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Mod-2 Wind Turbine Development

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Work performed for
U.S. DEPARTMENT OF ENERGY
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Prepared for
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SUMMARY

This paper addresses the development of the Mod-2 turbine, which was designed to achieve a cost of electricity for the 100th production unit that will be competitive with conventional electric power generation. The Mod-2 wind turbine system (WTS) background, project flow, and a chronology of events and problem areas leading to Mod-2 acceptance are addressed. The role of the participating utility during site preparation, turbine erection and testing, remote operation, and routine operation and maintenance activity is reviewed. The technical areas discussed pertain to system performance, loads, and controls. The proposed role of the Goodnoe Hills Cluster Research Test Facility for research and technical development of multimegawatt turbines is summarized.

INTRODUCTION

The Mod-2 wind turbine is a horizontal axis machine using a 300-foot-diameter, partial-span-control, upwind rotor. (See fig. 1.) The rotor's center of rotation is 200 ft above ground. The rotor is coupled to the low-speed shaft through an elastomeric teeter bearing. A 2500-kW synchronous generator is driven by a step-up planetary gearbox and "soft" quill shaft for torque transmission. The generator, gearbox, hydraulic systems, electronic controls, and other support equipment are enclosed in a nacelle, which is 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 maintain a constant rotational speed of 17.5 rpm, to maintain the proper power output at wind speeds above rated wind speed (27.5 mph at the hub), and to provide for shutdown by feathering of the rotor tips. The Mod-2 is controlled by a microprocessor. The microprocessor, which monitors wind conditions and the operational status of the wind turbine, allows unattended operation of the WTS. 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. Specific configuration features and characteristics are given in the following table:

Rated power, kW	2500
Rotor diameter, ft	3 00
Rotor type	Teetered tip control
Rotor orientation	Upwind, 2.5 tilt
Rotor airfoil	NACA 230XX
Rated wind at hub, mph	27.5

Cutoff wind speed at hub, mph	45
Rotor tip speed, ft/sec	275
Rotor speed, rpm	17.5
Generator speed, rpm	1800
Generator type	Synchronous
Gearbox type	Compact planetary
Hub height, ft	200
Tower type	Soft shell
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient (max)	0.382

PROJECT FLOW

The U.S. Department of Energy (DOE) Office of Solar Electric Technologies has overall responsibility for conceiving and directing research and development of wind energy systems. The DOE has delegated project management responsibility to NASA Lewis Research Center for the design, fabrication, and field testing of large (100 kW and larger), horizontal-axis wind turbine systems (WTS). The ultimate objective of the Federal Wind Energy Program and the projects by which it is implemented is the development of the technology base necessary to produce cost effective wind-powered generation of electricity by the industry.

The Mod-2 wind turbine project began in 1977 with the design, installation, and research testing of an experimental wind turbine system. Eventually, three turbine systems were erected near Goldendale, Washington, for the evaluation of interactive turbine/grid effects of multiple, identical, turbines integrated into a utility network. Figure 2 shows the schedule of events leading to first rotation in November 1980, cluster dedication in May 1981, and final acceptance in November 1982. This schedule also shows the downtimes of the turbines resulting from an overspeed incident on turbine 1 in June 1981. Before the overspeed incident, the project also experienced delays in site selection and site access (1979), rotor-fabrication union strike (mid-1980), winter weather and low winds (1980-81).

Currently, the Mod-2 project team is determining the cause of a failure of the low speed shafts in the Mod-2 turbines. This incident occurred on November 1982 shortly after the final acceptance milestone. Before this failure, the Mod-2 cluster had generated over 4 gigawatthours in some 3700 hours of operation. This energy output surpasses the total energy generated by the four Mod-0A's (3676 MWh). Specific synchronous hours and energy produced by each Mod 2 turbine as well as maximum periods of continuous and simultaneous operation are in table I.

PROBLEM AREAS

Two failures have occurred during the course of this project: (1) an overspeed failure on turbine 1 and (2) a low speed shaft failure also on turbine 1.

Overspeed Failure

The June 8, 1981, overspeed failure occurred in the emergency shutdown system during an emergency shutdown test of turbine 1.

While the turbine was operating at a rated power of 2500 MW, a failure shutdown was initiated by commanding the emergency shutdown system through the emergency stop button located on the manual control panel at the base of the tower.

The blade tips failed to feather, but the generator, as designed, was automatically disconnected from the utility grid, removing all load from the drive train.

The rotor accelerated from the operating speed of 17.5 rpm to 29.5 rpm damaging the drive train as it did so.

Both blades started emergency feather at T + 28 seconds, shutting the machine down safely without major structural damage.

The NASA failure review committee—concluded that the failure was caused by contaminated hydraulic fluid, which silted the stop-start values (one may have been pre-silted) during the 4-hour run. The electrically actuated valves were unable to close when power was removed and were thus unable to prevent the feather valves from supplying the emergency accumulator hydraulic oil to the blade tip actuators. No electrical system failure to interrupt the command circuit was detected.

The design changes included the continued connection of the generator until low-generator output power is obtained, the addition of yet another independently sensored emergency feather control (IESS), and keeping the servovalves active in the system to provide redundancy to the IESS.

Corrective actions recommended by the committee were incorporated in all of the turbines, and turbines 2 and 3 returned to service during October and November of 1981.

Low-Speed Shaft Failure

On November 12, 1982, turbine 1 shut itself down during normal operation, while producing approximately 2.0 MW of power in gusty winds averaging 18 mph. An investigation of the incident revealed a large crack in the low-speed shaft which supports the turbine rotor. The NASA failure review committee concluded that the failure to be low-stress, high-cycle fatigue of the shaft. The fatigue cracks started at stress concentrations around multiple bracket holes and propagated from hole to hole during operation. The cause of failure was inadequate design of the low-speed shaft and of the hydraulic tubing and electrical conduit hole details in the shaft resulting in a negative design margin of safety. A contributing cause was the presence of working fasteners in the mounting holes.

The primary recommendation for returning to remote, unattended, automatic operation was the necessary redesign and retrofit of the low-speed shafts on all turbines. However, limited-attended operation with frequent inspections will be conducted after minor hardware reworks. As of this writing, a recovery plan has been authorized for both attended and unattended operation of the cluster to support research tests.

Other Problems

During the investigation of overspeed failure, it was found that the life of the bolts in the rotor field joint at station 360 was considerably shorter than predicted. This necessitated a change in the bolts and the redesign of the joint. The turbine 1's rotor field joint was rebuilt and reinstalled after the overspeed incident, and the field-joints of rotors 2 and 3 were removed and rebuilt in June and July of 1982. Inspections, changes, and strain gage testing of selected bolts to preclude and correct failures have contributed significantly to system downtime.

The distribution of failures among the various WTS components is shown in figure 3, and the contribution of these component failures to downtime is shown in figure 4. In addition to hardware failure, special tests, logistics problems, and utility outages all contributed to system downtime. Special tests are an ongoing part of the wind energy research and technology development program and include acoustical and electromagnetic interference tests.

