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Government Review of the Mod-2 Wind Turbine (As-Built)

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SUMMARY

A Government committee was formed to conduct an as-built review of the three Mod-2 wind turbine units at Goldendale, Washington. The purpose of the review was (1) to identify any critical components and subassemblies which may be deficient in either strength or predicted service life, the failure of which would cause safety hazards or significant downtime and expensive repairs; and (2) to recommend any corrective action necessary to enable continued safe attended and unattended machine operation.

Detailed site inspections together with a review of all project documentation and some additional analysis were used to establish a list of 29 candidate critical components. From this list, seven components were selected as critical components needing more extensive study and analysis, and accordingly given major emphasis in this review. However, the concerns associated with all 29 components were addressed and closed out in this review process.

This report documents the findings and recommendations of this review process. The recommendations are grouped in four categories to establish the specific time frame in which these recommendations should be implemented. The Mod-2 project office will make the final decisions regarding implementation, when considering any new information, available funding, schedules, and overall program redirection.

The key conclusions of this study are as follows:

(1) There were no deficiencies identified in this review process that would preclude planned near-term attended operation of the two available Mod-2 units. However, some of the concerns require immediate corrective action and/or careful inspection at frequent intervals during the attended operation.

(2) Several of the critical components reviewed, such as the teeter system and rotor cap, have potentially serious deficiencies that require corrective action in order to increase the long-term operational life of the machines in the unattended mode of operation.

INTRODUCTION

BACKGROUND

The Mod-2 wind turbine program was initiated in August 1977 when Boeing Engineering and Construction (BEC) was awarded the contract for development of a multimegawatt wind turbine system. This project was a continuation of the U.S. Department of Energy programs specifically structured to achieve a significant advancement towards early commercial generation of cost competitive electrical energy from wind power.

The design characteristics and features of the Mod-2 system are shown in figure 1. The first of the three units installed at the Bonneville Power Administration site near Goldendale, Washington, achieved first rotation in November 1980, with the other two following in March and May of 1981. Although subsequent operation has been faced with various operational problems as well as major component failures, the three machines have accumulated over 3700 hr of operation to date. This operation has led to the establishment of an extensive engineering data base essential to the continued development of wind turbine technology.

In addition to the three units at Goldendale, Boeing has installed a Mod-2 unit at Medicine Bow, Wyoming, for the Department of the Interior, and a fifth unit at Solano County, California, for Pacific Gas and Electric. The operational history and hardware inspections of all five units were used as input to this as-built review process. This report will refer to the Goldendale units as WT1, WT2, and WT3; the Medicine Bow unit as WT4; and the Solano unit as WT5.

The failure of the low-speed shaft on WT1 in November 1982 prompted the Government to initiate an as-built review of the Mod-2 units. The justification for this review is the need to avoid additional machine failures resulting from undetected deficiencies in design and/or manufacture. These deficiencies could result in component failures that could cause safety hazards, or result in costly repairs and significant periods of machine downtime. It should be recognized that some deficiencies resulted from measured loads data not available at the time of initial design.

The rotor on WT1 has been removed rendering this machine inoperable until a new low-speed shaft is installed. However, there was a need to perform research testing on WT2 and WT3 during the interim period in the attended mode of operation, providing this could be accomplished safely. Thus, this review not only recommended corrective action for any deficiencies identified for the long-term unattended operation of the units, but also determined what corrective action was needed for the short-term attended operation of WT2 and WT3. This attended mode of operation extended from April into August of 1983. All three units were scheduled to be returned to full-time unattended operation by the end of the year.

A memo establishing the Government Review Committee and its charter is found in appendix A. Several personnel changes in the committee have been made since the date of the memo. The current committee includes seven NASA Lewis personnel people and one Bonneville Power Administration representative listed as the eight authors of this report.

OBJECTIVE

The objectives of the Mod-2 Government review were (1) to identify any critical components and subassemblies which may be deficient in either strength or predicted service life, the failure of which would cause safety hazards or significant downtime and expensive repairs, and (2) to recommend any corrective action necessary to enable continued safe attended and unattended machine operation.

MILESTONES

The objectives stated previously were realized with the successful completion of the following three milestones:

(1) Establish a list of critical components or subassemblies which could be deficient in either strength or predicted service life

(2) Establish which (if any) of the above deficiencies were critical to future attended and unattended operation

(3) Recommend any corrective actions that must be taken before attended and unattended operation can be resumed

APPROACH

BOEING SUPPORT ACTIVITIES

The Mod-2 Project Office issued a contract task order to Boeing Engineering and Construction, the Mod-2 contractor, on January 27, 1983, to provide the necessary support to the Mod-2 Government Review Committee. (See fig. 2.) This task order enabled the contractor to supply the necessary personnel, services, analysis, tests, materials, equipment, and facilities to accomplish the following items:

(1) Conduct detailed site inspections of Mod-2 units at Goldendale and Medicine Bow (results of the WT5 inspection at Solano provided by Boeing were outside the scope of this task order)

(2) Establish a list of components or subassemblies which could have critical deficiencies

(3) Conduct whatever analysis or study is needed to establish which (if any) of the above deficiencies are critical to future attended or unattended modes of operation

(4) Prepare and recommend any corrective actions that must be taken to permit future attended and unattended operation

(5) Document all findings in a final as-built review report

The Government Review Committee worked very closely with Boeing during this review. Government and Boeing personnel with similar specialities and areas of responsibility were encouraged to communicate on a one-on-one basis.

SITE INSPECTIONS

Boeing personnel representing their operations group, project engineering, and quality control office participated in the engineering site inspections. The same inspection team was used at all three sites (Goldendale, Medicine Bow, and Solano) in an attempt to provide consistency in the inspection process and uniformity in the subsequent assessments. At the start the inspection team was limited to looking for the following items:

(1) Nonconformance of components with drawings
(2) Evidence of movement of bolted parts
(3) Corrosion
(4) Cracked paint

Documentation such as drawings, nonconformance reports (NCR's), problem reports, appropriate failure mode and effects analyses (FMEA's), etc. were also reviewed.

Several of the Government Review Committee members also inspected the Mod-2 units at Goldendale and Medicine Bow. In general their findings concurred with the Boeing assessment. The inspections for each of the components are discussed in the section FINDINGS AND RECOMMENDATIONS; some of the major findings are summarized in appendix B.

CANDIDATE CRITICAL COMPONENTS

The initial requirement of this review was to establish a complete list of Mod-2 components and/or subassemblies that were candidates for selection as critical components. The following criteria were used:

(1) Failure of this component would cause a safety hazard to personnel, result in a long machine downtime, and/or be very costly to repair.

(2) Concern for this component must be supported by physical evidence of defects and/or nonconformance to drawings, or structural analysis predicting an inadequate margin of safety or dramatically decreased service life. As discussed later, however, this was not applicable to all of the electrical components.

The initial list of candidate critical components established jointly by Boeing and the Government, after a review of the site inspection reports and other project documentation, included 16 structural and mechanical components and 12 electrical components. Two of the structural and mechanical items were combined into one item, one electrical item was separated into two items, and one item switched from electrical to mechanical (emergency hydraulic system). Although the concerns regarding potential spar buckling were discussed during the course of the review process, the rotor spar was not formally added to the list of candidate critical components being studied. For completeness in this report, however, rotor spars will be discussed resulting in the list of 29 components shown in table I. For convenience in analysis and discussion, these 29 items were further categorized into various subsystems as indicated in the table. The ordering does not reflect any priority used in the analysis and study of the components.

The low-speed shaft and nacelle control unit were excluded from consideration by the Government Review Committee. The investigation of the low-speed shaft failure and the design and fabrication of a replacement shaft was considered by another committee. For the nacelle control unit Boeing has reviewed and analyzed this system in depth, and has implemented all corrective actions that appeared necessary.

SELECTION OF CRITICAL COMPONENTS

The Chief Engineer of the Wind Energy Project Office, with the consensus of the Government Review Committee and the Mod-2 Project Office, established a list of critical components. The rationale used to select these items from the list of candidate components was as follows:

(1) Priority established jointly by the Government Review Committee and Boeing
(2) Existing data base available for assessment and/or absence of previous reviews
(3) Impact of potential failure of that particular component
(4) Available resources

The following seven components, as indicated in table I, were selected as critical components:

Item No. 3 - Emergency hydraulic system
Item No. 7 - Teeter system
Item No. 8 - Rotor cap
Item No. 9 - Nacelle structure and major bearing supports
Item No. 11 - Yaw drive system
Item No. 16 - Tower, base, and foundation
Item No. 17 - Gin pole system

All of the above seven critical components were structural and mechanical components having a significant impact on operations if failure occurred. The failure of any one of the candidate electrical components would not cause significant direct downtime of the wind turbine. The seven critical components were selected as the ones needing more extensive study and analysis. Boeing was subsequently directed to concentrate their efforts on these items. However, the concerns associated with all 29 candidate components were addressed and closed out in this review process.

REVIEW PROCESS

Following completion of the site inspections and an assessment of these findings, the various candidate components were analyzed by using the updated loads shown in appendix C. Appropriate fatigue analysis described in appendix D was used to estimate component and subassembly lives. In some cases additional loads data, and/or further disassembly were needed to completely understand the problem or concern.

The Government Review Committee made two trips to Seattle to review in-depth with Boeing the work being accomplished in the review process. The first visit occurred near the start of the review process to identify the candidate critical components, and the second occurred at the end to review the overall findings and recommendations.

In the interim periods, information was exchanged by either one-on-one telephone calls, or by conference calls. In addition, Government representatives attended the weekly status review meetings at Boeing. The prime purpose of frequent communications was to confirm that all items were adequately addressed, as well as to reach a consensus between the Government and Boeing on the conclusions of the study.

DOE COMMITTEE REVIEW

In order to ensure the proper coordination between organizations involved with the Mod-2 wind turbine units, DOE established a Mod-2 wind turbine program review group. This advisory group monitored progress and provided overall coordination of management and policy issues regarding the Mod-2 repair and testing program. Thus, this group needed to be kept informed of the findings of the Government Review Committee during the conduct of this review. To accomplish this the Chief Engineer of the WEPO, with the support of the Government review committee chairman and the Mod-2 Project Manager, made three presentations to the DOE committee on the status of the review. The overall schedule of review activities, shown in figure 2, indicates when these three presentations were held.

FINDINGS AND RECOMMENDATIONS

The findings and recommendations of the Government Review Committee for each of the 29 components studied in this review (see table I) are presented in this section. The seven critical components are discussed in the first group of components, followed by a discussion of the remaining 10 noncritical structural and mechanical components comprising the second group. As stated in the previous section all of the seven critical components selected for in-depth study were structural and mechanical components. The 12 noncritical electrical components are discussed in the final group.

The discussion for each component defines the function of the component, the definition of the problem and/or concern, appropriate findings or analysis, and the recommendations for future operation. For both the critical as well as the noncritical components, there were no deficiencies identified that would preclude planned attended operation of WT2 and WT3, provided some corrective action is implemented. Several of the critical components such as the teeter system and rotor cap have potentially serious deficiencies that will require corrective action in order to increase the operational life of the machines in the unattended mode of operation.

The recommendations made for the various components are listed in four categories that define when these recommendations should be implemented. The categories are (1) prior to attended operation, (2) during attended operation, (3) prior to unattended operation, and (4) during unattended operation.

CRITICAL COMPONENTS

The seven critical components include the emergency hydraulic system, teeter system, rotor cap, nacelle structure and major bearing supports, yaw drive system, tower-base foundation, and the gin pole system.

Item No. 3 - Emergency Hydraulic System. - The rotor-pitch hydraulic system is designed to control the pitchable blade tips during normal wind turbine operation, and to pitch the blade tips to the feather position for system shutdown. The pitch hydraulic system consists of standard, off-the-shelf hydraulic components, with the exception of a specially designed hydraulic reservoir.

Concern: Undetected internal leakage in the pitch hydraulic system could cause loss of emergency shutdown capability. This concern was established by tests conducted on WT5.

Findings: System and accumulator check valves from WT1 were examined and found to be of a design in which the poppet could cock and jam open, particularly after wear. Evidence of poor poppet contact on the seat was also found. Procedures to detect and isolate internal leakage were found to be inadequate.

Recommended action: Recommended actions prior to unattended operation are as follows:

(1) Replace system check valves with an acceptable type to reduce leakage potential

(2) Revise Operations and Maintenance Manual to provide more detailed internal leakage check and isolation procedures

Item No. 7 - Teeter System. - The teeter system, shown in figure 3, provides the rotor with a single degree of rotational freedom that is limited to ±6.5° out of the plane of rotation. The primary structural elements, shown in detail in figures 4 to 6, include the following:

(1) Two elastomeric radial bearings
(2) Two elastomeric thrust bearings
(3) Two teeter bearing (radial and thrust) housings
(4) Teeter-stop support structure
(5) Teeter brake

The elastomeric radial bearings allow angular teeter motion of the rotor with respect to the low-speed shaft. These elastomeric radial and thrust bearings transmit the rotor loads into the rotor cap. These loads flow through the rotor cap, and into the low-speed shaft. The thrust bearings are oriented so that they carry the maximum component of rotor weight when the rotor is horizontal. When the rotor is vertical, the weight of the rotor is carried by the radial bearings. The rotor cap structure interfaces with the low-speed shaft at one end and supports the rotor cap trunnion at the other end. The radial and thrust bearing housings, due to their planform shape, are commonly referred to as the "horsecollars." Each horsecollar is attached to the rotor spar with 12, 1.5-in-diameter grade 5 body fit bolts. A plastic shim material was used to fill small irregularities, and thus provide optimum flatness to the mating surfaces. A large diameter steel cylinder serves as the housing for the elastomeric radial bearing. This cylinder is welded circumferentially, both on the inside as well as on the outside, to the horsecollar, thereby securing the elastomeric bearing to the horsecollar. The horsecollar provides the means to limit the rotor-teeter angle. A portion of the horsecollar structure is designed to bear against a teeter-stop support structure. The teeter-stop support structure is mounted to the low-speed shaft. When the rotor-teeter angle is at its maximum travel (±6.5°) the horsecollar bears against the teeter stop (metal-to-metal contact), thereby limiting its motion. Finally the rotor cap is attached to each elastomeric radial and thrust bearing by 16, 1.0-in-diameter grade 8 bolts.

Concern: The results of the engineering site inspections led to the following concerns:

(1) Possible movement at horsecollar-to-rotor spar interface might indicate higher loads than anticipated.

(2) Teeter-stop loads might be higher than those used in the analysis.

(3) Elastomeric surface cracks might impact structural integrity.

Findings: A summary of the BEC findings, as a result of the site inspections and analysis, are as follows:

(1) Iron oxide stains, indicating fretting at the horsecollar-to-rotor spar interface, were observed at location 1, figure 5, on all five Mod-2's.

(2) Evidence of plastic shim failure was observed at location 7, figure 5, on WT4 and WT5.

