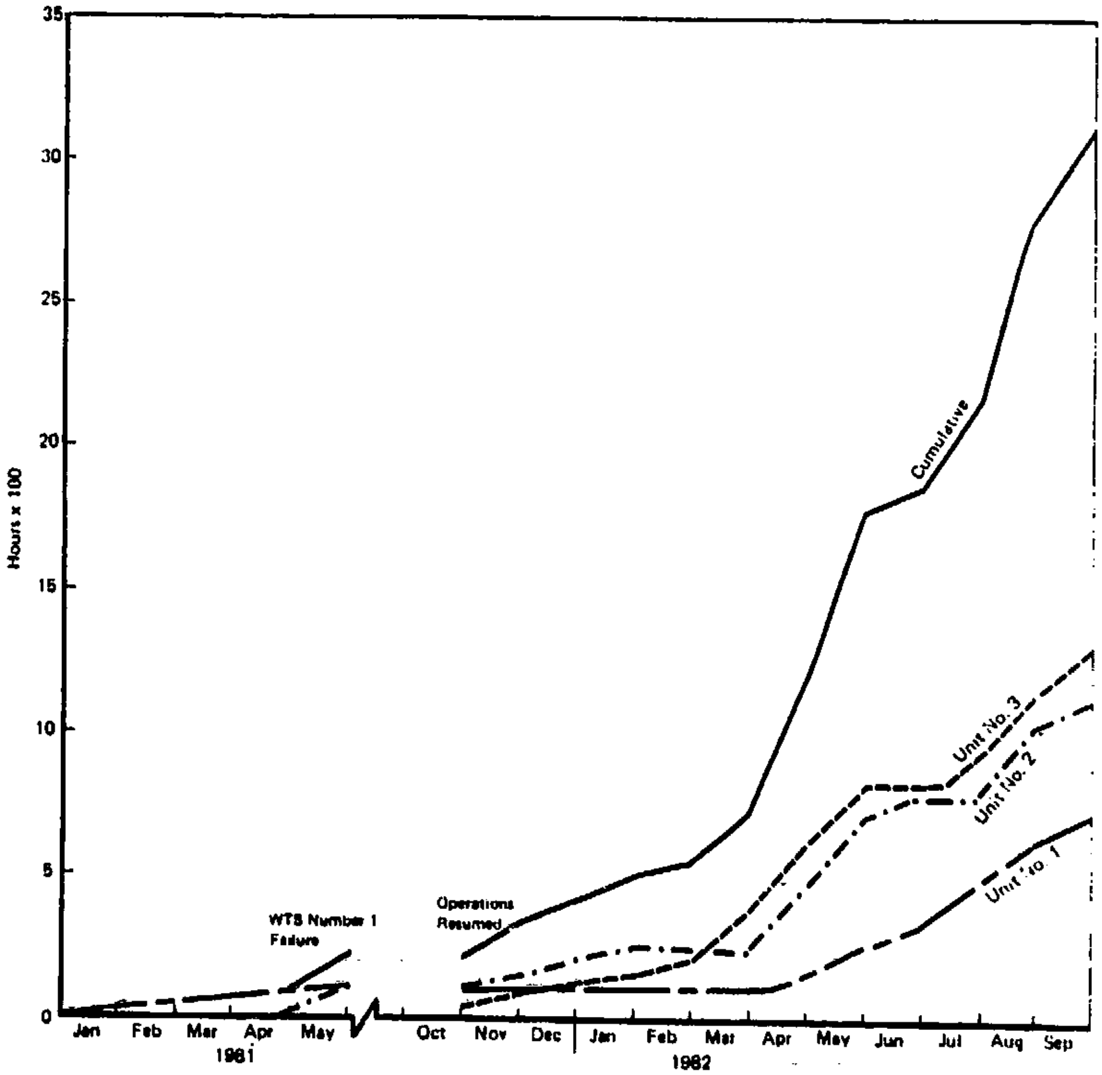

Figure 5-12. Operating Time

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The maintnenace actions accomplished at the site have ranged from major repairs of unit #1 (after the overspeed incident) to minor actions such as sampling of hydraulic fluid. The distribution of failures by major subsystem is shown in Figure 5-13 and their relative contribution to maintenance downtime is shown in Figure 5-14.

All required actions have been completed with the WTS work environment providing no significant problems. Many of the unique maintenance tools designed for the MOD-2 have been successfully utilized. Rotor maintenance has been accomplished using the specially designed rotor access device. Figure 5-15 shows the rotor access device in operation. Training of maintenance personnel has been completed and the Operations and Maintenance Manual is being validated by use during maintenance actions.