UTILITY PARTICIPATION/MAINTENANCE

The DOE selected the Bonneville Power Administration (BPA) as the participating utility for the Mod-2 wind turbine project. This utility is a large regional power marketing and transmission organization in the Pacific Northwest and has the capability of providing valuable support in the attainment of the DOE/NASA project goals in the federal Wind Energy Program as well as its own Wind Regional Energy Assessment Program (WIND-REAP). Bonneville's participation in the Goodnoe Hills site (shown in fig. 5) included:

(1) Obtaining site property and access roads
(2) Installing a substation and tie-in to the respective turbine stepup transformers
(3) Furnishing a stationkeeping power
(4) Providing storage for spare parts
(5) Participating in reviews and preparation of procedures and schedules
(6) Conducting remote operation
(7) Conducting routine maintenance (2 months, 6 months, and annual) and minor repairs

Nonroutine maintenance (rotor removal, etc.) is performed for NASA by the turbine contractor.

The maintenance actions accomplished at the site have ranged from major repairs of rotor 1 (after the overspeed incident) to the sampling of hydraulic fluid as part of a scheduled 2-month maintenance. All required activities have been completed with no major problems encountered due to the elevated location of the nacelle or lack of adequate space for maintenance or repair. Transportation of tools and parts to the nacelle is easily accomplished by use of the tower manlift or a pulley-and-bucket system rigged in the tower.

Transportation of large or heavy items to and from the ground has been accomplished using the monorail mounted hoist through the aft nacelle door.

The time required for maintenance tasks has generally been close to the estimated value. For example, changing an actuator seal required approximately 16 hr and two workers. While experience shows that three men will always be required for safe completion of this task, as a crew becomes experienced in the rigging and operation of the rotor access device, it is expected that the time required for the task can be reduced to 10 to 12 hours.

A typical example of a less major maintenance activity was the replacement of an O-ring in the yaw hydraulic system valve manifold. A similar activity was predicted to require 9 manhours for a mature system with an experienced maintenance crew. The task actually required 13.5 manhours the first time it was done. Again, it is reasonable to believe that the mature system prediction is achievable as experience is gained by the crews.

One area where significantly more time is required than the prediction is in scheduled maintenance. The present documented requirements for scheduled maintenance are 270 manhours, while the original maintenance analysis of mature production in large farms predicted 72 manhours. It is expected that, as confidence is gained in the WTS subsystems, the frequency of many of the scheduled actions will be reduced and that subsystems be modified to reduce maintenance requirement. The effect of this increased scheduled maintenance on system power output is not as significant as an equal amount of unscheduled downtime because much of the scheduled maintenance can be completed during low wind periods. Experience at Goodnoe Hills has shown that activities can be scheduled around wind availability.

Data gathered during the disassembly of turbine 1 following the overspeed failure further supports the accuracy of maintenance requirement estimates. A comparison of the estimated and actual times required for various tasks is shown in table II.

TECHNICAL RESULTS

This section discusses the most significant aspects of the performance of the Mod-2 WTS during its initial operating period. The areas discussed are power performance, loads, and the control system. Information presented on system performance and loads is based on data gathered from January 1981 to mid May 1982. Improvements to the control system continued as run time and knowledge of the control system behavior accumulated. The status through July 1982 is discussed.

System Performance

The power variation with wind speed for turbine 2 is shown in figure 6. This is typical for the three Mod-2 units at Goodnoe Hills. The power 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.

The data were reduced by computer analysis of magnetic tape recordings. Each data point represents an average value for a 10-min interval, selected by searching the real time brush recorder charts from the site. For operation below rated power, the pitch angle throughout the entire time interval was either +3° or +5°. To minimize data scatter, intervals were selected where the wind was reasonably smooth. The total variation in power during any time interval was usally less than 500 kW. The time scale for these power variations was several minutes. Almost all of the below rated power data points occurred during the night hours. For operations at rated power the only criterion used to identify time intervals was that the entire interval be rated power operation. After the time intervals were identified, the wind speed and generator power channels were digitized at a sampling rate of 10 per second. Average values were then computed. The data correlate very well with the predictions made by Boeing from the GEM computer program used to predict performance. In addition, there do not appear to be any significant differences between the power output measurement for the three units at Goodnoe Hills.

Loads and Fatigue Analysis

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 the predicted minimum time until repairs are required, based on fracture mechanics analyses. 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 obtained in testing at the Goodnoe Hills site and their correlation with analysis.

Rotor analysis. - Initial operation of the units at Goodnoe Hills showed 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 on unit 3 are compared with design loads in figure 7. The design loads were based on the MOSTAB computer program developed by NASA. Loads predictions of the GEM computer program are shown for reference. As figure 9 indicates, the rotor mean load predictions were quite accurate.

The cyclic flapwise bending moments at station 370 for unit 3 are shown in figure 8. The cyclic load predictions (not shown) were based on a model developed for Mod-2 and checked against cyclic rotor loads on the Mod-0. A correlation with Mod-0 was achieved, but Mod-2 test data gave a cumulative fatigue spectrum considerably higher than predicted. It is believed that the large cyclic loads caused by tower shadow for the downwind Mod-0 rotor (included in the verification analysis) masked the true interaction with the small-scale turbulence in the wind, which causes the Mod-2 cyclic loads. Considerable progress in understanding and developing a prediction capability for the cyclic flapwise bending load has been made since the Mod-2 data were collected.

To determine the cumulative probability of cyclic flapwise moments, the test data were combined with the Weibull wind speed frequency distribution shown in figure 9. The cumulative probabilities are shown in figure 10. A summary of the fatigue life analysis is shown in table III. This analysis is based on a flaw size of 0.05 in. deep by 0.25 in. long; weld inspection criteria repair of all flaws greater than 0.05 in. deep by 0.125 in. long, and cracklike defects of any size. Table III indicates that most critical areas of the rotor can attain 30-year life when flaws detected and repaired during inspection.

As shown in figure 9, the Goodnoe Hills wind frequency distribution is considerably less severe than the specified Weibull distribution. Table IV summarizes the fatigue life in this Goodnoe Hills environment.

Tower analysis. - Table V presents the-assessment of tower fatigue life (time between repairs) for both the Weibull and Goodnoe Hills wind speed distributions. These analyses are based on the existence of a flaw in a critical area 1.5 times longer than the rejectable flaw size. For the Goodnoe Hills wind distribution there are only two weld seams with less than 30-year life. For these two seams the minimum life is 20 years. However, these-areas have 30-year lives at Goodnoe Hills if the maximum flaw detected is no more than 1.45 times the inspectable flaw size. Periodic inspection can be used on the tower to detect incipient crack propagation.