(3) Poor fit up (gap) at horsecollar-to-rotor spar interface was observed at location 3, figure 5, on WT5.

(4) Weld flaws were observed at location 4, figure 5, on WT4; and a possible weld crack at the same location on WT2.

(5) Surface cracks were observed on the elastomeric radial bearing at location 5, figure 5, on WT4.

(6) A gap was observed at location 6, (see fig. 5) on WT4 between the elastomeric thrust bearing and rotor spar for the lower thrust bearing with the rotor horizontal, indicating a significant reduction in preload.

(7) The bolts, location 7, figure 5, used to attach the horsecollar to the rotor, were torque checked. The torque measurements were lower than the original torque values at assembly.

(8) Evidence of high teeter-stop loads at location 8, figure 5, were observed on WT5 This was presumably a result of nonoperating rotor-teeter motion in winds above cut-out velocity.

(9) Analysis showed that the preload on the teeter-stop fitting bolts, figure 6, was insufficient to prevent slippage of the fitting.

The Government Review Committee and BEC performed a visual inspection on WT4 at Medicine Bow, in February 1983. The results of the inspection of the elastomeric teeter bearing, teeter stops, and horsecollar are summarized below.

(1) Cracking over the surface of the elastomer was found.

(2) A weld separation, in excess of 0.03 in extending one-third of the circumference, was found in the weld attaching the steel retainer of the radial bearing to the horsecollar.

(3) The steel teeter stop was torn and galled. The bolts used to fasten the teeter-stop to the teeter-stop support structure showed evidence of being loose.

(4) The horsecollar showed signs of shifting with respect to the rotor blade spar.

Inspection of this same hardware on the three Mod-2 machines at Goldendale was conducted in March 1983. The elastomeric bearing surfaces contained cracks, but these were less severe than those found on WT4. Cracks found in the painted surface over the weld joining the steel retainer of the radial bearing to the horsecollar on WT2 were an indication of possible cracks in the weld joint. The horsecollar showed signs of shifting on WT1. However, this discrepancy was not noted on WT2 and WT3.

Inspection was carried out to check the preload in the elastomeric thrust bearings. The inspection results were analyzed and the estimate of preload was between 50 000 to 70 000 lb. The design preload range for the thrust bearings was between 166 000 to 270 000 lb. The lower design preload value was determined by using the lowest specified spring rate (1.11×10^6 lb/in) for the thrust bearing and the minimum deflection of 0.15 in. The 270 000-lb value was obtained by using the highest spring rate (1.35×10^6 lb/in) and maximum preload deflection of the bearing of 0.20 in. BEC did not conduct an analysis to assess the effects of loss of thrust bearing preload.

A review of BEC drawings indicated a lack of information on the procedure for installing the teeter bearing assembly in the rotor. For example, the procedure for obtaining the proper preload in the elastomeric thrust bearing is not adequately described. Also the location of the shim material used to control the thrust bearing preload is not called out.

The mechanical shifting of the horsecollar and the damaged teeter stops are probably a result of the teetered rotor impacts that occur when the rotor is stopped and subjected to winds above the cut-out velocity. Further structural and mechanical damage can be eliminated by damping the teeter motion of the rotor while the rotor is stopped. In addition to the teeter motion damper, rotor azimuthal positioning control may be an effective means of reducing teeter motion in high winds. During the attended operations made in high wind conditions, the effectiveness of rotor azimuthal positioning on teeter motion should be investigated.

Recommended action: Recommended actions prior to attended operation are as follows:

(1) Retorque bolts attaching teeter bearing to rotor blade

(2) Increase torque on teeter-stop support-structure attachment bolts to 80 percent of yield

Recommended actions during attended operation are as follows:

(1) Establish procedure for and monitor motion between the following:

(a) Rotor blade and horsecollar
(b) Low-speed shaft and teeter stop
(c) Trunnion and pilot ring

(2) Establish procedure for and monitor elastomeric thrust bearing gap

(3) Disassemble WTI horsecollar structures from rotor and inspect

(4) Provide strain measuring instrumentation

(5) With the manufacturer, evaluate the seriousness of the surface cracks in the elastomeric bearings

(6) Determine cause of weld separation between horsecollar and radial bearing retaining ring

(7) Determine effect of parked rotor position on teeter motion

Recommended actions prior to unattended operation are as follows:

(1) Design, fabricate, and install a teeter motion damper

(2) Replace plastic shim between horsecollar and rotor with steel shim

(3) Determine cause of loss of preload in thrust bearing and take corrective action

Item No. 8 - Rotor Cap. - The rotor cap structure is shown in figures 4 and 7. The large cylindrical portion of the rotor cap has a flange at one end for mating with the low-speed shaft flange. The rotor cap and low-speed shaft flanges are connected with bolts, as shown in figure 7. The smaller diameter flanged cylindrical portion of the rotor cap is called the trunnion. The trunnion is welded to the inside and outside walls of the larger cylinder along the intersection of the two cylinders. Reinforcing gussets are welded at two locations as shown in figure 7. The trunnion flanges are bolted to the elastomeric teeter bearing.

Concern: The loads used to design the rotor cap are significantly lower than the loads currently acting on the structure.

Findings: A summary of the BEC findings are as follows:

(1) Evidence of corrosion at the rotor cap trunnion and teeter bearing interface, was found on the WT4 and WT5.

(2) Evidence of motion at the thrust bearing and teeter bearing interface was observed on WT5.

(3) Cracked paint and evidence of corrosion on the gussets of WT2 was found. Also, poor weld quality at the ends of the gussets was noted on WT4.

(4) An inspection of the rotor cap and low-speed shaft bolted flange joint showed the following:

(a) Wrench marks in the flange fillet radius of the rotor cap on WT1
(b) Machine marks in the flange bolt holes on WT1
(c) Evidence of fretting corrosion at the flange joint interface on WT5

A structural analysis of the rotor cap was performed by BEC as part of the inspection and audit review. In the case of high cyclic loading (fatigue) conditions the critical parts of the rotor cap were identified. An estimate of the fatigue performance for each part was made. The results are summarized in the following table:

Rotor cap part	Fatigue performance (hr before repair)
Trunnion and teeter bearing pilot ring	4700
Trunnion and teeter bearing bolts	19 after failure of pilot ring
Welded gusset	400
Intersection weld trunnion	3300

A critical structural area is the trunnion-to-elastomeric bearing interface. If the pilot ring fails to carry the interface loads, the bolts at the trunnion to elastomeric bearing interface will carry the load for an estimated 19 hr. The potential advantage of increasing the diameter of these bolts was not analyzed. Further analysis is needed to determine if larger bolts are desirable and practical. Methods for strengthening the pilot ring should be considered. Installation of a close tolerance backup ring is one possible method for increasing the fatigue performance of the pilot ring. Another approach is to investigate inserting steel dowel pins between the bolts.

The BEC analysis of the rotor cap shows negative margins of safety for limit loads applied to certain portions of the rotor cap. This particular load condition accounted for teeter "banging" that occurred when the rotor was stopped and subjected to high winds. All negative margins can be eliminated by the installation of an effective rotor-teeter damper. The teeter damper should substantially reduce the high impact type loads currently being absorbed by the rotor cap.

The Government inspection found 8, 0.5-in-diameter holes drilled through the cylindrical wall of the rotor cap at station 1 and station 19 as shown in the BEC drawing 032-418000. The purpose of these holes is for inserting bolts used to secure hydraulic line brackets. Structural analysis of the rotor cap to take into account the effects of these holes on the structural integrity of the rotor cap was not done.

Recommended action: Recommended actions prior to attended operation are as follows:

(1) Grind gusset weld details to improve weld to a class "C"

(2) Increase bolt torques of rotor cap and low-speed shaft bolted flange joint

(3) Increase bolt torques at trunnion and teeter bearing assembly joint

Recommended actions during attended operation are as follows:

(1) Monitor movement indicators (e.g., dental paste) at rotor cap-to-low-speed shaft and at trunnion-to-teeter interfaces

(2) Conduct further analysis and/or experimental evaluation of the following:

  (a) Rotor cap and low-speed shaft bolted flange to determine cyclic stress range
  (b) Trunnion and rotor cap intersection weld to determine stress variation around circumference
  (c) Rotor cap cylinder wall stress in presence of drilled holes

(3) Instrument the following for strain determinations:

  (a) Critical gusset weld
  (b) Critical circumferential location at the trunnion and rotor cap intersection weld
  (c) Rotor cap near rotor cap and low-speed shaft bolt flange

Recommended actions prior to unattended operation are as follows:

(1) Increase bolt size and preload at low-speed shaft-to-rotor cap interface

(2) Install additional gusset plates, as required, at trunnion and rotor cap intersection weld

(3) Repair or redesign pilot interface

(4) Grind fillet weld wrench marks and increase washer thickness to provide adequate clearance

<u>Item No. 9 - Nacelle Structure and Major Bearing Supports</u>. - The primary functions of the nacelle are as follows:

(1) Provide a rigid mounting platform for the major subsystems such as drive train, generator, yaw bearing and drive, and associated support equipment

(2) Serve as the structural path for loads that must be transmitted from the rotor to the tower

(3) Provide environmental protection for components

The nacelle structure is of welded steel truss construction. The downwind low-speed shaft bearing supports are bolted to the nacelle structure, and the upwind low-speed shaft bearing support is welded to the nacelle structure.

Concern: The differences between the original design loads and the Mod-2 acceptance test data could impact the structural integrity of several areas in the nacelle, including the major bearing supports.

Findings: Inspection of the downwind bearing supports, shown in figure 8, indicated the following:

(1) Two out of the eight bolts were undertorqued by 20 percent on WT3.

(2) Undesirable gaps existed at bolt clamp up interfaces on all units.

(3) Cracked paint was present at the edges of shims indicating possible working on all units.

(4) In WT5 there was an apparent 0.060-in upwind shift of the downwind bearing support.

A visual inspection of critical weld areas in the nacelle did not identify any failures. The fatigue analysis estimated "time to repair" values varying from 6 mo to 10 yr as shown in figure 8. The analysis was based on the assumptions listed in appendix D.

Recommended action: Recommended actions prior to attended operation are as follows:

(1) Reshim the downwind bearing bolted joints to obtain proper clampup at the interface, and install new bolts, washers, and nuts

(2) Grind welds on the secondary verticals of the primary truss structure

Recommended action during attended operation is as follows:

(1) Install instrumentation to obtain stresses at critical locations in the downwind bearing support and primary nacelle truss structure

<u>Item No. 11 - Yaw Drive System</u>. - The original Mod-2 yaw drive system, as shown in figure 9, consisted of a hydraulic power supply and drive motor, speed reducing gearbox, pinion gear, ring gear, six yaw parking brakes, and a drag brake to provide damping during yaw motion. The drag brake was removed in March of 1982 because it was ineffective in providing yaw damping.

Concern: The structural integrity of the yaw drive system was a concern because of a history of problems, as well as recent data showing the system was being subjected to high impulsive loading.

Findings: By using BEC nonconformance reports the following history was developed: Evidence that the yaw drive was being overloaded began to be observed in June of 1981 on WT2 after 122 hr of operation. Tapered dowel pins in the yaw drive retaining plate were found to be loose. Further examination revealed that most of the retainer bolts were loose. Additional dowel pins were inserted and the bolts retorqued. In March of 1982 these same bolts were again found to be loose in WT2 and WT3 after a total of about 250 hr of operation on each machine. The bolts were replaced with longer bolts so that lock nuts could be installed. At about this same time, after a history of numerous problems, the yaw drag brake was disconnected because tower torque measurements showed that it was ineffective in damping yaw motions. On August 24, 1982, after about 120 hr of operation, a crack was found in the yaw drive gearbox case of WT5 and the gearbox was replaced.

Of all the components examined during the Government inspection of the Goldendale site, the yaw drive system showed the most obvious signs of damage and improper installation. Examination of the ring gear showed yielding and wear of the teeth over a sector of about 25°. Because of the predominant directionality of the winds at this site, the pinion works the ring gear over a relatively small sector most of the time. Alignment between the pinion and ring gear was such that contact between these two gears was maintained along only about one-third of the tooth width. The manufacturer of these gears recommends a minimum of 85 percent tooth surface contact. BEC measured backlash values between pinion and ring gear as large as 0.110 in. The manufacturer recommends backlash of 0.023-in minimum to 0.044-in maximum.

The pinion gear specification calls for heat treatment to BHN 350/425. The ring gear specification calls for heat treatment to BHN 250/300. With the pinion gear having the harder surface, alignment and tooth surface contact become very important. Without proper alignment and tooth contact, excessive wear and possible tooth breakage can occur. Slivers of metal, as shown in figure 10, were removed from one ring gear.

During Mod-2 operation, just prior to the low-speed shaft failure, measurements of hydraulic pressure at the yaw drive motor ports were made. These measurements, shown in figure 11, showed pressure impulses of close to 2000 psi (system design pressure) when yawing took place while the rotor was at normal operating speed (17.5 rpm). If yawing took place when the rotor was coming up to operating speed, higher peak impulse pressures were observed. The impulsive nature of the pressure measurements is a result of the cyclic yawing moments produced by the rotor and backlash in the gear teeth. Because of the backlash, the nacelle can rotate through a small angle unrestrained except for friction in the yaw bearing. This motion continues until the ring gear impacts the pinion gear causing a pressure spike in the drive motor.

These pressure measurements provide evidence that the yaw drive system was being subjected to loading that was not considered in its design. Design torques for the yaw drive gearbox were 11 600 ft-lb steady and 37 500 ft-lb limit. There was no specification for cyclic loading. Estimated actual loading was based on yaw drive motor pressure measurements. Measured steady or mean torque was about 5000 ft-lb and measured cyclic peak torque was about 32 500 ft-lb. The frequency of the cyclic torque was about one per rev, instead of the anticipated two per rev, indicating blade-to-blade imbalance. The effect of this loading on yaw gearbox life has not been assessed.

The consequences of a failure in the yaw drive system were considered. The most serious failure was one that would leave the nacelle totally unrestrained in yaw. The nacelle and rotor would yaw out of the wind in an uncontrolled manner. Large yaw errors could result in severe teeter-stop impact loads that may damage the rotor and drive shaft. Because shutdown for yaw error is based on a two-minute average, a condition of large yaw error (greater than 20°) could exist for that length of time.

A number of steps could be taken to reduce yaw drive system cyclic loading. The most severe loading could be alleviated by preventing yaw corrections when the machine is starting up or shutting down. This could be done manually during attended operation and with software changes during unattended operation.

During attended operation, additional methods for reducing yaw drive system impulsive loading should be investigated. These methods should include the following:

(1) Placing a crossover relief valve in the hydraulic system to limit the pressure buildup in the system

(2) Dragging one or more of the yaw parking brakes during yaw corrections to introduce additional damping into the yaw drive system

The latter method has been found to be very effective in protecting the yaw drive system in the Mod-0 and Mod-0A wind turbines from high cyclic loading. Additional yaw position instrumentation and yaw control logic should be introduced to reduce the length of time the wind turbine can operate with large yaw errors.