A comparison of the actual time required for specific maintenance activities and the times predicted by a maintenance-analysis are shown in Table 5-5. This shows very good correlation considering the improvements which can be expected as the maintenance crews gain experience and the maintenance procedures improve.

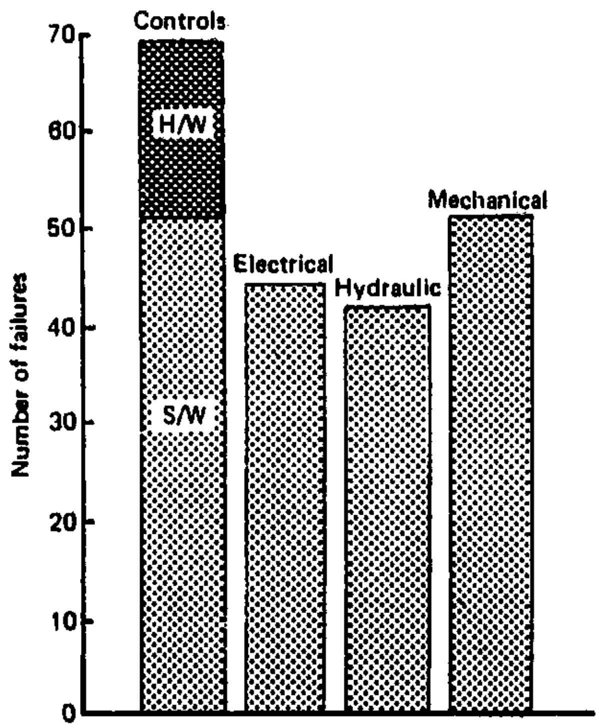

Figure 5-13. Failure Distribution

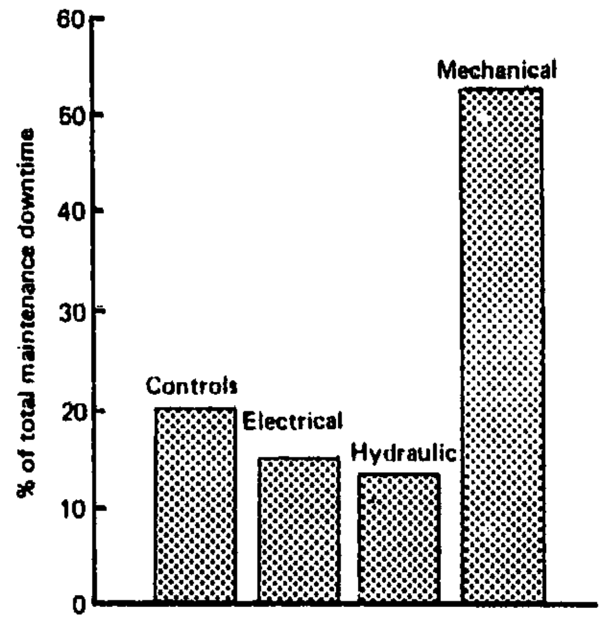

Figure 5-14. Maintenance Downtime Distribution

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Figure 5-15. Rotor Access Device Installation

Table 5-5. Maintenance Time Comparisons

	Maintenance manhours		Time to complete (hours)	
	Analysis estimate	Actual experience	Analysis estimate	Actual experience
Prep for rotor removal	48	60/64	16	16/16
Rotor removal	56	88/88	8	8/8
Prep for nacelle removal	48	30	16	8
Nacelle removal	72	80	8	8
Teeter bearing removal	48	60	8	24
Tip separation from mid	64	40	16	8
Actuator seal change	32	48	16	16
HPU "O" ring change	9	14	6	7
Two month scheduled	19	24/32	10	11/13
Six month scheduled	32	78/84	20	22/36

5.3.7 Availability

Availability of the MOD-2 units has been tracked to assist in evaluating machine performance. Two methods of computing availability have been used. The first presents the percentage of time the turbine could have operated if wind and crews were available. It is computed using the equation:

$$A = \frac{\text{Period Time - Downtime}}{\text{Period Time}} \quad \text{where}$$

Period time is calendar time. Calendar time has been adjusted to shift time during initial operations which have required a monitor on the site. Downtime is any time the machines were not capable of operation during the period.