Other Components

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

Pitch actuator loads. - Proper operation of the pitch actuators is essential to startup, operation, and shutdown of the Mod-2. The pitch actuator must have both the required stroke and force capacity over all ranges of operation. The actuator forces were calculated from the pressure measurements of the head and rod end hydraulic pressures and the respective areas. Figure 11 shows the pitch actuator moment during emergency shutdown. This crossplot represents approximately 5 minutes of real time. A positive moment denotes that aerodynamic moments are acting to drive the blade tip toward feather. The scatter of points labeled "operating" represent the normal variation of pitch actuator loads when the rotor is producing power under active pitch control. The mean pitch actuator load is compressive. The aerodynamic moments that tend to drive the blade tips toward feather cause a tensile load in the actuator. As the blade tips continue to feather and the rotor speed decreases, the primary actuator loads are produced by 1P gravity loading of the blade tips.

The shutdown actuator loads are in good agreement with design loads predictions and within the pitch actuator capability, represented by normal (2000 psi) and minimum (1500 psi) stall limits.

Drive train loads. - Loads measured on the quill shaft provided a good measure of the drive train loads. The torque and bending moment in two planes were measured. Test data revealed that the quill shaft bending loads were very small (~ 2 percent of rated torque). The relative flexibility of the quill shaft in relation to the low speed shaft proved very effective in minimizing bending of the quill shaft.

Statistical analysis was performed on the cyclic quill shaft torque and presented in the form of a wind bins plot. A very conservative estimation of the 0.999 probability was used with the Weibull wind distribution shown in figure 9 to develop the cumulative cyclic torque curve of figure 12. The Mod-2 (0.999) design loads exceed measured data whereas the (0.50) design loads are unconservative. Fatigue life with the measured loads spectrum exceeds 30 years.

Quill shaft cyclic torque is another measure of power quality to which it is directly related. Figure 13 shows representative power quality data in the below and above rated modes of operation. Although there were no specific power quality requirements for Mod-2, test data reveal peak cyclic values on the order of 15 percent of rated as shown in figure 13.

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 load 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 motion and tower and rotor natural frequencies. Table VI summarizes the revisions that have been made to the control system in these areas.

RESEARCH AND TECHNOLOGY DEVELOPMENT TESTING

As previously noted, the installation of three Mod-2 turbines at a single site was done to test and evaluate interactive and machine-grid effects of multiple, identical, turbines integrated into a utility network. Specifically, this research testing has been structured initially to indicate four test project areas.

(1) performance, (2) environmental impact, (3) transmission and distribution, and (5) wind data/wake effects.

These tests are being conducted under the auspices of a Test Project Review Board with participation from BEC, BPA, Pacific Northwest Laboratory (PNL), Solar Energy Research Institute (SERI). (See fig. 14 and ref. 2.)

To make the most of the research opportunities afforded by the Mod-2 turbines, each turbine has been assigned a separate primary test function, while still working as part of the cluster. As shown in figure 5, turbine 2, nearest the visitor's center, will be kept in operation whenever possible, and will be quickly brought back on line by Boeing or BPA crews in the area when it shuts down, in order to determine the maximum energy yield that can be produced by the Mod-2 at the Goodnoe Hills site.

Turbine 3, nearest the county road, will run under "real world" utility conditions. When the machine shuts down and requires inspection, crews from BPA substations will be scheduled to work on it. This will give utilities an idea of the staff commitment necessary to maintain a wind turbine and of the energy production achievable under routine operating conditions.

Unit 2 is the machine where advanced research will ~~first~~ be tested, to further develop large wind turbine technology.

Research testing began in the spring and summer of 1982 in acoustics noise, television interference, and wakes. Detailed reports are currently being released by the various participants (refs 3. and 4) as well as being the subject of several papers at this respective workshop. However, a brief summary of these tests is given below.

Acoustic Noise

SERI conducted a series of tests over a period of 6 weeks to measure the acoustic noise emission and effects during single and multiple wind turbine operations. The tests included the use of noise measuring instrumentation on the ground, on the wind turbine tower, and airborne using a balloon. Sufficient data were obtained which show that the sound is broadband, rather than impulsive, in nature. Within the cluster, the sound level is approximately that of a moderately busy street (60 dBA) and decreases to a residential street level (53 dBA) about a quarter mile downwind. Personal observations corroborate that the sound can not be perceived 16 rotor diameters (4800 ft) downwind in a 15 to 25 mph wind.

Television Interference (TVI)

SERI, University of Michigan, and BPA collaborated in measurements of television interference from the Mod-2 wind turbine system. Specific measurements were taken to determine (1) received field strength, (2) static or blade scattering, (3) dynamic (operating) blade scattering. Although the signal strength is considered to be very weak at Goodnoe Hills, background noise interference was acceptable. Equivalent scattering was very close to model predictions.

Wakes

Battelle coordinated wake testing being performed by Flow Industries, AeroVironment, and Oregon State University. Qualitative and quantitative data were obtained using smoke generators and balloon/kite supported instrumentation. Although wakes were observed by all techniques, correlation of the results was difficult because of terrain effects. To date, no effects have been noted on downwind turbines at spacings of 7 to 10 rotor diameters. Establishing terrain effects on wakes and wake characteristics 2 to 5 rotor diameters will be the subject of this year's investigation.

CONCLUDING REMARKS

The Mod-2 wind turbine project described is the second generation phase of the Federal Wind Energy Program managed by the NASA for DOE. Industry, public utilities, and the government have been working parties in this program designed to produce the technology to supply wind-generated electric energy. Industrial involvement in turbine development provides the necessary commercial base, and utility operation of the evolving machines assures a viable product in this government-supported program. The design, fabrication, assembly, and synchronization of the three Mod-2 turbines at Goodnoe Hills represents a major advance in the development of large horizontal-axis wind turbines.

The Mod-2 project is now in a 2-year research experimental operations phase which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment. To date, performance of the turbines has been acceptable but also has indicated areas for improvement in controls, loads, and life. Corrective actions have been taken to modify the turbines as necessitated by the November 1982 low-speed shaft-fatigue failure. Full cluster operation is anticipated in early calendar year 1984.

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TABLE I. - GOODNOE HILLS OPERATION SUMMARY
(AS OF NOVEMBER 12, 1982)

	Turbine 1	Turbine 2	Turbine 3	Cluster
Hours of operation	1008	1186	1514	3708
Hours of generation	918	1100	1415	3433
Energy generated, MWh	1059.8	1373.4	1615.1	4048.3
Average power, kW	1154	1248	1141	1179
Maximum continuous run time, hr	51	30	36	-----
Maximum simultaneous run time, hr, for -				
Two units	36	-----	36	-----
Three units	13	13	13	-----
Maximum winds, mph, for -				
Operating	50	50	50	-----
Nonoperating	90	90	90	-----

TABLE II. - MAINTENANCE TIME COMPARISONS

	Maintenance manhours		Time to complete, hr	
	Estimate	Actual	Estimate	Actual
Preparation for rotor removal	48	60/64	16	16/16
Rotor removal	56	88/88	8	8/8
Preparation for nacelle removal	48	30	16	8
Nacelle removal	72	80	8	8
Teeter bearing removal	48	60	8	24
Tip separation from midsection	64	40	16	8
Actuator seal change	32	48	16	16
HPU O-ring change	9	14	6	7
Two-month scheduled maintenance	19	24/32	10	11/13
Six-month scheduled maintenance	32	78/84	20	22/36

TABLE III. - SUMMARY ROTOR FATIGUE STATUS - WEIBULL WIND SPEED

[Total weld length with <30-yr life: Chordwise length, 106 ft.; Spanwise 330 ft.]