Recommended action: Recommended actions prior to attended operation are as follows:

(1) Assess the effect of impulsive loading on yaw gearbox life

(2) Clean and relube pinion and ring gear teeth

Recommended action during attended operation is as follows:

(1) Prevent yaw corrections from taking place during wind turbine startups and shutdowns

Recommended actions prior to unattended operation are as follows:

(1) Rotate the ring gear 90°

(2) Align pinion gear to ring gear so as to bring tooth contact and backlash within the specifications of the manufacturer

(3) Install crossover relief valves

(4) Make software changes to prevent yaw corrections during startups and shutdowns, and to limit the duration of large yaw errors

(5) Experimentally determine the effect of dragging one or more of the yaw parking brakes during yaw corrections

<u>Item No. 16 - Tower, Base, and Foundation</u>. - The tower is a 193-ft-tall cylindrical shell structure, comprised of welded ASTM A572 steel plate. The tower is 10 ft in diameter with a base section flaring to 21 ft in diameter at

the ground. It is bolted to a foundation of reinforced concrete. At the Goldendale site 72 rock anchors, 28 ft long, attach the foundation to the bedrock.

Concern: Boeing reported that the WT5 tower had experienced fatigue crack growth from a large slag inclusion located at the 500-in station shop weld. Undetected cracks in the tower could eventually contribute to a catastrophic failure.

Findings: It is important to note that the Solano flaw, shown in figure 12, was first detected by an observation of rust stains on the exterior surface of the weld. Furthermore, this observation made by a BEC individual involved in another site assignment, proves that a 1.75-in crack can be detected by a visual inspection.

The following three approaches to detection of tower cracks were considered:

(1) Audit all radiographs now in existence and/or reradiograph

(2) Remove all reinforcement from the inside welds and penetrant inspect

(3) Visually inspect tower every 600 hr

The first approach of auditing radiographs was not considered feasible because only 10 percent of the welds were required to be radiographed on WT1 through WT4 as the inspection requirement. Reradiography would be expensive as well as present a safety problem.

The second approach was technically attractive because it provided reduced stress risers by smoothing the weld surfaces. In addition, this would make future inspections easier. However, the degree of weld surface preparation needed for subsequent penetrant inspections tend to make this approach less desirable.

The WT5 experience proved that simply inspecting the towers visually is an effective method of detecting crack lengths even under 2 in. Fracture mechanics predicts that the critical crack size for this particular location is 24 in for a 120-mph wind. The predicted tower crack growth rate is shown in figure 13. Thus, planned inspections at 600 hr intervals would give ample time to identify a crack before it became critical. Visual inspections of the inside of the towers for units WT1 through WT4 did not reveal any cracks in the welds. However, there was some mismatch detected that was in excess of drawing tolerance.

Additional inspections by Boeing as well as Government personnel resulted in the following observations:

(1) Inspection of base-to-tower studs on WT1 through WT4 showed disturbed paint on WT1 and WT2.

(2) Visual inspection of the tower grout revealed some hairline cracks, but no gaps or other indications of failure.

(3) A preload check of selected bolts on WT1 indicated that the initial preload of 85 000 ± 5000 ft-lb had dropped 15 to 20 percent on one-third of the bolts checked.

The integrity of the 72 rock anchors that attach the foundation to bedrock was not checked in this review due to manpower limitations when considering higher priority items.

Recommended action: Recommended actions prior to unattended operation are as follows:

(1) Visually inspect tower welds every 600 hr for cracks

(2) Retension all studs to 85 000 ± 5000 ft-lb

(3) Seal tower grout to prevent entry of water and possible corrosion

(4) Repaint base details

(5) Check preload on rock anchors

Item No. 17 - Gin Pole System. - The gin pole system, shown in figure 14, is used to hoist and bring down heavy components of the wind turbine. The system consists of a 250-ft boom (gin pole), two backstays, a boom rest tower, winch, and associated anchors, pulleys, and cables. The maximum safe lifting capability of the system is 200 000 lb.

Concern: The gin pole system was included as a part of this review because a structural problem with the system could possibly cause a catastrophic failure and/or excessive wind turbine downtime.

Findings: The gin pole system has performed satisfactorily to date except for a failure of a backstay anchor plate on WT1. Fortunately, the failure did not occur during a lift but while the cables were being straightened with the boom on the boom rest. The anchor plate failed because it was subjected to offset loading not considered in its design. All anchors were subsequently modified to handle offset loading.

The design specifications of the entire gin pole assembly, including the operational procedures to be followed during use, were reviewed in depth with Boeing personnel. The main element or gin pole is a 250-ft-long boom procured as a standard catalogue component used on cranes. The analysis used by the supplier established the load capacity of the boom at 700 000 lb. This translates to considerable load margins when considering rotor and nacelle lift weights approaching 200 000 and 175 000 lb, respectively.

As stated above the backstay anchors were redesigned following the failure and now have the capability to accommodate all loads within the established load envelope, including boom overloads. The base plate was analyzed and reinforced to yield a design margin of 1.41 for a rotor lift. The design margins on the cables and pulleys were greater than 3.5. Many of the catalogue items such as the shackles were procured having significant load margins.

No additional analysis was deemed necessary for some items such as wind stay anchors, support tower, winch, and anchor foundations. These items were designed initially with extremely high load margins, and, thus, did not warrant further examination.

A visual field inspection of the gin pole system indicated some evidence of rust on cabling, blocks, and moving parts. Obviously, the integrity of the system is a function of the degree of rusting present. If left unchecked there certainly would be further degradation that could make the system unusable when required. The safety considerations involving a catastrophic failure of the system during use are somewhat minimized by the proof load testing imposed prior to use.

Due to an increase in the weight of the new low-speed shaft design of 10 250 lb, additional weight must be added to the proof load test assembly to meet the requirements of ANSI B 30.7-1977, para 7-2.2.2.

Recommended action: Recommended actions prior to unattended operation are as follows:

(1) Add additional weight to the existing gin pole proof load to compensate for the increase in weight from modifications including new low-speed shaft assembly

(2) Incorporate formal gin pole Operations and Maintenance procedures which include assembly, disassembly, operation, proof test loads, maintenance, inspection, and corrosion prevention in the Operations and Maintenance manual

(3) Provide environmental protection of the gin pole winch assembly

NONCRITICAL STRUCTURAL AND MECHANICAL COMPONENTS

As shown previously in table I, the 10 noncritical structural and mechanical components are conveniently grouped into three separate subsystems as follows: Rotor assembly, nacelle, and drive train.

Rotor Assembly

The Mod-2 WTS has a steel, two-bladed, teetering, tip control type rotor with continuous carry through structure at the hub. As shown in figure 15, the rotor is divided into three primary sections as follows: the tip, the midsection, and the hub. A hydraulic actuator pitches the tip (outer 30 percent of the blade length) from approximately -5° to 90° with respect to the remainder of the blade to control rotor speed and power, and to provide aerodynamic damping of the power train.

The basic construction of the rotor blade is a welded steel shell with steel spar members. The blade has a field assembly bolted flange splice at blade radial station 360 which attaches the blade midsection to the hub.

The five noncritical rotor assembly items discussed in this section include the rotor pitch actuator, rotor spindle, rotor welds, rotor spars, and rotor blade equipment mounting holes.

Item No. 1 - Rotor Pitch Actuator. - Each blade tip is controlled by a hydraulic actuator attached to the tip by a rod-end spherical bearing as shown in figure 16. The other end of the actuator is attached to the rotor spindle bearing assembly. The outer bearing assembly is rigidly secured to the blade midsection by six, grade 8 bolts. After the bolts are properly torqued, the bolt heads are safety wired.

Concern: The overall concern questioned the strength of the actuator rod-end bearing assembly, and the resultant blade tip motion if this assembly should fail.

Findings: A review of the loads on this rod-end coupling showed a high margin of safety. The failure modes and effect analysis confirms that the wind turbine system will shut down if the actuator fails. A one blade shutdown was demonstrated as part of the original acceptance testing. Furthermore, a free rotor-tip flutter analysis indicates no teeter-pitch coupling that would cause the rotor to impact the teeter stops.

Recommended Action: No action required.

Item No. 2 - Rotor Spindle. - The attachment of the tip spindle assembly to the blade midsection, as shown in figure 16, is made by six bolts for ease of assembly and removal. The spindle protrudes into the blade midsection in a way which provides a load path for centrifugal and bending moments. Tapered rings at the outboard rib and a close tolerance machined bushing at the inboard rib assure a tight fit between the spindle sleeve and the midsection of the rotor. The bearings are lubricated with a long-life grease through a Zerk fitting. A vent plug is removed during greasing to assure that adequate greasing has occurred.

Concern: The three concerns that could impact the safe continued operation of the machines are as follows:

(1) Loss of rotor-spindle bearing grease and/or bearing preload could lead to premature bearing failure

(2) Loss of torque in bolts and/or the use of lower strength bolts than specified in the attachment of the spindle assembly flange to the blade midsection could cause loss of blade tip

(3) Use of plastic shim material between highly loaded mating steel surfaces

Findings: The bearing preload was maintained by six Belleville spring washers installed on the rotor spindle in two stacked sets of three washers for each blade. These washers were installed as specified on Boeing drawing 032-411311 and bench calibrated for exact stack height versus 168 000-lb design preload. Each match stacked set was cycled through a minimum of four, 0 to 168 000-lb loads, versus measured heights. Data reviewed showed excellent consistency or uniformity of spring rates (nominally 400 000 lb/in) with a maximum deviation of 0.001 in between the four heights measured during the calibration bench tests. The stacked height measurement is then permanently stamped to the rotor-spindle flange for the respective Belleville washer set installed. Each set is lubricated with grease during final installation to prevent corrosion.

Evidence of leaking grease was found during the inspection of blade No. 1 on WT1 at the rotor-spindle attachment interface flange. Closer inspection revealed that the grease seal was puckered out of its housing groove. Upon disassembly of the rotor-spindle assembly from the blade midsection, the large bearing was found to be damaged. Inspection of the grease seal revealed evidence of poor installation with two lumps of hardened white paint embedded in the face of the seal. The paint lump size, about 0.125-in square, caused the seal to pucker out of the bearing housing. Loss of grease due to high centrifugal force created a dry bearing, resulting in bearing failure. The bearing outer race that is shrunk-fit into the blade midsection housing had bearing roller impression depths of approximately 0.01 to 0.02 in. This occurred over approximately 90° of the circumferential surface of the bearing race. A reddish dry grease residue was very evident. Inspection revealed that the smaller inboard bearing was also damaged. Measurements of the bearing Belleville spring washers revealed a change in stack height of 0.10 in, which corresponds to a loss of 40 000 lb of bearing preload. Grease seal installation procedures, as described on Boeing drawing 032-421000, note 10, must be followed to prevent loss of grease.

Prior to disassembly of the rotor spindle, flange bolt torques were measured at station 1249. The specified torque was down by as much as 30 percent in two bolts. In addition, two other bolts were unmarked grade 2 bolts, and thus were of much lower strength than the grade 8 bolts required by the specification.

An inspection of the flange face of the blade midsection to which the rotor spindle assembly mates revealed that several of the tapped holes had been modified with threaded inserts. These were used because the original threads were stripped during handling operations prior to shipment to the site. This handling was accomplished by using too few bolts for the load, and thus the threads were stripped. If all bolts had been used in maneuvering the blade, no problem would have occurred. In any event, the use of inserts does not degrade the structural integrity or load capacity of an individual hole. However, as a precautionary measure, a recommendation for inspection of these inserts has been made.

Plastic shim material was used to assure that flat surfaces exist between the rotor-spindle flange-to-blade interface. This material has a strength and modulus considerably less than that of steel. Under the high bolt preload required for this application, its compressive strength may be inadequate. Thus, plastic materials should only be used as a weather seal and not as a load bearing material.

Recommended action: Recommended action prior to attended operation is as follows:

(1) Measure the Belleville spring lengths for conformance to specification initially and every 2 mo thereafter

Recommended actions prior to unattended operation are as follows:

(1) Inspect the flange attachment bolts for conformance to specifications on type and torque

(2) Replace the plastic shim material between highly preloaded flange faces with steel material

(3) Inspect the flange to determine if inserts provide a satisfactory long-term repair

Item No. 4 - Rotor Welds. - Any undetected crack in the welded steel rotor blade that reached critical flaw length (e.g., 28 in at station 360) could cause a catastrophic failure. The only means of crack detection being used since the original acceptance of the welded structure is the crack detection system described in appendix E.

Concern: The rotor welds in the chordwise direction are of primary concern because of the following observations:

(1) Higher than expected flatwise cyclic loading

(2) Fracture mechanics data used by BEC do not fully agree with data found in published literature (ref. 3)

Findings: The interiors of the blades on units WT1 through WT4 were visually inspected, with no evidence of any weld cracking noted. However, the following observations were made:

(1) Incomplete weld repair noted in some areas

(2) Evidence of poor use of backing bars on leading and trailing edges of the center rotor section (see appendix B)

Although tested by a simulated crack, the detection of an actual crack in the rotor blade has never been demonstrated. An unintentional leak at the blade interior access ports did trip the system, providing verification that the leak detection system does operate as intended. Thus, the recommendations made in appendix E are directed at assuring or increasing the reliability of this system, rather than correcting any deficiencies.

Other means of identifying cracks that develop during field operation, before they reach a critical length, have been discussed. They include dye penetrant, radiography, ultrasonics, and acoustic emissions. None of these are fully acceptable, practical approaches when considering safety, cost, accessibility, and the qualifications or training required of the personnel conducting the test. The reliability of these alternate crack detection techniques is highly influenced by the personnel involved in conducting the test.

The visual inspection of the rotor blades, while the rotor is in the air, must, from practical considerations, be limited to the interior of the blades. Because of the number of welds, the time required to inspect, and the human error associated with a tedious process, it also seems practical to limit the inspections to the most critical welds. Thus, the process of identifying those welds for visual periodic inspection is extremely important. The criticality of the welds should be established by an analysis that includes the following:

(1) Cyclic load level severity
(2) Weld sink-in and mismatch
(3) Quality of the weld based on radiographs

(4) Potential for stress redistribution due to skin buckling
(5) Other factors that may increase the potential for an existing flaw to grow

To aid inspections these critical welds should be appropriately identified on the inside of the blade.

Recommended action: Recommended action prior to attended operation is as follows:

(1) Requalify the crack detection system (as discussed in appendix E) to assure its reliability

Recommended action prior to unattended operation is as follows:

(1) Identify critical welds in accordance with the guidelines established above, clearly mark critical welds on the inside of the blade, and perform visual inspections of these welds at an interval to be established by additional analysis

Item No. 5 - Rotor Spars. - The structural integrity of the rotor spars must be maintained in order to a achieve the intended design life of the machine, and to avoid any catastrophic failures.