The second method of computing availability, known as adjusted availability, attempts to determine what the availability of the machines would be if no modification or special tests associated with machine development were being conducted. The equation used for this calculation is:

$$A = \frac{\text{Period Time - Downtime}}{\text{Period Time-Modification Time-Special Test Time}}$$

The cumulative availability history trends are shown in Figure 5-16 and this data is tabulated in Table 5-6. Since January 1982, recurring problems for which fixes are being developed, modification and special tests account for 90% of the total system downtime. As problems are resolved and machine availability improves, it is becoming evident that when the machines mature and are placed into a commercial operatingg scenario the predicted availabilities in excess of 90% can be achieved.

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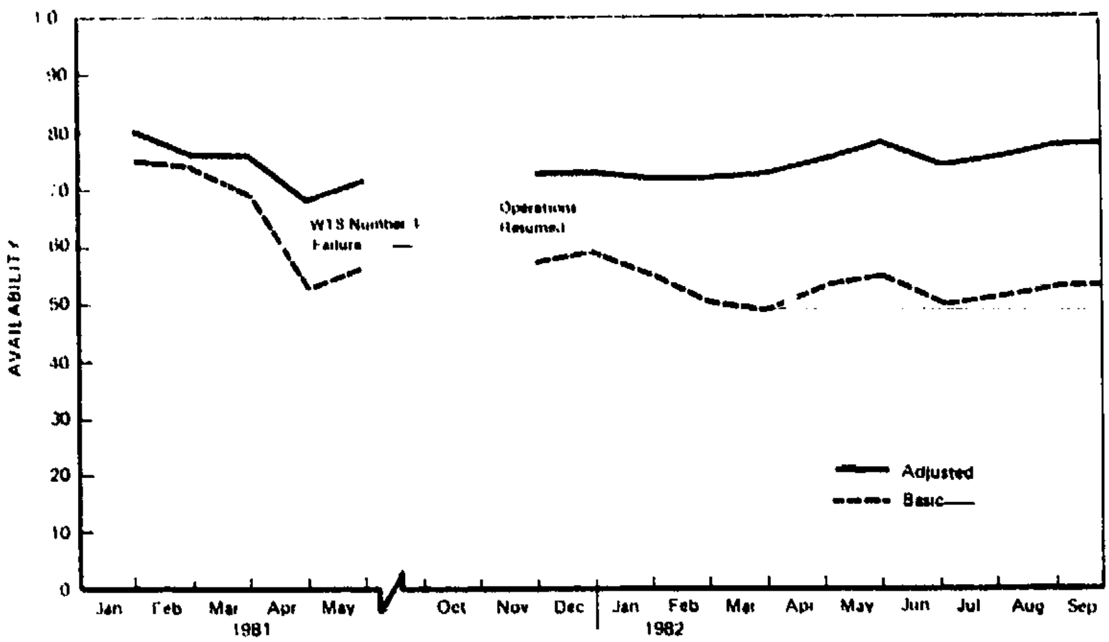

Figure 5-16. Cumulative Availability all Three Units

Table 5-6. Cumulative Availability

	Unit no. 1		Unit no. 2		Unit no. 3		All units	
	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted
January 1981	.76	.80	–	–	–	–	.75	.80
February 1981	.72	.73	–	-	–	–	.72	.73
March 1981	.58	.73	–	–	–	–	.6[illegible]	.73
April 1981	.22	.51	.26	.40	–	.	.24	44
May 1981	.28	.67	.82	.85	.71	.80	.64	80
November 1981	.	–	.53	.62	.77	.91	66	78
December 1981		–	.79	.88	.32	.42	52	69
January 1982	-	–	.28	.76	.34	.55	.31	62
February 1982	–	-	.04	.42	.47	.81	.30	78
March 1982		–	0	–	.63	.75	44	75
April 1982		–	.62	.79	.72	.84	.67	.81
May 1982	.57	.94	.64	.81	.61	.88	.61	87
June 1982	.24	.36	.51	.86	–	–	.25	.52
July 1982	.77	.87		-	.78	93	.59	90
August 1982	.56	.83	.62	.91	.66	.95	.61	.90
September 1982	.42	.67	.53	.70	.73	.95	.57	.79

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6.0 CONCLUSIONS AND RECOMMENDATIONS

The MOD-2 project has been successfully concluded after a five year effort by BEC and its subcontractors, under the contractual direction of NASA Lewis Research Center for DOE. The project has developed a wind turbine design meeting the contractual design requirements and has fabricated and tested three machines of this design, which have demonstrated fulfillment of the project goals. These machines will continue the demonstration as remotely controlled power generators within the Bonneville Power Administration network. The project has produced considerable valuable technical data needed to bring large wind turbine systems to commercial status and contributing to the nation's energy production.