Rotor station	Estimated life[a] based on original criteria		Length of chordwise weld with <30-yr life[a], in.	Flaw size for 30 yr life[a], in.		Comments
	hr	yr		Depth	Length	
0	12 000	1.7	20	0.039	0.159	Fillet welds at aft spar <30-yr life (28 000 hr)
91	18 800	2.7	35	.040	.200	Fillet welds at aft and forward spar, <30-yr life (25 000 hr)
224	23 500	3.4	56	.040	.200	Fillet welds at aft and forward spar, <30-yr life (120 000 hr)
357	16 900	2.5	42	.030	.150	Fillet welds at forward spar, <30-yr life (75 000 hr)
363	7 200	1.0	121	.020	.100	Fillet welds at aft and forward spar, <30-yr life (33 000 hr)
492	12 800	1.9	72	.023	.115	Fillet welds at aft and forward spar, <30-yr life (70 000 hr)
620	13 000	1.9	96	.020	.100	Fillet welds at aft and forward spar, <30-yr life (80 000 hr)
750	21 400	3.1	67	.023	.115	Fillet welds at aft and forward spar, <30-yr life (85 000 hr)
880	31 000	4.5	44	.025	.125	Fillet welds at forward spar, <30-yr life (85 000 hr)
1012	51 800	7.5	32	.030	.150	Fillet welds at forward spar, <30-yr life (120 000 hr)
1144	150 000	21.8	19	.045	.225	Fillets OK
1360	90 000	13.1	40	.041	.205	Fillet welds at forward and middle spar, <30-yr life (100 000 hr)
Spindle	15 000	2.2	(b)	.021	.063	--------------------------------

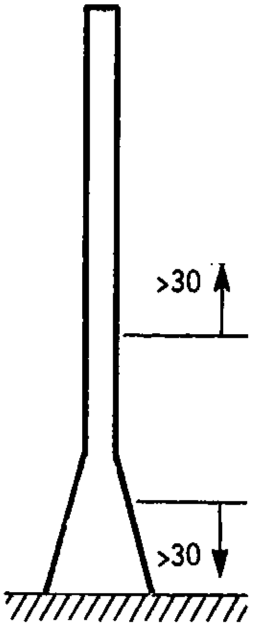
[a] Life = mean time between repairs.
[b] 20 percent of circumference.

TABLE IV. - SUMMARY OF ROTOR STATUS - GOODNOE HILLS WIND DISTRIBUTION

Rotor station	Estimated fatigue life[a],		Comments
	yr	hr	
0	3.4	15 300	Fillet welds at aft spar, <30-yr life (56 000 hr)
91	5.4	24 600	Fillet welds at aft spar, <30-yr life (56 000 hr)
224	7.0	32 000	Fillet welds OK
357	4.7	21 400	Fillet welds at forward spar, <30 yr life (140 000 hr)
363	1.8	8 100	Fillet welds at forward and aft spar, <30-yr life (60 000 hr)
492	3.5	15 800	Fillet welds at forward and aft spar, <30-yr life (130 000 hr)
620	3.5	15 800	Fillet welds at forward spar, <30-yr life (145 000 hr)
750	6.4	29 000	Fillet welds OK
880	9.6	44 000	Fillet welds OK
1012	20.0	90 000	Fillet welds OK

[a] Life = mean time between repairs.

TABLE V. - TOWER FATIGUE STATUS



Elevation	Estimated life[a]		Inches of weld with <30-year life[a]
	hr	yr	
Wieball wind distribution			
410	120 000	17.7	65
500	72 000	10.5	80
600	120 000	17.7	60
700	69 000	10.0	80
820	82 000	12.0	75
940	120 000	17.4	55
1060	129 000	18.8	50
Goodnoe Hills wind distribution			
500	113 000	25	35
700	90 000	20	45

[a] Life = mean time between repairs.

TABLE VI. - SUMMARY OF CONTROL IMPROVEMENTS

	Feb 1981 (Baseline)	June - Dec 1981	Jan 1982	Feb 1982	April 1982	July 1982
Configuration	2P Notch filter	-9 dB tower notch filter	Control loop gain changes hysteresis added	-23 dB 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 and below rated transition problems	Improved stability above and below rated transition problems	Improved stability above and below rated transition problems	Stable
Power quality, kW	±350	±750	±200	±250	±250	±250
Tower cyclic loads, percent	100	64	64	27	27	27
Rotor cyclic loads, percent	100	100	100	100	Negligible improvement	100

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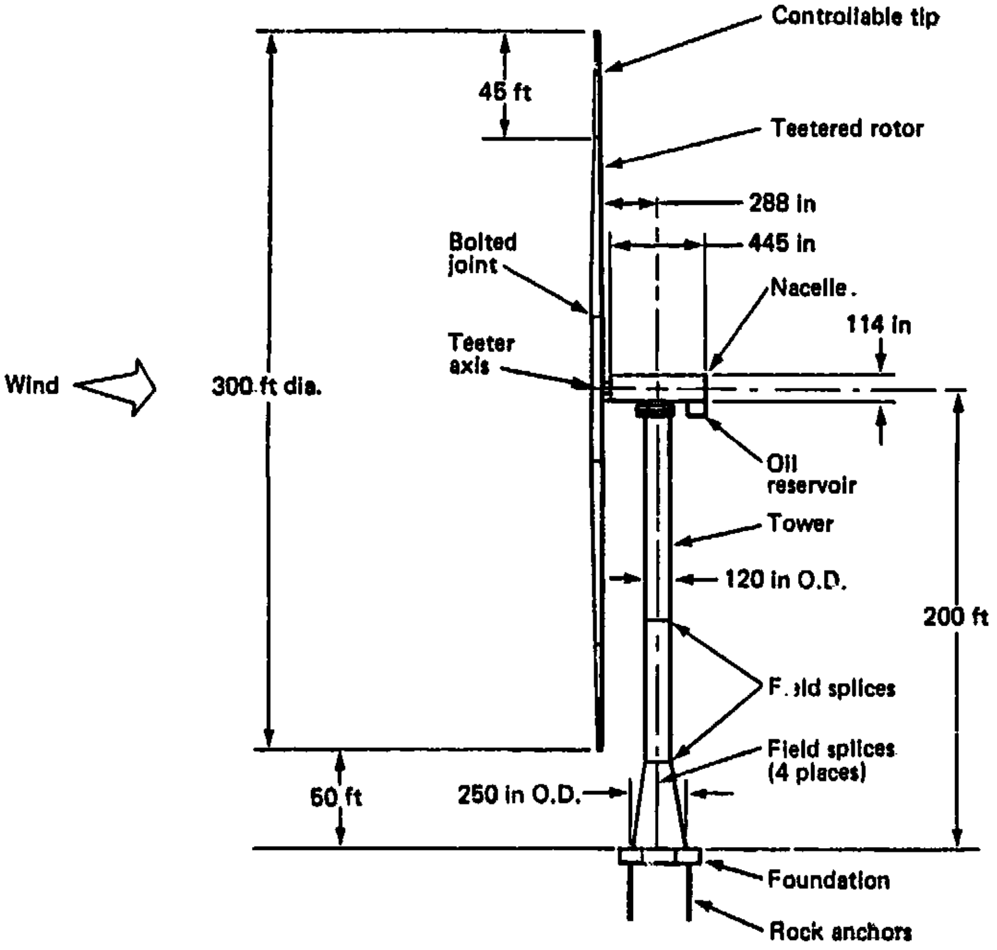

Figure 1. - Configuration features and characteristics.