Concern: In view of the growth of rotor load levels in the as-built configuration, the structural integrity of the rotor spars was reexamined to determine if adequate margin remained. If not, these higher load levels might cause spar buckling.

Findings: The most critical spar buckling condition occurs in the front spar at station 880. The analysis was performed by using higher loads that were representative of the as-built configuration in a 60-mph wind. The calculated safety factor, neglecting post-buckling strength, was 1.3. This factor is slightly less than the safety factor of 1.35 required by the design criteria.

Recommended action: No action required.

Item No. 6 - Rotor Blade Equipment Mounting Holes. - There are equipment mounting holes drilled in several locations in the rotor blade structure that are not in conformance with the Boeing design drawings.

Concern: These holes could degrade the operational life of the rotor blade structure if located in high stress areas.

Findings: During the inspections of the blades, the only holes located that were not called out on the BEC drawings were those used to mount the hydraulic and electrical lines to interior longitudinal spars. These spars have lower stresses than in the blade skins that form the primary airfoil surface. Furthermore, since these holes are located on the neutral axis of secondary low stress members, they will not degrade the operational life.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Show number, size, and location of holes, used to mount hardware, on the drawings.

Nacelle

Included in this assembly are the nacelle structure and major bearing supports, low-speed shaft bearings, and yaw drive system. Only the low-speed shaft bearings are discussed in this section, as the other two items are critical components discussed previously.

Item No. 10 - Low-Speed Shaft Bearings. - The low-speed shaft (LSS) bearings support the low-speed shaft and rotor. A LSS bearing failure would be expensive to repair, and has potentially catastrophic consequences, if the bearing seized due to lack of lubrication.

Concern: Examination of oil samples removed from the LSS bearing lubrication system showed contamination levels that could significantly reduce bearing life.

Findings: A review of the radial load capacity of the LSS bearings showed that the actual loading was well within the manufacturer's rating.

Recommended action: Recommended action prior to attended operation is as follows:

(1) Drain and clean LSS bearing sumps and refill with clean oil.

Prior to unattended operation, recommended actions are as follows:

(1) Install improved seals to eliminate leakage.

(2) Install a circulating forced lubrication system.

Drive Train

The function of the drive train is to transmit the torque developed by the rotor to the generator where it is converted to electrical energy. As shown in figure 17, it consists of a quill shaft, gearbox, high-speed shaft, generator, and related couplings. Drive train loads are within design levels except in a few instances when drive train instabilities have occurred.

Item No. 12 - Quill Shaft. - Torque is transmitted from the rotor to the gearbox through a torsionally compliant quill shaft. A friction coupling is used at the gearbox end of this shaft and a bolted flange joint at the rotor end.

Concern: Secondary bending loads in the quill shaft were not considered in the original design calculations.

Findings: The shaft and coupling have performed well with few problems. During the WT1 overspeed incident that occurred in June 1981 (ref. 1), the quill shaft carried an estimated peak torque load of 3.6 times the rated torque. Although the shaft was severely twisted, there were no fractures in the shaft, the coupling, or the bolts. There has been one incident of slipping in the coupling due to failure to clean the coupling friction surface prior to installation.

Analysis of the quill shaft showed that the bending loads had a negligible effect on shaft life. Bending stresses were less than 500 psi, compared with the peak torsional shear stresses of 36 000 psi. This results in an increase of less than 1 percent in the effective stress which determines fatigue life. In addition, the life of the bolts which attach the friction coupling to the gearbox was calculated. This analysis produced a negative margin of safety for both the fatigue and limit load condition. This negative margin does not require any immediate action because of the following:

(1) Conservative assumptions in the analysis.

(2) The overspeed incident, which produced a torque 3.6 times the rated torque, did not fail these bolts or cause movement in this joint.

Recommended action: Recommended action during unattended operation is as follows:

(1) Torque check the quill shaft coupling to gearbox bolts every 1000 hr of operation

Item No. 13 - Gearbox. - The three-stage epicyclic gearbox steps up the 17.5-rpm quill shaft speed to the 1800 rpm required by the generator for synchronous operation.

Concern: Another gearbox, used in a different application, produced by the manufacturer of the Mod-2 gearbox had a stress problem in a support leg to gearbox weld.

Findings: The gearbox, shown in figure 18, has proven trouble free with only a few instances of lubricating oil leakage. The overspeed incident has shown it to be capable of sustaining high overloads without damage. During the incident, input torque reached 3.96×10^6 ft-lb or 360 percent of rated torque, compared to the design limit torque of 1.65×10^6 ft-lb.

Site inspection revealed improper shimming under the feet of the gearbox support structure on WT2 and WT4.

Dye penetrant inspection and strain gauging of the suspect weld on the Mod-2 gearbox revealed no problems. However, analysis showed that stress could be reduced by minor rework of the weld detail.

Recommended action: Recommended action prior to attended operation is as follows:

(1) Reshim the gearbox support feet on WT2 and WT4

Recommended action prior to unattended operation is as follows:

(1) Rework the detail at the intersection of the gearbox case and support structure to reduce stress in the weld

Item No. 14 - High-Speed Shaft. - The high-speed shaft (HSS), shown in figure 19, transmits torque from the high-speed end of the gearbox to the generator. This hollow shaft incorporates disc pack flexible couplings at both ends and a chain drive sprocket. The chain sprocket is used in conjunction with an electric motor and gearbox to position the rotor for maintenance and inspection.

Concern: During a routine inspection of one of the wind turbines at Goldendale, a person from BPA reported seeing a crack in one of the disc packs.

Findings: A subsequent inspection of the disc pack conducted by personnel from both BPA and BEC concluded that no crack existed.

During the Government site inspection it was found that holes had been drilled at several locations through the shaft wall. Bolts through these holes fastened balance weights to the inside wall of the HSS. In addition, examination of the specification used to design the HSS revealed that no cyclic loading was included. However, analysis showed that even with the holes and cyclic loading a large positive margin of safety greater than three was maintained.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Show holes, used to fasten balance weights to the shaft, on the respective drawings

Item No. 15 - Generator. - The generator converts the rotational energy of the drive train into electrical energy. It is a three phase, 60-Hz, 4160-V synchronous generator, operated at 1800 rpm, and rated to provide 3125 kVA at 0.8 power factor (i.e., 2500 kW). The generator incorporates the disk and calipers for the rotor parking brake, as shown in figure 17.

Concern: A concern was raised that the vibration of rotating equipment in the nacelle could cause loosening of the mounting bolts and shifting of the generator.

Findings: Inspection of the three machines at Goldendale showed no evidence of any loosening of mounting bolts or shifting of the generator. As a part of the as-built review, a load and stress analysis of the generator mounting bolts and support structure was conducted. Under the assumed loading it was shown that, except for their preload, the mounting bolts carry no significant tensile load. Stress analysis of the welded generator support structure showed high positive margins.

Recommended action. - No action required.

NONCRITICAL ELECTRICAL COMPONENTS

The 12 noncritical electrical components are conveniently grouped into three separate categories that include electrical power system, electronic controls, and sliprings. Unlike the mechanical sections, concerns in this area do not arise from life predictions of the electrical components themselves. Malfunctioning components rarely cause significant direct downtime or repair cost, but rather could damage the wind turbine structure by allowing structural overloads to occur, or by not detecting failures in process.

As a result, most items were evaluated in terms of likelihood of failure, and potential effect on the wind turbine. The recurring theme is the need to frequently verify the functioning of the protection systems.

Electrical Power System

This section discusses the following five items: Vibration effects on generator protection relays, substation and wind turbine trip coordination, protection adequacy, BPA substation, and tower power cable mountings.

Item No.18 - Vibration Effects on Generator Protection Relays. - The generator accessory unit (GAU) relays are electrical system fault detection sensors (i.e., overcurrent, overtemp., etc.) used to trip the GAU breaker. These are standard components used in a conventional manner, except they are mounted in the nacelle at a 2.5° slope instead of level, and subjected to vibration. The type and function of the relays examined are listed in table II.

Concern: The vibration environment might change calibration or cause failure of the relays. Relay failures could result in loss of the electrical power system protection for the wind turbine generator.

Findings: All eleven induction disk and induction cup relays were removed by BPA from the GAU cabinet of WT2 for investigation of calibration and environmental effects. They were each bench operated to verify acceptable response. Seven relays were checked for calibration drift. These relays were found to be within acceptable tolerance of the original calibration points (see table II).

Five of the induction disk relays were opened to permit examination of the shaft, bearing, and bearing surface. Figure 20 shows a back view of a typical induction disc relay. The disk is mounted on a vertical shaft which pivots on upper and lower pins. The top bearing consists of a pin in the relay body which fits into a sleeve insert in the shaft. The bottom bearing consists of a pin which protrudes from the bottom of the disk shaft that rides on a jeweled surface. The disk is actuated by an induced magnetic field. The disk shaft is restrained by a spiral spring and its motion is retarded by a permanent magnet acting on the disk to give the correct time delay. The differential relay (87) and the loss of excitation relay (40) were not opened for examination because of the difficulty to "tear down".

In all the relays checked there was no evidence of wear or damage to the bearings. The overcurrent relay (50/51) which was inspected had a shiny upper pin but no wear at this time. The permanent magnets that govern disk rotation have more dust and metal filings on the surface than what is found on similar relays in a substation environment. However, it was not enough to effect relay operation.

Normal inspection frequency, by BPA standards, would have been 2 yr from the date of installation for all GAU relays except for the overcurrent relay which is on a three year maintenance schedule. With this 2 yr schedule, inspection of most relays would have occurred in the period February through April of 1983, if it had not been requested for this review. Because of the close quarters, BPA will continue to remove the GAU relays from the cabinet in order to perform a bench calibration check. BPA would not expect to perform a relay "tear down" unless the relay operation was abnormal.

It appeared that the GAU environment had no adverse effects on the installed and tested relays with regard to calibration, reliability or wear. The GAU relays should continue to be checked for calibration drift and acceptable operation on a regularly scheduled basis.

Recommended action: No action required.

Item No. 19 - Substation and Wind Turbine Trip Coordination. - There is no transfer trip capability between the Goodnoe Hills Substation and the Mod-2 wind turbine system. The presence of utility power is monitored by both voltage and frequency monitor relays.

Concern: In the event of a utility fault which causes the substation, but not the wind turbine, to trip, the wind turbine will continue to operate into the open substation until a microprocessor controlled shutdown is initiated by a frequency, speed, or undervoltage trip. In the period before the shutdown is initiated, the generator output voltage might be quite high or low, resulting in potential damage to the wind turbine or substation.

Findings: The frequency relay operates when the frequency drifts below 59.5 Hz or above 60.5 Hz. The relay takes some 8 to 10 sec to operate in a low to high frequency environment. The voltage on the output side of the bus tie connection unit (BTCU) must drop from 12.5 to 5.5 kV before a trip occurs. The power drop would result in brownout conditions to local loads before the undervoltage relays operated.

The signal from these relays is used by the nacelle control unit (NCU) to indicate an absence of utility power. A significant amount of time (ranging from 8 sec to more than 1 min) can pass before the NCU senses and responds to a loss of utility power. An added trip contact placed in series with the contacts of relays 94X and 36V (see fig. 21) would provide an immediate signal to the NCU of loss of utility power resulting in WT shutdown.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Provide transfer trip capability between substation and wind turbine

Item No. 20 - Protection Adequacy. - The electrical protection system consists of a set of protective relays sensing electrical system faults such as overcurrents and frequency or voltage errors. When any of these sensors trip or the wind turbine control system senses a fault, the 48V dc battery system is used to energize a solenoid which trips the GAU or BTCU breaker.

Concern: The concern in protection adequacy involves the general adequacy of the generator protection system. The design is based on a standard utility practice, and uses an appropriate assortment of sensors in a conventional manner. These systems have been shown to be highly reliable and have not caused a problem in the Mod-2 or other DOE/NASA wind turbine programs. However, this type of generator protection system was developed for plants where the normal operation is for the generator to stay on line for long periods of time, and the requirement is to maintain generation, if at all possible. Thus, failure modes generally leave the generator on line and backup protection is provided by the next set of sensors and breakers. In contrast, a wind turbine is expected to shut down when the wind is too low or too high, and because of the small size, maintaining generation from any single wind turbine is not critical. A failure which results in not being able to disconnect the generator from the utility grid during a shutdown will typically result in the generator trying to motor the wind turbine, with the tips feathered. The resulting overload could damage the generator, and possibly the drive train due to torque pulses, as the generator slips poles.

Findings: There are two classes of situations which would result in a serious failure. The first is the combination of loss of the protection system, which could be undetected, and the occurrence of a generator fault or utility system fault, which is not isolated by the substation. This situation is common with all utility generators, where, due to the equipment reliability, normal maintenance practices, and the backup protection from the substation, it is an acceptably small risk. Some reliability improvement can be obtained through redundancy. Dual wires through the sliprings are currently used, but a second tripping relay could be added. Also, more frequent battery maintenance and better physical protection would help. However, the current battery maintenance and level of redundancy are adequate.

The second class of situations with higher potential for a serious failure is a loss of the 48V system combined with a normal shutdown. Due to the frequency of normal shutdowns, this is far more plausible. The 48V system is highly reliable but does have single failure points. Frequent battery checks and improved physical battery protection would lessen the odds of failure. Also, adding a loss of 48V (no-volt) trip to the breaker, or providing an equivalent alternate tripping scheme would provide safe failure modes.

Recommended action: Recommended action during attended operation is as follows:

(1) Install protective cover on 48V battery

Recommended action prior to unattended operation is as follows:

(1) Install no-volt trip to the BTCU breaker

Item No 21 - BPA Substation. - The BPA substation is the link between the wind turbine cluster and the utility distribution system. The wind turbine outputs, at a 12.5-kV level, are combined at the substation, and transformed up to the 69-kV utility distribution voltage. The substation also contains sensors and breakers to protect the utility system.

Concern: Two occurrences have caused outages at the Goodnoe Hills Substation, shutting down all three generators.

Findings: BPA Engineering, and Operations and Maintenance personnel inspected the Goodnoe Hills Substation facility as part of the review. The cable termination cabinet was the location of the latest occurrence causing an outage. All three 12.5-kV phase cables from each of three WTs terminate in this cabinet. The bus to which they are attached was not adequate to support the cable weight. This resulted in a phase bus-to-ground fault in June 1982, causing damage to two cable terminations and the phase bus. This problem was corrected by installing cable hangers and a support bar in the cabinet. The termination arrangement does not isolate the individual underground conductors. This could lead to all three units being out of service as a result of a single power cable failure.

The bypass and disconnect switches were single phase with no correlation between adjacent switches. It was difficult, if not impossible, for the operator to trace connections to these switches. The switches were hot-stick operated. There was no interlocking between the present switches.

The power circuit breaker recloser has functioned satisfactorily except for one incident where a rodent climbed on the bushings causing a flashover and extensive damage.

Also considered was the provision of alternative station service from the Public Utility District of Klickitat County's 12.5-kV distribution lines located south of the WT site.