The major system accomplishments demonstrated at Goodnoe Hills are as follows:

(1) The feasibility of fabrication and installation of a multi-megawatt (2.5 MW) horizontal axis machine with a 300 foot diameter rotor. The MOD-2 rotor is the largest rotor fabricated and tested to date, and the MOD-2 has produced higher power output than any other wind turbine system to date.

(2) Unattended operation with remote monitoring, enable/disable control and energy management capability.

(3) Power variations of less than ±6 percent (50 percentile data) for power delivered to the utility grid. Three sigma values are within ±18 percent at the maximum wind speed of 45 mph.

(4) The feasibility of the controlled yaw upwind rotor, which has more efficient energy capture than a downwind rotor, and which has demonstrated fully acceptable noise characteristics.

(5) The feasibility of the partial span (30%) tip controlled rotor.

(6) The adequacy of the failsafe shutdown system protection.

(7) Evaluation of early prototype operations have shown that the machines are achieving an availability of 0.83 for those periods when system design modifications or special tests are not included as period time in the calculation. Projections indicate a capability to achieve greater than 0.92 as early operational problems are solved.

Testing of the MOD-2 units at Goldendale has verified many unique design features of the MOD-2 and is providing invaluable technical data on loads and control system dynamics. Major areas of technical interest where the data will contribute to future development and commercialization include:

(1) The large-scale elastomeric teeter bearings successfully completed accelerated life-cycle laboratory testing and have exhibited no problems during operation.

(2) Actual teeter motions are less than had been expected. No teeter stop contacts have been observed during rotation. The teeter brakes appear to be unnecessary and have been deactivated which will improve overall reliability.

(3) The yaw damping brake has proven to be unnecessary and has been deactivated which will improve overall reliability.

(4) The measured yaw drive cyclic loads are higher than predicted. These loads can be reduced by sizing the drive motor to stall and allowing backdriving during peaks in the cyclic loads.

(5) Structural rotor loads prediction methods were verified for all loading conditions except for rotor flapwise cyclic loads which are higher than predicted by analysis methods. Prediction methods have been modified to reflect this inadequacy and can be used with confidence to predict cyclic rotor loads of other machines. Control system interactions are being evaluated and current control system testing is expected to provide some alleviation of cyclic loads.

(6) The compliant quill shaft, in conjunction with the pitch control system, has demonstrated the capability of damping power oscillations from rotor to gearbox. The three sigma cyclic torque loads are 50 percent of the predicted design loads.

(7) A system simulation model has been developed and correlation with actual system dynamics is providing the capability to optimize the control system for loads reduction and power stability while achieving maximum energy output.

(8) Measurements of actual power output versus meteorological tower wind speeds show good correlation with predicted values. The data are based on 10 minute averages (at a data rate of 10 samples per second) during selected periods of relatively steady winds. Approximately one-third of the data points are higher than predicted values. Two thirds of the data points are less than predicted values. The maximum data scatter of approximately 20% can be attributed to windspeed at the turbines being different than wind speed at the meterological tower, losses due to yaw error, and accuracy of the data systems.

In summary, the MOD-2 project goals have been achieved. A wide base of suppliers involvement has contributed to the program. Utilities have participated in the design and evaluation. The three MOD-2 machines at Goldendale, plus a MOD-2 machine at Medicine Bow, Wyoming, operated by the Bureau of Reclamation and a MOD-2 machine at Solano, California, operated by Pacific Gas and Electric are contributing to the data base. The feasibility of the large machines has been demonstrated and provide the technical confidence for development of even larger next-generation machines. Continued operation will demonstrate the economic viability of wind energy systems operated to save expendable and costly fossil fueled generating systems.

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The existing three units at Goldendale provide an excellent test facility for continued industry evaluation and development of advanced systems. This facility is continuing in a test mode under the program direction of NASA/BPA. Specific areas of continued evaluation and test should include:

(1) Control system/performance optimization with continued development of analytical modeling including wind turbulence induced effects.

(2) A continued operational evaluation of performance, component reliability, maintenance timelines, and system availability to provide the utility industry with a firm basis for economic evaluation.

(3) A product improvement program to correct any potential design deficiencies impacting system availability, maintenance procedures or personnel and equipment safety.

(4) Long term evaluation of environmental impacts.

(5) Cluster array analysis with testing for wake effects.

(6) Advanced concepts verification including new materials, airfoil shapes, tip speed effects, etc.