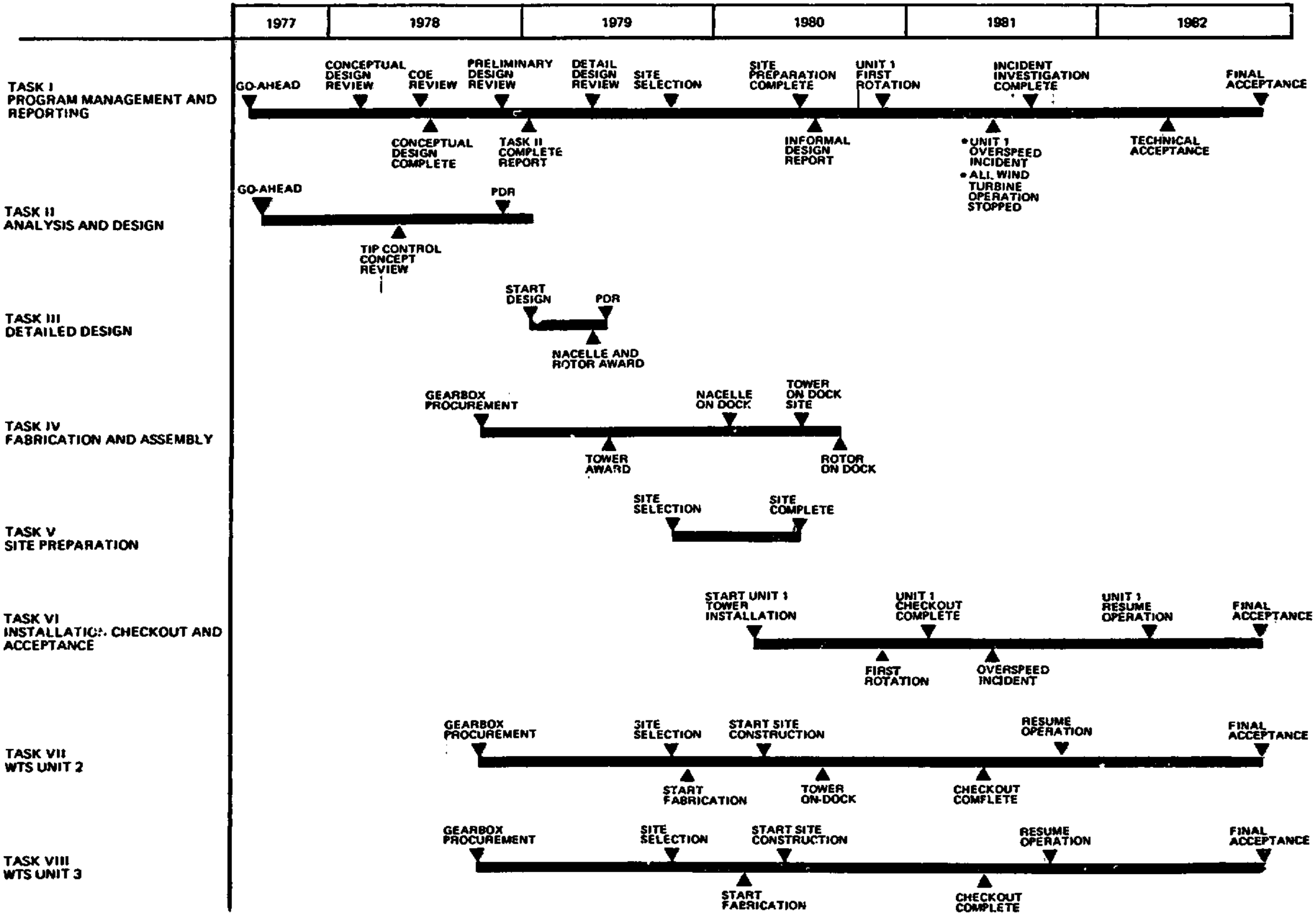

Figure 2. - As completed mod-2 contract schedule.

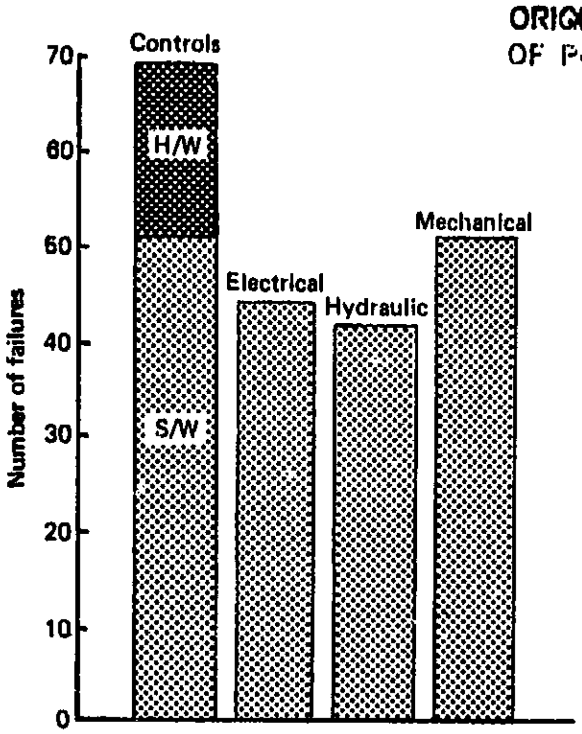

Figure 3. - Failure distribution.

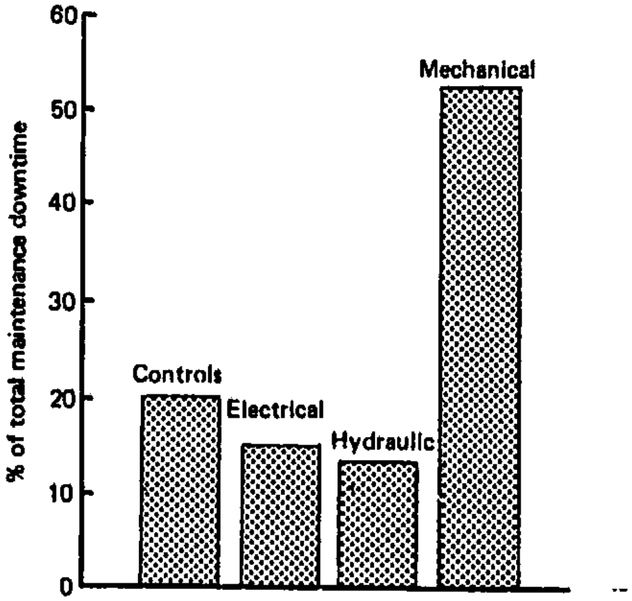

Figure 4. - Maintenance downtime distribution.