The conclusions reached include the following:

(1) Outage time in the event of a fault could be reduced by expanding the selection and number of spare components.

(2) The acquisition of a different termination cabinet could provide automatic isolation of a faulted cable, manual isolation of each WTG underground cable set, and improved cable terminations, through fused disconnect switches. This would permit operation of units not directly affected by a substation fault.

(3) Disconnect switches are available with dead-front control, group-operated and key interlocked. Replacement with this different kind of switch would correct the problems with the present switch arrangement.

Recommended action: Recommended actions prior to unattended operation are as follows:

(1) Increase inventory of substation equipment spare parts

(2) Install screening beneath the recloser to prevent entry of rodents

Item No. 22 - Tower Power Cable Mountings. - Three individually jacketed cables are used to carry the 4.16-kV alternator output to the base of the tower. These conductors are secured by individual metal clamps (see fig. 22) to the cable ladder. These clamps are placed about 1.5 ft apart, at every ladder rung, except one rung is skipped at the cable ladder extension joints (every 12 ft) (see fig. 23). Nylon tie-wraps are used to secure the 2/0 neutral cable to the ladder.

Concern: Excessive distance between clamps and clamping mechanisms for the three phase conductors from the nacelle through the yaw slipring assembly terminations and down the tower cable ladder might result in failure of the cable insulation.

Findings: The high voltage power cables which run from the generator to the yaw slipring assembly had a free run of about 5 ft in length between the point where they emerge from the nacelle floor conduit and attach to the slip ring terminations. The three phase conductors were tied off and supported by a nylon rope in WT3 and nylon tie-wrap in WT2 (see figure 24). The suspension tether supported the conductor weight and relieves strain on the rotation side termination elbows. WT1 was partially disassembled following the LSS failure in November 1982 so its method of suspension could not be determined.

BPA/BEC inspected the power cable runs in all three units at Goldendale. In WT2 four cable clamps were observed to be lightly pinching the outer hypalon coating. The four clamps were all located near station 410 but were spaced out and attached to different phases. No damage to the plastic insulation or conductor strands was apparent.

Two cable ladder joints were found loose at the bolted expansion joint in WT2 near station 2000 and in WT3 near station 500.

The major conclusion was that no damage to the conductors or ladder was apparent. All clamps and joints will be monitored and corrected as required during future maintenance activity.

Recommended action: Recommended actions during attended operation are as follows:

(1) Correct cable clamp pinching

(2) Tighten loose cable ladder joints

Electronic Controls

This section discusses the following four items: Low-speed shaft bearing failure detection, overspeed sensing adequacy, fault memory retention, and CRT shutdowns.

<u>Item No. 23 - Low-Speed Shaft Bearing Failure Detection</u>. - The low-speed shaft bearings are critical to the structural integrity of the wind turbine. Although these bearings support the rotor, a bearing failure which allows the rotor and low-speed shaft to separate is not plausible. Although unlikely, a bearing failure causing the shaft to seize and possibly overload the rotor or shaft torsionally is plausible. Simply replacing a bearing is a major task in that the rotor and low-speed shaft must be removed to replace the bearing.

Concern: Undetected incipient failure of low-speed shaft bearings might result in a major failure.

Findings: In the present design, temperature sensors are used to detect failure of the bearings and cause a shutdown. However, temperatures will not warn of impending failure; such as when the WT2 machine aft bearing had no lubricant due to the low-bearing speed, high-thermal mass, and high-thermal conduction situation present in the Mod-2. Vibration sensors were also incorporated in the design, but they did not detect the shock pulses generated by the low-speed shaft failure. Although these sensors were functioning, the bedplate did not see high g levels (0.1 to 0.2 g) during the failure.

Various sensor systems applicable to bearings were considered, such as lubricant level, lubrication flow, lubrication pressure, lubrication temperature, proximity probes, and noise sensors. The lubrication level sensor system was found to be adequate based on ease of installation and reliability considerations.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Incorporate LSS bearing lubrication level sensors.

Item No. 24 - Overspeed Sensing Adequacy. - WTG overspeed is probably the most common cause of catastrophic machine failure. Consequently, overspeed protection has been the subject of extensive design and review, particularly after the overspeed incident of June 1981. However, that effort concentrated on protection and actions after the overspeed was detected.

Concern: The concern was not due to any inspection or analysis, but as a result of general sensitivity to overspeed detection and generating the shutdown commands.

Findings: The overspeed protection was analyzed through a review of the schematic drawing (BEC 032-457013 sh-1 and 032-457025 sh-2) and a discussion of maintenance procedures. Circuit analysis was performed by BEC and NASA.

The sensing, shown in figure 25, consists of two encoders of similar but not identical installation and manufacture, thus eliminating the likelihood of simultaneous generic failures. One sensor used for the speed control function, also generates the primary overspeed signal which actuates the start and stop valves. This circuitry, located in the microprocessor rack was used continuously during normal running. Thus, most failures were detectable and failsafe or had a built-in backup mode, such as feathering the blade with servo valves if the start and stop valves did not function.

The backup overspeed circuitry used the second encoder, and was processed through circuitry also located in the microprocessor chassis. Overspeeds detected by this circuitry actuate the independent emergency shutdown system (IESS) valves. A portion of the circuitry was checked against the primary speed sensor, providing a self-check feature, and some of the circuitry was failsafe. However, a portion of the circuitry was neither failsafe nor self-checked, and could have become an undetected failure, defeating the purpose of the IESS.

The analysis identified two methods to improve the design. The most effective method was to institute periodic testing of the system. This required injecting a signal in place of the encoder output and checking for actuation of the IESS valves. The second improvement involved adding circuitry to cause a microprocessor shutdown if the oscillator used in the overspeed circuitry fails. The oscillator was singled out for this internal checking because it was easy to check and also is inherently less reliable than the rest of the circuitry which was not checked.

Recommended action: Recommended action prior to attended operation is as follows:

(1) Perform functional check of the overspeed sensor circuit

Recommended action during unattended operation is as follows:

(1) Incorporate periodic functional check in routine maintenance

Item No. 25 - Fault Memory Retention. - Operational data and the control system record of history preceding a fault shutdown are currently displayed on the CRT used for remote or local control. The only permanent record of this data is that which is written down by the operator.

Concern: Operational and failure data captured prior to and during a fault, required to diagnose the cause, could now be lost through operator error or loss of station service.

Findings: The nacelle control unit (NCU) retains history data in memory which includes some operating parameters and fault code information. The parameters stored include wind turbine operating mode, power output level, and blade rotational speed. The fault code, displayed in hexidecimal, can be decoded to determine the kind of fault(s) that caused shutdown.

One minute of history data is stored and refreshed every second. These data represent 10 sec of operation prior to shutdown followed by 50 sec after the shutdown is initiated. In addition, 6 sec of history data are stored and refreshed every 0.1 sec. These data represent 1 sec of operation prior to shutdown followed by 5 sec after shutdown initiation.

Review of this history data might aid the troubleshooting procedure and assist in determining parts, tools, and maintenance experience required to correct the problem. The history data, available for display on the CRT, should be recorded by an operator. A printer would provide a hard copy of NCU fault codes, fault history, and provide operational data. Experience has shown that occasionally the operators did not or could not record the fault information.

Recommended action: - Recommended action prior to unattended operation is as follows:

(1) Add hard copy print capability to display terminals

Item No. 26 - CRT Shutdowns. - The utility or local operator monitors and controls the wind turbine operation through the local or remote CRT's connected to the wind turbine through a communication link. The link may be hardwired or use telephone lines, radios, or microwaves.

Concern: A hardware failure would result in the loss of displayed operational data, history data, local manual mode operation, and remote machine disable. Currently this loss is not alarmed and would only be noted by observing the loss of displayed information. Thus, the loss of manual supervisory control could result from the following hardware failures:

(a) CRT screen display or keyboard failure
(b) Communications link to the remote CRT (modems and microwave transmitter/receiver)
(c) Data and control link drivers in NCU may fail

Findings: Utility operating philosophy permits continued conventional generator operation with loss of manual supervisory control, if so alarmed to permit possible dispatch of an operator to the site. However, loss of manual supervisory control of an operating WTG might not be acceptable.

An answerback feature could be added to the CRT display terminal (see figure 26). Software added to the NCU would send a signal to the local and remote CRT's, which would echo back an ID message response to the NCU. If the answerback loop is broken, then an alarm is initiated at the local and remote terminals. A message counter would be added to the remote receiver line to power the remote alarm. This scheme will check all wires and circuits of the transmit and receive serial links for proper function.

To obtain a hard copy failure printout, a microprocessor could be used. This is part of a system being developed by BEC to provide operation availability data. It is configured to connect to the extension port of the terminal.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Add answerback feature hardware and software to the display terminals

Sliprings

This section discusses the following three items: Yaw slipring, low-speed shaft slipring, and low-speed shaft slipring bearing.

Item No. 27 - Yaw Slipring. - The yaw slipring is used to transmit the alternator power output, and all of the control, signal, and data lines across the yaw interface.

Concern: The three concerns in this area are as follows:

(1) Brush wear material might contaminate the sliprings resulting in heat buildup and failure of the sliprings.

(2) Degradation of the insulation quality of the molded high voltage (HV) cable boots at the yaw slipring interface by oil contamination.

(3) The antirotation bracket may place bending loads into the assembly which could preload the slipring bearings.

Findings: The yaw sliprings were to be inspected for brush wear annually per the Operations and Maintenance Manual. The yaw sliprings were inspected on WT2 and WT3 during their annual maintenance in 1982. WT1 was inspected following the overspeed incident in June 1981. There was no evidence that brush wear is a current problem to the life of the yaw slipring assembly.

BEC nonconformance reports (NCR's) documented that oil leaks in the nacelle were resulting in oil dripping onto, or potentially dripping onto the HV cables where they attach to the yaw slipring. (See fig. 27.) Oil will eventually deteriorate the insulation of the HV cables, and both the insulation and semiconducting coating of the molded HV connectors, causing faults between phases and from phase to ground.

The antirotation bracket on WT2 (see figure 28) showed some deformation where the existing bolts, that act as antirotation restraints were attached. Inspections of this installation and others give the impression that misalignment might exist between the rotating and stationary fixtures of the yaw slipring assembly. This could cause bending loads to be placed on the assembly by the antirotation brackets and bolt restraints.

Recommended action: Recommended actions prior to unattended operation are as follows:

(1) Inspect the sliprings for contamination and measure resistance on the power rings

(2) Inspect and replace the molded HV cable termination boots as required, and install a drip shield to prevent further oil contamination

(3) Replace the existing antirotation restraint with an improved design which can not load the yaw slipring

<u>Item No. 28 - Low-Speed Shaft Slipring</u>. - The low-speed shaft slipring, located on the low-speed shaft just forward of the rear bearing, transfers the following from the rotor and low-speed shaft to the nacelle:

(1) Control and data signals

(2) Power for the pitch hydraulic system and the crack detector

(3) Commands to the start and stop valves and the backup overspeed protection (IESS) valves.

Concern: The rapid brush wear on the low-speed shaft slipring could result in ring-to-ring shorts that could cause loss of sensors or control capability.

Findings: The low-speed shaft slipring was reviewed for progress on reducing the rapid brush wear experienced in the field, and the potential effects of the wear, such as shorts in the slipring. Rapid wear has been a continuing problem, in that there have been instances of ring separator breakage and ring shorts. The unexplained short which caused the shutdown when the low-speed shaft cracked was generally attributed to the slipring. Ring-to-ring shorts due to separator failures and/or brush material deposits could be likely with the current design and associated wear rates. Most shorts tripped breakers or simulated fault conditions which caused safe shutdown. Depending upon the assignment of sliprings to control signals, ring-to-ring shorts could cause loss of sensors or control capability. In general, rings were found to be assigned to separate power signals from low level signals, and used grounded rings or empty rings to isolate critical circuits.

The brush wear data were reviewed, and the available general status is as follows:

(1) Reduced spring tension generally showed marked improvement in brush life.

(2) Brush materials did not show a strong effect on life.

(3) The vendor's simulation showed very good brush life.

(4) Test data (not taken on Mod-2) showed a dramatic life degradation due to either very high or very low humidity. The humidity was not controlled in the Mod-2 installation, and might be significant.

(5) There was some feeling that the cantilever support for the brush assembly might affect the wear rate due to brush vibration.

(6) The maintenance procedures were appropriate and were not significantly affecting brush life.

The brush life investigation is an on going activity which should be continued at the present level of activity. Current life is on the order of 3 mo to 1 yr.

The slipring assignments were reviewed in detail by BEC to determine the effect of all adjacent ring-to-ring shorts. Most shorts resulted in immediate failsafe shutdowns. However, the following potential adjacent ring shorts could cause undetected failures:

(1) Short - ring 23 to 24: This short bypasses the crack detection sensors, in effect disabling the crack detection system.

(2) Short - ring 24 to 25: This short applies the crack detector command voltage to the crack detector sensor, resulting in a loss of crack detector function.

(3) Short - ring 20 to 21: This short results in a loss of the pitch hydraulic oil high-temperature sensor. Damage is limited to hydraulic system components.

(4) Short - ring 16 to 17: Loss of pitch-system fluid level sensor could result in loss of system pressure, causing a safe shutdown. Damage is limited to the hydraulic system.

(5) Short - rings 9 to 10, 28 to 29, or 32 to 33: These shorts result in loss of one or both ice detectors.

The only serious slipring shorting concerns were the crack detection rings. A control system self check should be implemented to check for proper detector operation, and rings 25 and 26 interchanged. In the long term, the slipring design should be changed to strengthen the separators and reassign the rings to eliminate the secondary concerns, but this is not necessary for the research test operations. In general, end-to-end checks are required to verify proper function and should be performed at 6 mo or 1 yr intervals.

Recommended action: Recommended action prior to unattended operation is as follows:

(1) Implement a self check of the crack detection system and interchange rings 25 and 26.

Item No. 29 - Low-Speed Shaft Slipring Bearing. - The slipring design is a brush set and dust cover over the slipring that is cantilevered off a large-diameter thin ball bearing. The ball bearing is not a standard design, being split so that it can be assembled over the shaft.

Concern: The original slipring bearing had failed in one unit resulting in a somewhat undefined but apparently safe shutdown by ripping out the wiring to the slipring. The review committee was concerned with the possible reoccurrence of this failure, and assessed the adequacy of the present mechanical design and the shutdown mode if the failure did occur.

Findings: The previous failure was analyzed by BEC, and was felt to have been due to failure of the wire ball separator. The redesign incorporated a brass separator in the bearing and an improved torque link. The design bearing load was two orders of magnitude greater than the estimated actual load. Proposed changes in this area, as a result of the low-speed shaft redesign, specified the addition of a second support bushing, to minimize vibrations transferred from the brushes to the holder. Based on an inspection of the actual hardware, and an analysis in the previous section (LSS Slipring) of the effects of adjacent ring shorts, and the load calculations, there was no justification for changes or increased inspections for unattended operations.

Recommended action: No action required.