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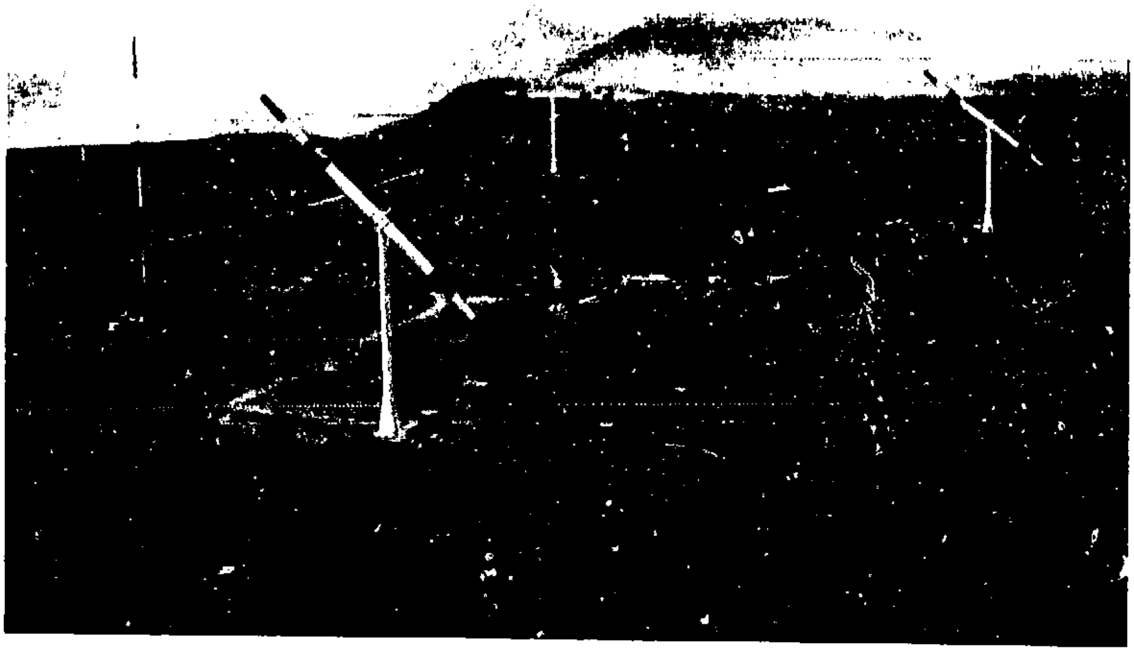

Figure 5. - Goodnoe Hills site near Goldendale, Washington.

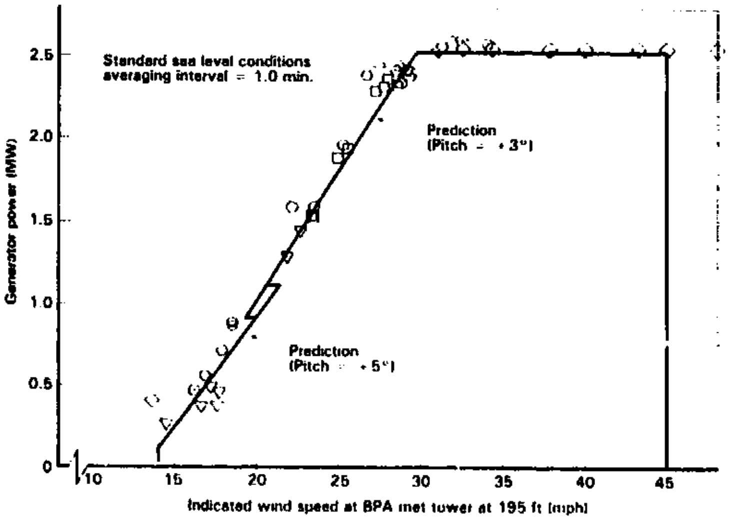

Figure 6. - Performance curve for Mod-2 (turbine 2).

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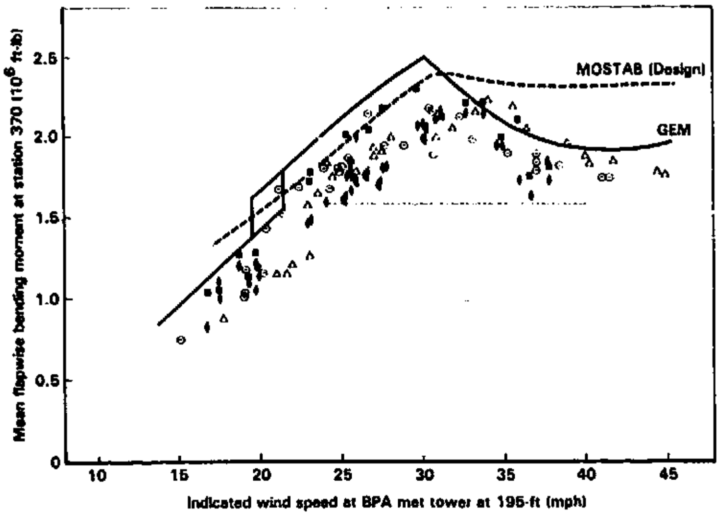

Figure 7. - Mean flapwise bending moment at station 370 (turbine 3).

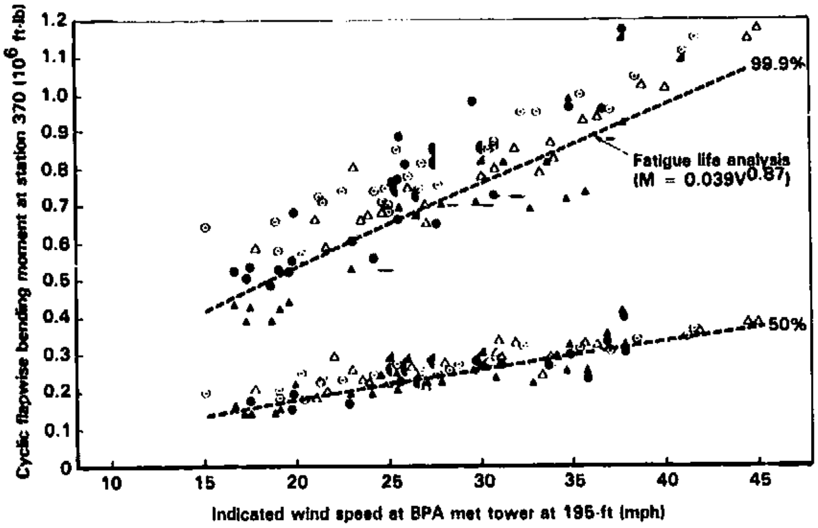

Figure 8. - Cyclic flapwise bending moment at station 370 (turbine 3).