SUMMARY OF RECOMMENDATIONS

The recommendations of the Government Review Committee discussed in detail in the previous section are summarized in table III for the critical components; table IV, for all other or noncritical structural and mechanical components; and table V, for noncritical electrical components. In order to establish an urgency or suggested time frame for implementing the recommendations, the recommendations were grouped in the following four categories:

(1) Prior to attended operation

(2) During attended operation

(3) Prior to unattended operation

(4) During unattended operation

CONCLUSIONS

The major conclusions reached by the Government Review Committee are as follows:

1. There were no deficiencies identified in this review process that would preclude planned attended operation of WT2 and WT3. However, some of the concerns required immediate corrective action and/or careful inspection at frequent intervals during the attended operation.

2. Several of the components reviewed such as the teeter bearing and rotor cap areas have potentially serious deficiencies that require corrective action in order to increase the operational life of the machines in the unattended mode of operation.

3. The recommended disassembly of the teeter bearing in WT1 was necessary to provide information for any additional corrective action and/or design modifications that might be required for the unattended mode of operation. Additional input and assessment such as the effect of temperature during installation and operation was needed from the vendor supplying the elastomeric bearing material.

4. Additional loads data, specifically for the rotor cap, yaw drive system, and downwind bearing support were needed to resolve the concerns expressed as well as to confirm the recommended corrective actions.

5. Design practice by the contractor regarding widespread use of friction joints and plastic shim material contributed to problems in the field. Use of shear pins, locking devices, and hard material shim stock should be considered wherever practical.

6. Most of the items in the electrical area were evaluated in terms of likelihood of failure, and the potential effect on the wind turbines. The recurring theme was the strong requirement for repeated functional checks to assure the proper operation of all protective systems.

7. Implementation of quality control procedures during the installation of the Mod-2 wind turbines was inadequate. Numerous instances of improper installation (e.g., use of wrong fasteners, improperly aligned components, etc.) were identified during the as-built review. These instances were primarily due to failure to follow installation instructions. However, a contributing factor was incomplete or vague instructions on some of the Mod-2 drawings.

APPENDIX A

MEMO ESTABLISHING GOVERNMENT COMMITTEE

4513 January 27, 1983

TO: 4100/Chief, Transportation Propulsion Division

FROM: 4510/Manager, Wind Energy Project Office

SUBJECT: Appointment of Mod-2 As-Built Review Committee

This memo establishes a government committee to conduct an as-built review of the three Mod-2 wind turbine units at Goldendale, Washington. The objective of this review is to identify any design or fabrication deficiencies which could potentially cause safety hazards or significant periods of downtime for repairs. Recommendations for corrective actions are also to be made by the committee. This as-built review is the first step in a program of preventive maintenance which was recommended by the committee investigating the recent low-speed shaft failures at Goldendale and supported by DOE/NASA management.

I have asked William R. Johnson, Deputy Manager of the Mod-5 Project, to head this committee. Bill is well-qualified for this assignment, having successfully completed the technical management of the SVU Project for the Bureau of Reclamation. In addition, he is in an excellent position to transfer to the Mod-5 Project the lessons learned on the Mod-2. A list of the government personnel requested to serve on this committee is as follows:

Name	Organization	Specialty
W. R. Johnson, Chr.	Wind Energy Project Office	Project Management
T. L. Sullivan	Wind Energy Project Office	Loads and Stresses
A. G. Birchenough	Wind Energy Project Office	Electro-Mechanical Components
B. S. Linscott	Wind Energy Project Office	Structural Components
P. J. Sirocky	Engineering Design Div.	Mechanical Components
W. E. B. Mason	Reliability & Quality Assurance Office	QA and Materials
TBD	Bonneville Power Admin.	Electrical Components

The committee will work closely with the Mod-2 contractor, Boeing Engineering and Construction of Seattle, which will supply required support services and data such as detail drawings, inspection reports, test data, and engineering analysis. All liaison with BEC will be provided by the Mod-2 Project Manager.

Findings, conclusions, and recommendations of this committee will be presented to the Lewis Wind Energy Project Office Chief Engineer by April 15, 1983, with a written report to follow within 15 days. Resulting recommendations and project plans will be presented to DOE and NASA Headquarters management personnel in late April or early May 1983. To define the scope of the review, the committee will first list the critical assemblies and components to be investigated and obtain the concurrence of the WEPO Chief Engineer before starting detailed study.

Darrell H. Baldwin

cc:
BPA/W. Myers
BPA/D. Seeley
BPA/G. Stemler
BEC/M. Bovarnik
BuRec/W. Fite
DOE/L. Divone
DOE/D. Ancona
DOE/P. Goldman
NASA-HQ/R. Wasel, RET-1
4510/WEPO Files
4510/D. Baldwin
4510/L. Gordon
4510/T. Cahill
4510/B. Linscott
4510/W. Johnson
4512/R. Puthoff
4512/A. Birchenough
4513/T. Sullivan
4513/D. Spera
8200/R. Rohal
8220/W. Mason
8500/J. Yuska
8512/P. Sirocky

APPENDIX B

GOVERNMENT SITE INSPECTIONS

On February 24, 1983, members of the Government committee inspected the Medicine Bow machine and on March 7 and 8 inspected the Goldendale units. These inspections were unstructured assessments in support of the Boeing effort.

The following notation is used in the discussion:

WT1, WT2, and WT3 - Goldendale units
WT4 - Medicine Bow unit

(a) Denotes items not identified by Boeing during their inspections
(b) Denotes conditions indicative of substandard workmanship and/or quality control

MANLIFTS

WT1, WT2, and WT3. - Condition of units appeared good.

WT4. - Condition of the manlift was good, but the entrance to the manlift was loosely constructed of discarded lumber and railroad ties.[b]

TOWER-TO-BASE ATTACHMENT

WT1 and WT2. - General evidence of disturbed paint observed on nuts; grout cracking evident.

WT3. - No evidence of nut movement observed, grout cracking evident.

WT4. - No evidence of nut movement observed, not inspected for grout cracking.

TOWERS

WT1, WT2, and WT3. - These towers were observed on the inside only during the lift to the nacelle. Mismatch was observed, particularly in WT1 but was not judged to be grossly out of specification. No power cable tray movement was observed.

WT3. - This tower was more thoroughly inspected than the others, however, no serious condition was noted. Documented for the record are the following:

(1) Mismatch judged to be minor
(2) Minor porosity
(3) Possible power cable tray movement
(4) Evidence of weld repair
(5) Minor banding

YAW DRIVES

WT1, WT2, and WT3. - Evidence of excessive bull gear wear and pinion misalignment.[a]

WT4. - Bull gear wear and pinion misalignment were not noted but could be present.[a]

WT4. - A potentiometer attached to the pinion with a belt drive was in disrepair. The belt was very loose, the shaft support was loose and misaligned, and the use of washer stacks 8 to 10 washers deep was judged unacceptable.[b]

GENERATOR MOUNTS

WT1, WT2, and WT3. - Generator mounts were not inspected for these sites.

WT4. - The generator is not sitting on a full bearing; this is not thought to be serious.

GEARBOX SUPPORTS

WT1 and WT3. - Gearbox mounts appeared tight to the mount in all areas.

WT2 and WT4. - Gearbox mounts had noticeable gaps on both legs. On WT4 the gap exceeded 0.040 in.[a] [b]

REAR BEARING SUPPORT

WT2, WT3, and WT4. - All machines showed evidence of gaps under bottom and or side mounting pads which could lead to early fatigue failures.[b] All machines show cracked paint on the reaction member indicative of high loading and flexing.

LOW-SPEED SHAFT

WT2 and WT3. - Paint had been removed from critical areas but there was much to be desired in the thoroughness of the action. Rust had set in on all bare metal areas.

WT4. - An excellent job of paint removal had been accomplished; there was no rust present.

TEETER BEARING

WT1. - Movement was apparent in the bearing-to-hub assembly, although not as pronounced as for WT4. There was slight ozone like cracking of the elastomer, but to a far less extent that at WT4.[a] Weld cracking in the elastomer mount was not observed.

WT2. - Movement was apparent in the bearing-to-hub mount. One mount of the horse collar attaching bolts showed washer movement of approximately 0.125 in. There was minor deterioration of the elastomer similar to WT1.[a] Both sides of the elastomer mount showed possible weld cracking.[a]

WT3. - Movement was not apparent through casual observation. Elastomer deterioration is minor as in WT1.[a] Weld cracking was not observed.

WT4. - Movement was apparent in the bearing-to-hub mount. The elastomer was deteriorated as evidence by ozone like cracking. At least one side of the elastomer mount weld was cracked.

TEETER BRAKE

WT2 and WT3. - Brake was disconnected. Wear was apparent, but could not be readily seen due to rain impairing access.

WT4. - Brake was disconnected and severely damaged by abnormal wear. Torn metal was clearly visible along with galling and possible bolt movement.

ROTOR CAP

WT1, WT2, WT3, and WT4. - All machines had eight auxiliary holes apparently drilled for mounting hydraulic and electrical lines.[a]

HUB CENTER SECTION

WT1. - Inside: Not inspected. Outside: General poor use of backing bars were observed. On one side of the spar approximately 50 percent mismatch was observed in one area.

WT2. - Inside: Observed was the questionable application of backing bars and a flame cut hole on the tension face near the center line and neutral axis approximately 1 by 2 in by 0.375 in deep.[a] Outside: Observed general poor use of backing bars.

WT3. - Inside and outside: Generally okay in that most of the backing bars had been removed.

WT4. - Inside: Inspection of the main central spar at one end revealed paint cracks in the fillets and general poor use of backing bars. Outside: Observed general poor use of backing bars.

MIDSECTIONS

WT1. - Only one blade was inspected - no discrepancies were noted except poor use of backing bars.

WT2. - Five of the six compartments were walked through. A heavy slag-like deposit was observed at the 360 joint of one blade. Poor use of backing bars was obvious.

WT3. - At least one case of incomplete weld repair was noted. At a chordwise weld to bulkhead connection, porosity in a partially ground area was obvious. Most of the backing bars have been removed from these midsections.

WT4. - Five of six compartments were walked through. The only questionable area was again the poor application of backing bars.

TIP CONTROLS POSITION SENSORS

WT1, WT2, and WT3. - Observed tip sensors appeared in good condition.

WT4. - One sensor had at least one cracked lock washer, and the other tip had a control box potentiometer mounted in an askewed position with flat washer stacks used to create an angle condition.[a b]

WATER IN BLADES

WT1. - This blade was on the ground. Water was condensed in the midsections and hubs.

WT2. - Large amounts of water (gallons) had accumulated in this machine, probably due to the configuration of the crack detection system when the blade was parked vertically.

WT3. - The same condition was found as with WT2 but less water.

WT4. - This blade was essentially dry.

APPENDIX C

AS-BUILT REVIEW LOADS

A major reason for calculated lives of Mod-2 subsystems now being less than 30 yr was the increase in loading over that used in design. The three Mod-2 wind turbines at Goldendale were instrumented to measure loading in the blades, drive train, and tower. The blades were instrumented at four spanwise stations for measuring flatwise and chordwise bending moments; the quill shaft was instrumented to measure torque and bending moments in two perpendicular directions; and the tower was instrumented to measure torque and bending moments. (See table VI.)

Blade load measurements at Goldendale showed that while steady flatwise loading and steady and cyclic chordwise loading were close to design, cyclic flatwise loading was significantly greater than design. At spanwise station 370 this loading was about 50 percent greater than design; at station 1164 it was about twice design. This loading then translates into higher cyclic loading in the rotor cap and teeter bearing, LSS thrust bearing, a portion of the nacelle, and the tower.

Certain loads used during the review for calculation of subsystem static capability and fatigue lives were compared to design loads in table VII. As the table shows, the most significant increase occurred in the cyclic thrust load at the hub. This higher loading results in reduced fatigue performance in the rotor cap, nacelle, and tower. Another significant increase occurred in the teeter-stop impact loading. This increase has produced negative margins of safety in the teeter-stop structure and between the rotor cap and low-speed shaft joint. None of the remaining increases in loading listed in table VII had a significant effect on static or fatigue performance.

There were several areas where additional instrumentation would improve confidence in the accuracy of the loads used to calculate subsystem life. Extrapolation of measured rotor and tower loads through the rotor cap and nacelle is uncertain. In addition, site influence on certain loads was unclear. Many of these uncertainties could be resolved by additional instrumentation and testing at Goldendale. Resolution of site-to-site differences will require limited additional loads instrumentation and testing at Solano or Medicine Bow.

APPENDIX D

COMPONENT LIFE OR TIME-TO-REPAIR CALCULATIONS

Many of the recommendations in this report are the result of calculations which show a component fatigue life or the time to repair a weld is less than the Mod-2 design life of 30 yr. These calculations are based on a fracture mechanics approach, and presume the existence of a crack-like defect in the structural material. In addition, the analysis is based on a set of general assumptions and a set of specific assumptions, which depend on the location of the presumed defect.

The general assumptions used in the analysis are as follows:

(1) The gauge thickness is nominal.

(2) The defect is oriented with respect to the principal stresses to maximize stress intensity.

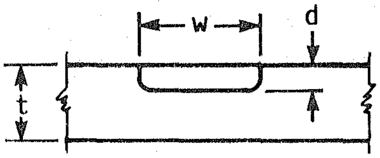
(3) The loading is phased to maximize peak stress.

The specific assumptions used in the analysis are listed in the following table.

Defect location	Defect dimensions, in (see sketch below)		Cyclic frequency	Weld distortion, in (sink in or "banding")	Weld stress magnification
	d	w			
Rotor chordwise welds	0.05	0.25	1 per rev	0.1	---
Rotor spindle	.03	.09	↓	-	---
Rotor cap pilot ring	.03	.09	↓	-	---
Rotor cap gusset weld	.05	.25	↓	-	(a)
Tower circumferential welds	.1t	.5t	2 per rev	.125	---
Nacelle weld	.05	.25	2 per rev	-	(a)

[a] Derived from weld code fatigue allowables, value dependent on category of weld detail.

The following figure shows a sample with dimensions d, depth; t, sample thickness; and w, width.



The loading used in the analysis was based on measured cyclic and calculated mean loads, and was dependent on windspeed. Calculations were made for two windspeed distributions. One was the measured distribution at the Goldendale site, and the other was the Mod-2 design windspeed distribution.

The latter was a Weibull distribution for a site with an average windspeed of 14 mph at 30 ft. The Weibull distribution produced more severe loading than the Goldendale distribution, and therefore, shorter lives or time to repair.

APPENDIX E

ROTOR CRACK DETECTION SYSTEM

The rotor crack detection system incorporated in the Mod-2 was designed to detect a through-thickness crack in the rotor blade, before this crack reached a critical length. The system would then shut the wind turbine down to prevent a catastrophic failure of the rotor.