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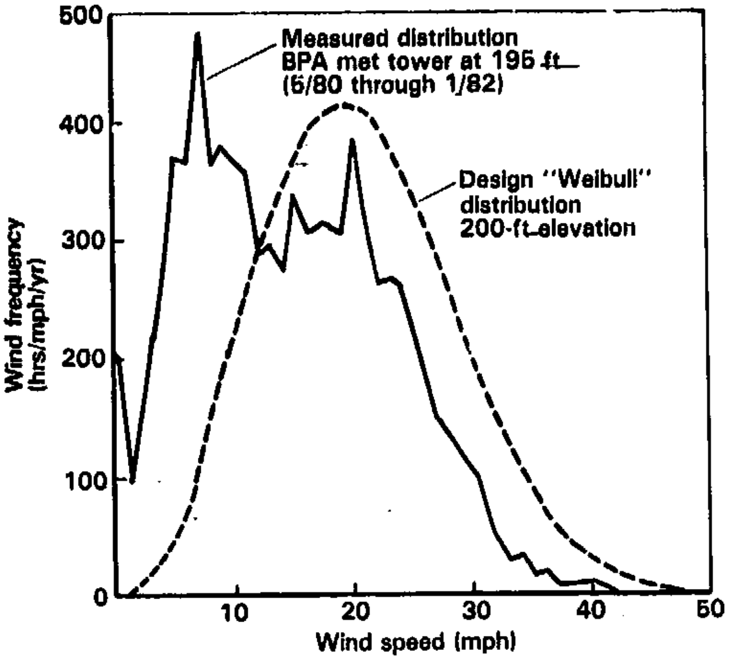

Figure 9. - Mod-2 wind speed frequency distribution.

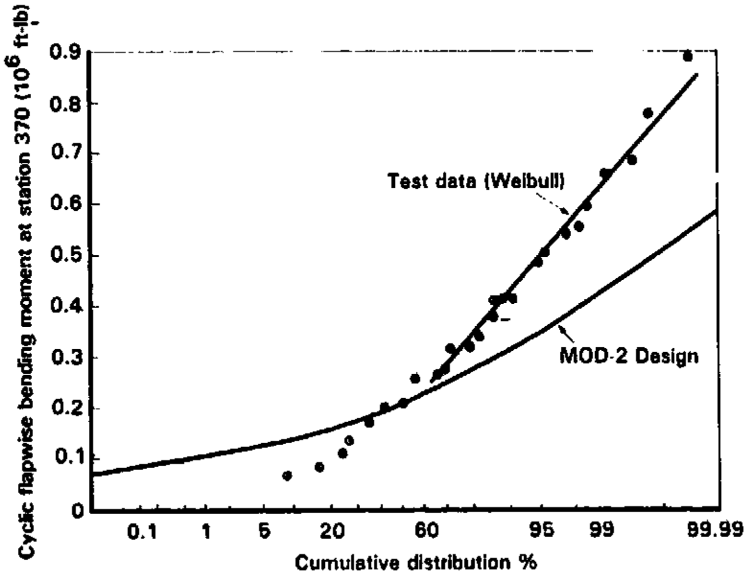

Figure 10. - Cumulative probability of cyclic flapwise moment at station 370.

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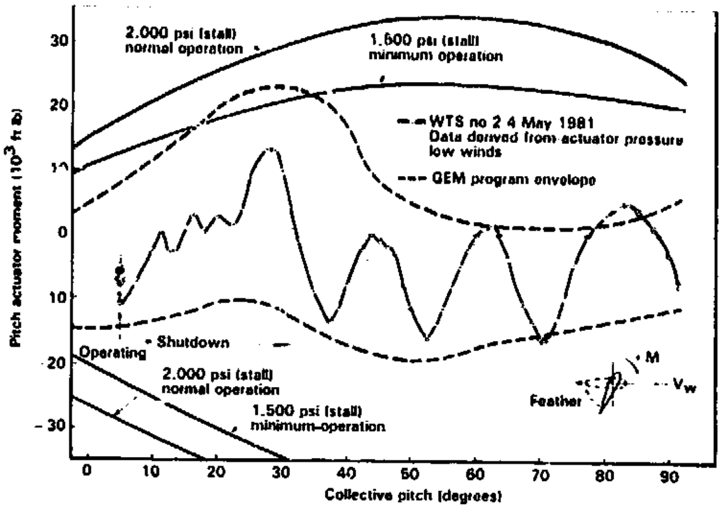


Figure 11. - Pitch actuator moments during emergency shutdown.