System Operation

The system pumps compressed warm dry air through the blade interior and vents the air overboard at the inboard end through an orifice. The flow into each blade is monitored, and the difference between blade flows is an indication of the existence of another exhausting orifice, which could indicate a through-crack. The differential measurement between the two blades eliminates effects like temperature and atmospheric pressure changes. An orifice in the blade allows some flow, so that thermal expansion does not overpressurize the blade, and to allow a no-flow check for a blocked system.

A low-speed shaft mounted compressor pressurizes the blade to 1.0 psig from station 90 out through the pitchable tip. The trailing edge sections of the tip are not pressurized. The system operates whenever the machine is synchronized, but requires 20 min to stabilize.

The system sensitivity was selected to enable detection of a 12-in crack at station 360. A 12-in crack at station 360 would grow to the critical crack length of 28 in during an estimated 70 hr.

The system was tested by using a large tank to simulate the blade volume and measured leak rates. Air flow rates for cracks grown in flat plates were also tested, and recently the air flow through cracks undergoing cyclic loading was verified. Recent analysis has also shown that it is improbable for cracks to grow simultaneously in both blades at near equal rates to avoid detection by differential flow. In field operation the system has been tripped for loose cover plates and other induced faults. However, there have not been any cracks in the blade to verify the system in actual operation.

Concern

The importance of the crack detection system has increased significantly with the results of this review that predict rotor weld time to repair estimates as low as 4500 hr. The specific concerns regarding the ability of the system to detect a crack are as follows:

(1) The system may not have the necessary reliability. The system is not failsafe, and contains no self testing features except the no-flow tests. The low-speed shaft slipring investigation revealed two potential single point undetectable failures, for which corrective action is recommended.

(2) The air compressor may be undersized. The air flow rate for a good blade is 4.5 to 8.0 ft^3/min, and the differential flow to initiate a shutdown

is 5.0 ft^3/min. Thus, two blades plus the design crack could flow 21 ft^3/min, and the compressor is nominally rated at 20 ft^3/min. Simultaneous cracks in both blades could raise this total flow slightly.

(3) The criterion of detection of a 12-in crack near station 360 appears adequate, but the system may not be sufficiently sensitive to cracks approaching critical lengths out near the blade tip.

Recommended action

(1) The design and all operating conditions for the crack detection system require a review.

(2) The crack detection system requires requalification to determine the airflow capabilities and failure modes.

(3) Implementation of appropriate system inspections and/or self testing features are needed.

(4) The crack detection system sensitivity requires reevaluation to determine if it is adequate to protect the entire blade.

REFERENCES

1. Mod-2 Wind Turbine System Development Final Report. Vol. 1, Executive Summary. NASA CR-168006; Vol. 2, Detailed Report. NASA CR-168007, 1982.

2. Mod-2 Wind Turbine System Concept and Preliminary Design Report. Vol. I, Executive Summary, and Vol. II, Detailed Report. NASA CR-159609, 1979.

3. Novak, S. R.: Resistance to Plane-Stress Fracture (R-Curve Behavior) of A572 Structural Steel. ASTM STP-591, ASTM, Philadelphia, 1974.

TABLE I - LIST OF CANDIDATE CRITICAL COMPONENTS

[C after item number indicates critical component.]

Item No.	Component	Subassembly
Structural and mechanical components		
1	Rotor-pitch actuator	Rotor assembly
2	Rotor spindle	
3C	Emergency hydraulic system	
4	Rotor welds	
5	Rotor spars	
6	Rotor blade equipment mounting holes	
7C	Teeter system	
8C	Rotor cap	
9C	Nacelle structure and major bearing supports	Nacelle
10	Low-speed shaft bearings	
11C	Yaw drive system	
12	Quill shaft	Drive train
13	Gearbox	
14	High-speed shaft	
15	Generator	
16C	Tower, base, and foundation	Tower assembly
17C	Gin-pole system	Site equipment
Electrical components		
18	Vibration effects on generator protection relays	Electrical power system
19	Substation and wind turbine trip coordination	
20	Protection adequacy	
21	BPA substation	
22	Tower power cable mountings	
23	Low-speed shaft bearing failure detection	Electronic controls
24	Overspeed sensing adequacy	
25	Fault memory retention	
26	CRT shutdowns	
27	Yaw slipring	Sliprings
28	Low-speed shaft slipring	
29	Low-speed shaft slipring bearing	

TABLE II. - COMPARISON OF RELAY SETTINGS

Relay device	As installed		As found	
	Pickup value	Test value	Pickup value	Test value
Generator winding overtemperature (49 G)[a]	132 °C		132 °C	
Reverse power (32)[b]	70 kW	5.1 sec at 278 kW	70 kW	4.86 sec at 278 kW
Differential (87)[c]				
Phase A from GEN	0.22 A		0.22 A	
Phase A from BTCU	↓		0.20 A	
Phase B from GEN	↓		0.265 A	
Phase B from BTCU	↓		0.25 A	
Phase C from GEN	↓		0.195 A	
Phase C from BTCU	↓		0.265 A	
Loss of excitation (40)[d]		270° at 44.23 Ω 211° at 23.0 Ω 319° at 23.0 Ω		270° at 46.93 Ω 215° at 23.0 Ω 324° at 23.0 Ω
Overcurrent (51) B0[e] [h]	400 A	0.45 sec at 1600 A	400 A	0.47 sec at 1600 A
Overcurrent (with restraint) (50/51 V)[f] [h]	400 A	2.60 sec at 400 A	400 A	2.52 sec at 400 A
Ground fault (64)[g]	5.9 A	0.65 sec at 23.5 A	6.1 A	0.64 sec at 23.5 A

[a] Induction disk type operated by voltage.
[b] Induction disk type operated by power (voltage and current).
[c] Induction cup type current operated.
[d] Induction cup type operated by impedance (voltage and current).
[e] Induction disk type operated by current.[h]
[f] Induction disk type operated by current.[h]
[g] Induction disk type operated by voltage.
[h] There are three relays of this type; only one of three relays was checked for calibration.

TABLE III. - SUMMARY OF RECOMMENDATIONS FOR CRITICAL COMPONENTS

Item	Recommended action		
	Prior to attended operation	During attended operation	Prior to unattended operation
(3) Emergency hydraulic system			(1) Replace system check valves with an acceptable type to reduce leakage potential (2) Revise Operations and Maintenance Manual to provide more detailed internal leakage check and isolation procedures
(7) Teeter system	(1) Retorque bolts attaching teeter bearing to rotor blade (2) Increase torque on teeter-stop support structure attachment bolts to 80 percent of yield	(1) Establish procedure for and monitor motion between the following: (a) Rotor blade and horsecollar (b) Low-speed shaft and teeter stop (c) Trunnion and pilot ring (2) Establish procedure for and monitor elastomeric thrust bearing gap (3) Disassemble WTl horsecollar structures from rotor and inspect (4) Provide strain measuring instrumentation (5) With the manufacturer, evaluate the seriousness of the surface cracks in the elastomeric bearings (6) Determine cause of weld separation between horsecollar and radial bearing retaining ring (7) Determine effect of parked rotor position on teeter motion	(1) Design, fabricate, and install a teeter motion damper (2) Replace plastic shim between horsecollar and rotor with steel shim (3) Determine cause of loss of preload in thrust bearing and take corrective action
(8) Rotor Cap	(1) Grind gusset weld details to improve weld to a class "C" (2) Increase bolt torques of rotor cap and low-speed shaft bolted flange joint (3) Increase bolt torques at trunnion and teeter bearing assembly joint	(1) Monitor movement indicators (eg., dental paste) at rotor cap-to-low-speed shaft and at trunnion-to-teeter interfaces (2) Conduct further analysis and/or experimental evaluation of the following: (a) Rotor cap and low-speed shaft bolted flange to determine cyclic stress range (b) Trunnion and rotor cap intersection weld to determine stress variation around circumference (c) Rotor cap cylinder wall stress in presence of drilled holes (3) Instrument the following for strain determinations: (a) Critical gusset weld	(1) Increase bolt size and preload at low-speed shaft-to-rotor cap interface (2) Install additional gusset plates, as required at trunnion-to-rotor cap intersection weld (3) Repair or redesign pilot interface (4) Grind fillet weld wrench marks and increase washer thickness to provide adequate clearance

TABLE III. - (continued)

		(b) Critical circumferential location at the trunnion and rotor cap intersection weld (c) Rotor cap near rotor cap and low-speed shaft bolt flange	
(9) Nacelle structure and major bearing supports	(1) Reshim the downwind bearing bolted joints to obtain proper clampup at the interface, and install new bolts, washers, and nuts (2) Grind welds on the secondary verticals of the primary truss structure	(1) Install instrumentation to obtain stresses at critical locations in the downwind bearing support and primary nacelle truss structure	
(11) Yaw drive system	(1) Assess the effect of impulsive loading on yaw gearbox life (2) Clean and relube pinion and ring gear teeth	(1) Prevent yaw corrections from taking place during wind turbine startup and shutdowns	(1) Rotate the ring gear 90° (2) Align pinion gear to ring gear so as to bring tooth contact and backlash within the specifications of the manufacturer (3) Install crossover relief valves (4) Make software changes to prevent yaw corrections during startups and shutdowns, and to limit the duration of large yaw errors (5) Experimentally determine the effect of dragging one or more of the yaw parking brakes during yaw corrections
(16) Tower, base and foundation			(1) Visually inspect tower welds every 600 hr for cracks (2) Retension all studs to 85 000 ± 5 000 ft-lb (3) Seal tower grout to prevent entry of water and possible corrosion (4) Repaint base details (5) Check preload on rock anchors
(17) Gin pole system			(1) Add additional weight to the existing gin pole proof load to compensate for the increase in weight from modifications including new low-speed shaft assembly (2) Incorporate formal gin pole Operations and Maintenance procedures which include assembly, disassembly, operation, proof test loads, maintenance, inspection, and corrosion prevention in the Operations and Maintenance manual (3) Provide environmental protection of the gin pole winch assembly

TABLE IV. - SUMMARY OF RECOMMENDATIONS FOR NONCRITICAL STRUCTURAL AND MECHANICAL COMPONENTS

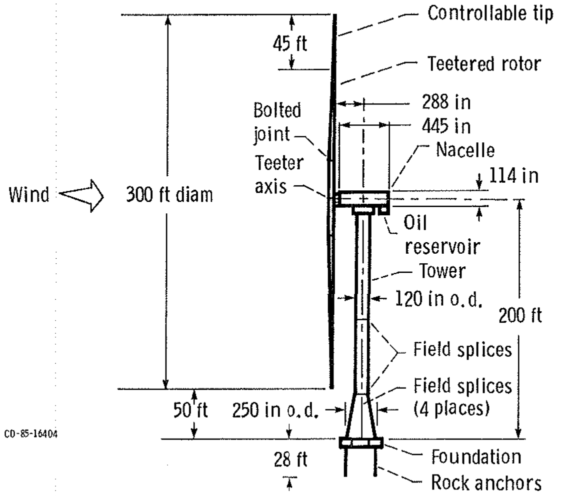
Item	Recommended action			
	Prior to attended operation	During attended operation	Prior to unattended operation	During unattended operation
(1) Rotor pitch actuator[a]				
(2) Rotor spindle	(1) Measure the Belleville spring lengths for conformance to specification initially and every two months thereafter		(1) Inspect the flange attachment bolts for conformance to specifications on type and torque (2) Replace the plastic shim material between highly preloaded flange faces with steel materials (3) Inspect the flange to determine if inserts provide a satisfactory long-term repair	
(4) Rotor welds	(1) Requalify the crack detection system (as discussed in appendix E) to assure its reliability		(1) Identify critical welds in accordance with the guidelines established in the subsection Rotor Assembly; clearly mark critical welds on the inside of the blade, and perform visual inspections of these welds at an interval to be established by additional analysis	
(5) Rotor spars[a]				
(6) Rotor blade equipment mounting holes			(1) Show number, size, and location of holes, used to mount hardware, on the drawings	
(10) Low-speed shaft bearings	(1) Drain and clean LSS bearing sumps and refill with clean oil		(1) Install improved seals to eliminate leakage (2) Install a circulating forced lubrication system	
(12) Quill shaft				(1) Torque check the quill shaft coupling to gearbox bolts every 1000 hr of operation
(13) Gearbox	(1) Reshim the gearbox support feet on WT2 and WT4		(1) Rework the detail at the intersection of the gearbox case and support structure to reduce stress in the weld	
(14) High-speed shaft			(1) Show holes, used to fasten balance weights to the shaft, on the respective drawings	
(15) Generator[a]				

[a] No action required.

TABLE V. - SUMMARY OF RECOMMENDATIONS FOR NONCRITICAL ELECTRICAL COMPONENTS

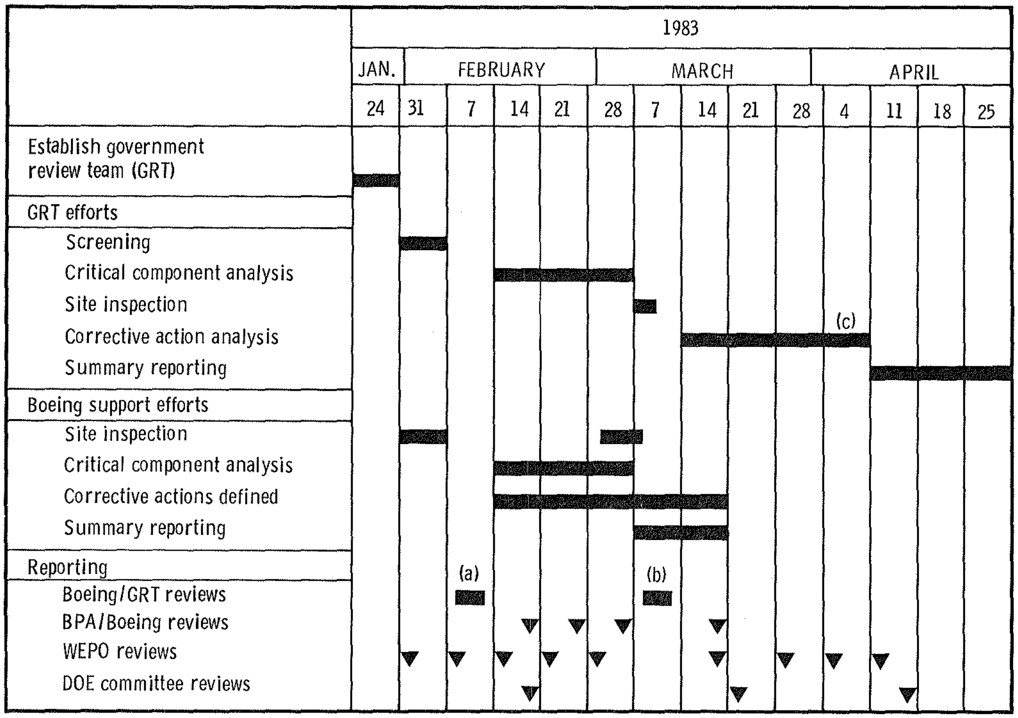
Item	Recommended action			
	Prior to attended operation	During attended operation	Prior to unattended operation	During unattended operation
(18) Vibration effects on generator protection relay[a]				
(19) Substation and wind turbine trip coordination			(1) Provide transfer trip capability between substation and wind turbine	
(20) Protection adequacy		(1) Install protective cover on 48 V battery	(1) Install no-volt trip to the BTCU breaker	
(21) BPA substation			(1) Increase inventory of substation equipment spare parts (2) Install screening beneath the recloser to prevent entry of rodents	
(22) Tower power cable mountings		(1) Correct cable clamp pinching (2) Tighten loose cable ladder joints		
(23) Low-speed shaft bearing failure detection			(1) Incorporate LSS bearing lubrication level sensors	
(24) Overspeed sensing adequacy	(1) Perform functional check of the overspeed sensor circuit			(1) Incorporate periodic functional check in routine maintenance
(25) Fault memory retention			(1) Add hard copy print capability to display terminals	
(26) CRT shutdowns			(1) Add answerback feature hardware and software to the display terminals	
(27) Yaw slipring			(1) Inspect the sliprings for contamination and measure resistance on the power rings (2) Inspect and replace the molded HV cable termination boots as required, and install a drip shield to prevent further oil contamination (3) Replace the existing antirotation restraint with an improved design which can not load the yaw slipring	
(28) Low-speed shaft slipring			(1) Implement a self check of the crack detection system and interchange rings 25 and 26	
(29) Low-speed shaft slipring bearing[a]				

[a] No action required.