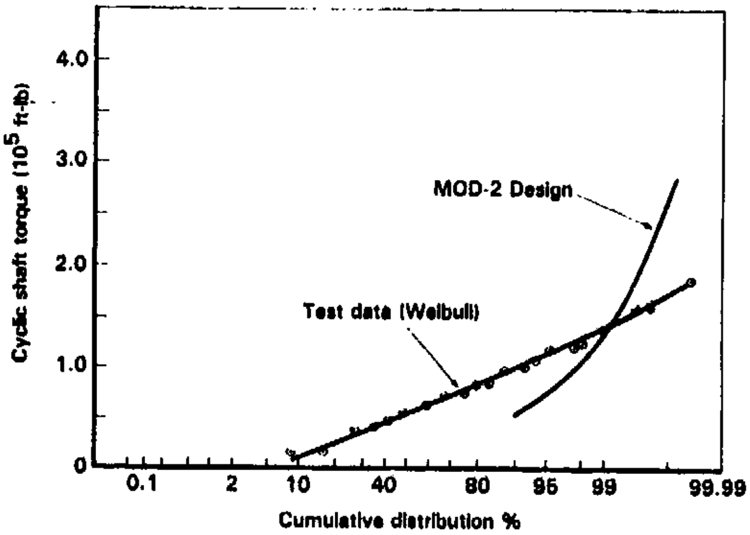
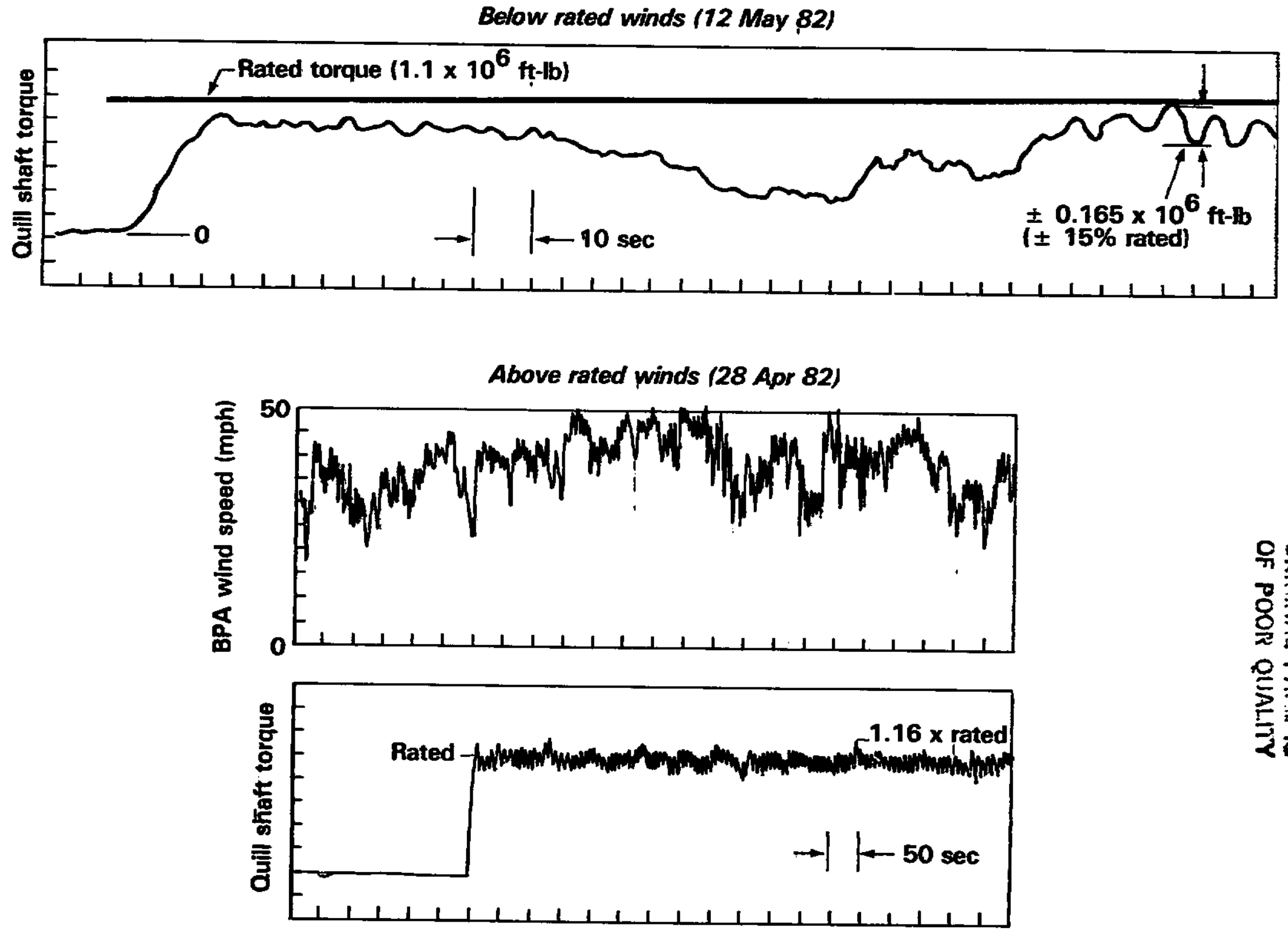


Figure 12. - Cumulative probability cyclic quill shaft torque.



Below rated winds (12 May 82)

Above rated winds (28 Apr 82)

Figure 13. - Quill shaft torque time histories.

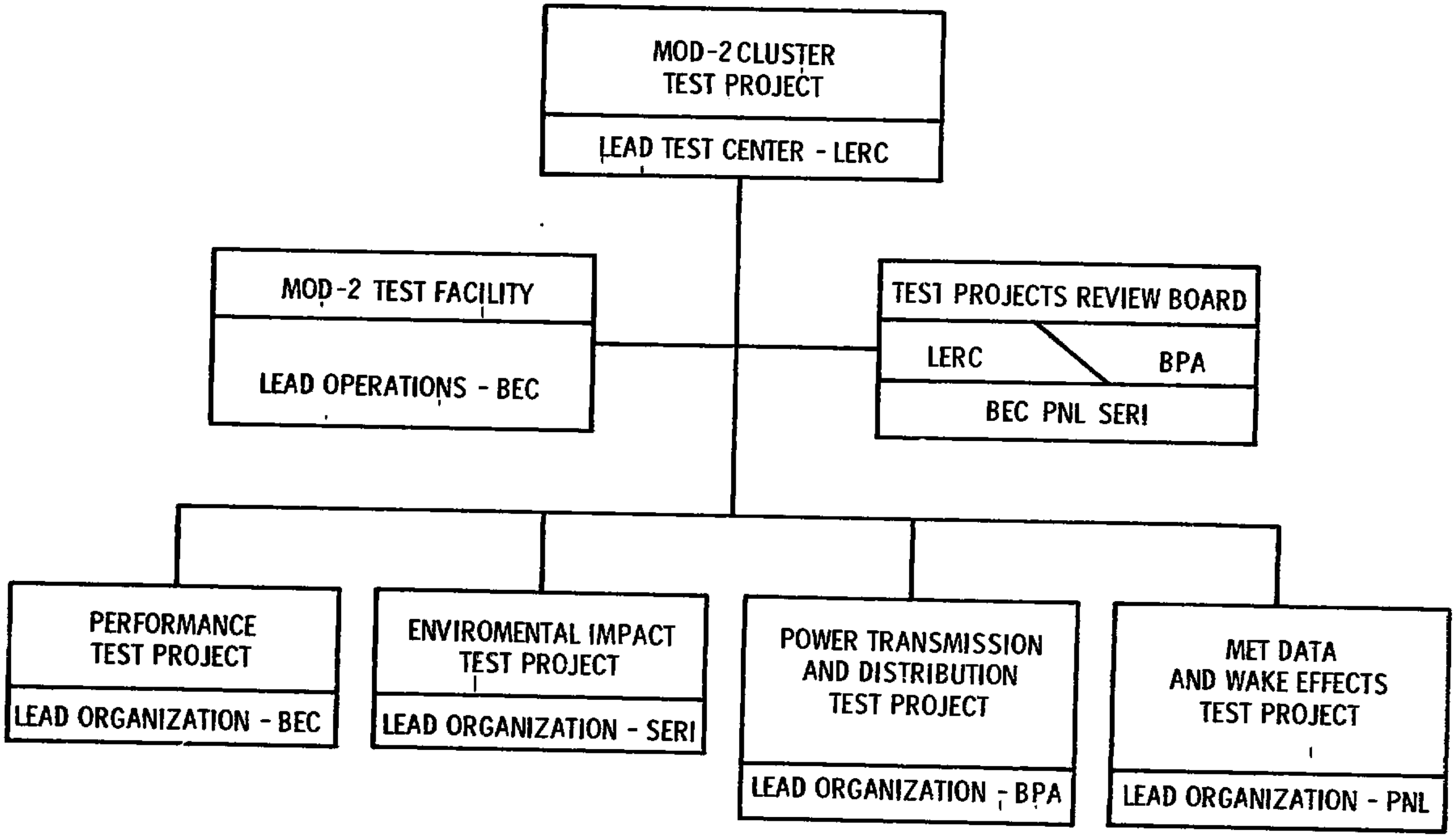


Figure 14. - Mod-2 research test management structure.