Rated power, kW	2500
Rotor diameter, ft	300
Rotor type	Teetered - tip control
Rotor orientation	Upwind - 2.5° tilt
Rotor airfoil	NACA 230XX
Rated wind at hub, mph	27.5
Cut-off windspeed at hub, mph	45
Rotor tip speed, ft/s	275
Rotor speed, rpm	17.5
Generator speed, rpm	1800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height, ft	200
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient (max)	0.382

Figure 1. - Mod-2 design characteristics



(a) Establish critical component and subassemblies, February 8 to 10, 1983.
(b) Establish deficiencies critical to attended and unattended operation, March 8 to 10, 1983.
(c) Recommend corrective actions for attended and unattended operation.

Figure 2. - Schedule of review activities.

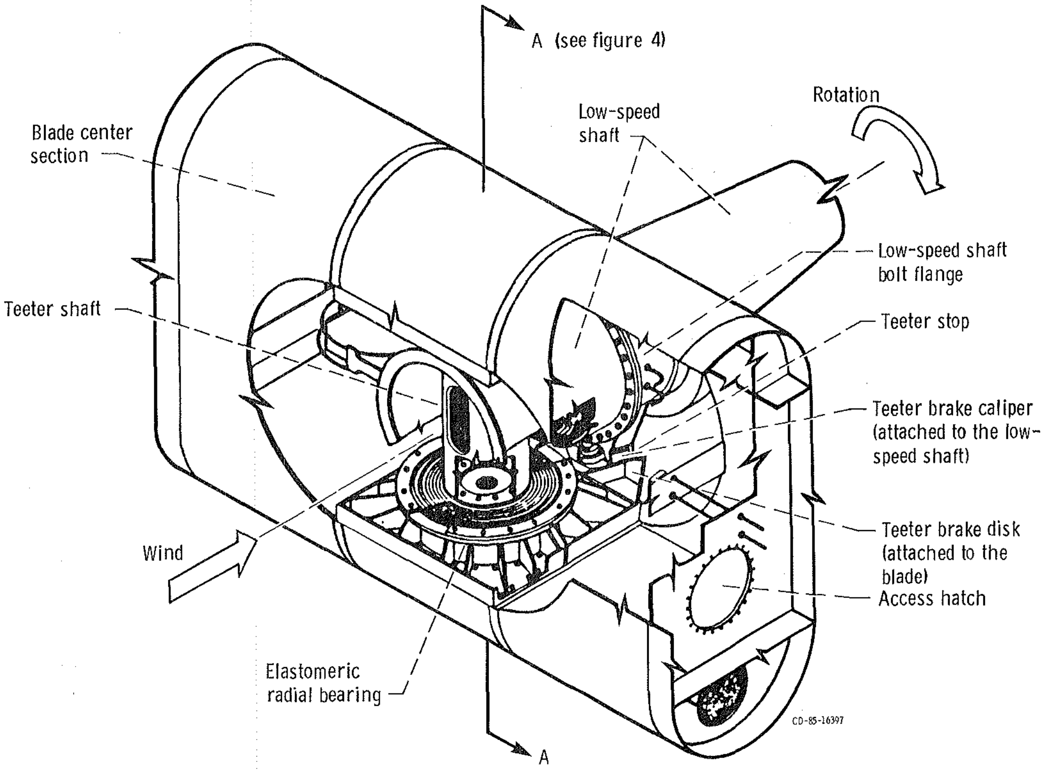


Figure 3. - Teeter system.

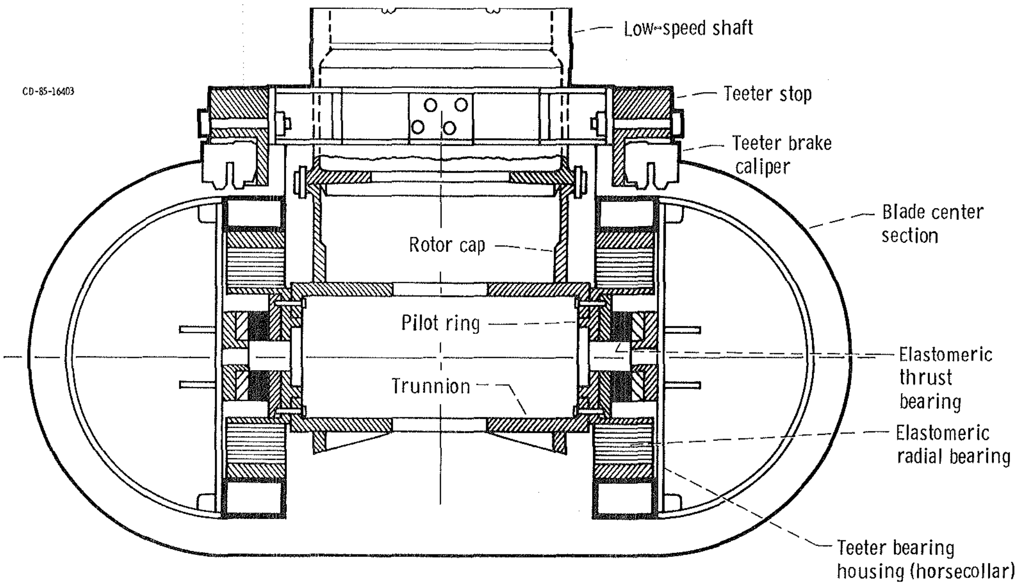


Figure 4. - Teeter system cross section. (View A-A in figure 3).

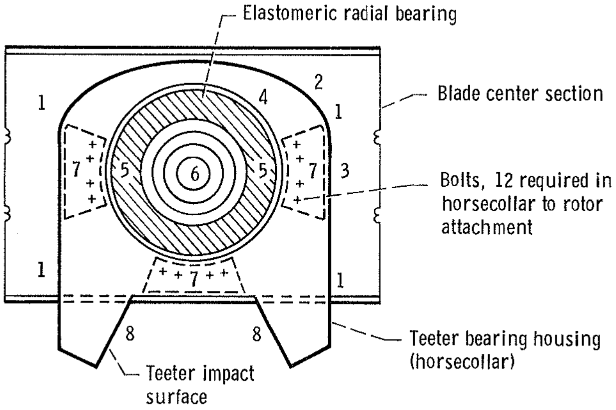
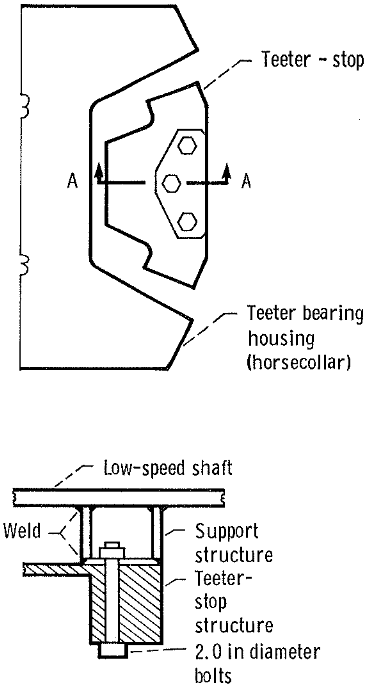
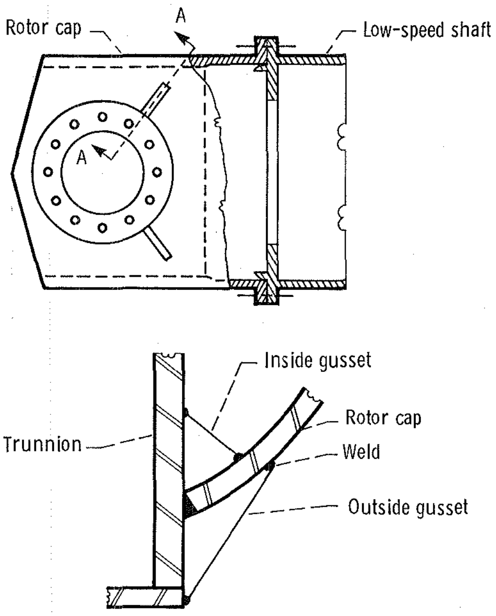


Figure 5. - Teeter bearing housing.



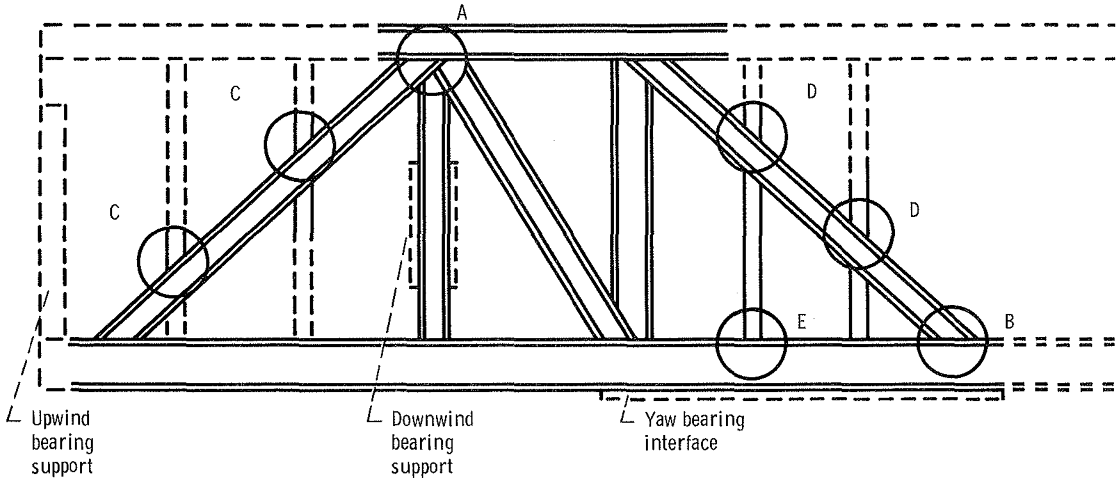
(View A-A)

Figure 6. - Teeter-stop details.

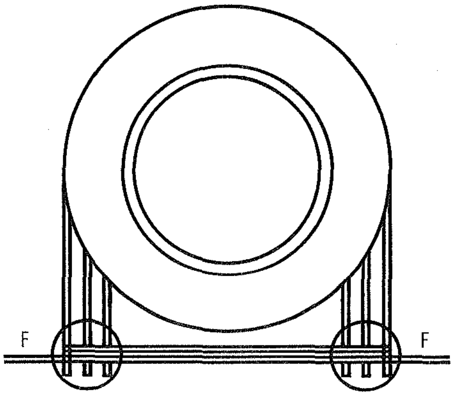


(View A-A)

Figure 7. - Rotor cap details.



(a) Primary truss structure. (Encircled areas denote critical weld areas.)



(b) Downwind bearing support. (Encircled areas denote critical weld areas.)

Area	Est. time until repair, hr
A	67 000
B	57 000
C	60 000
D	16 000
E	20 000
F	4 000

(c) Critical weld area data.

Figure 8. - Nacelle and major bearing support details.

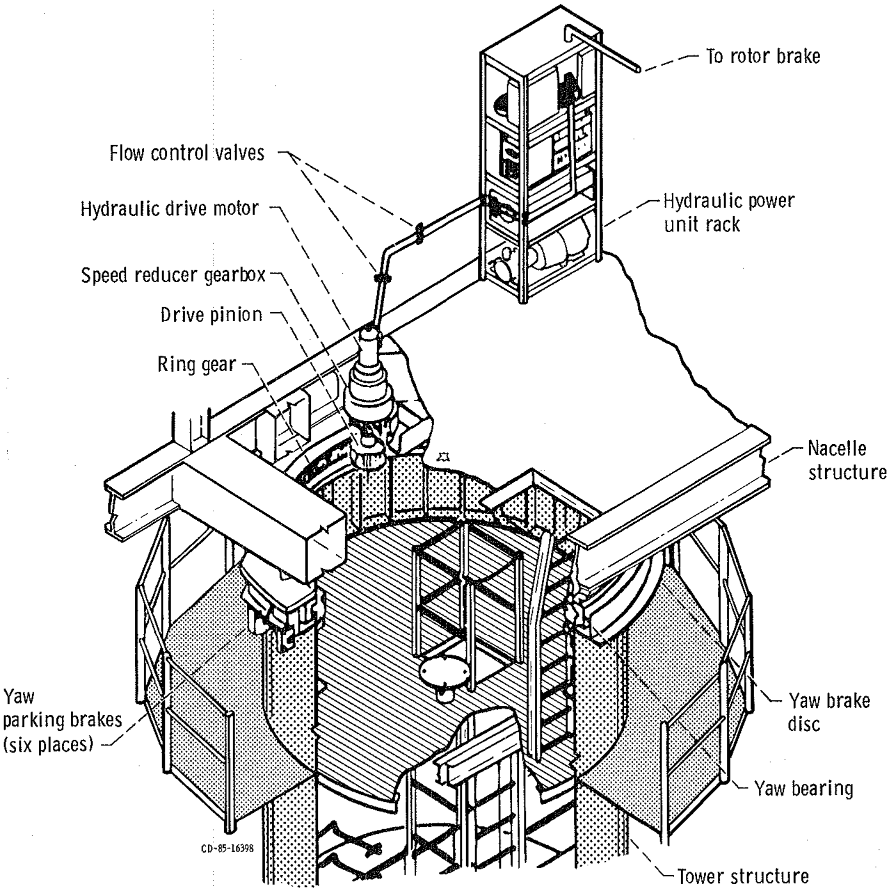


Figure 9. - Yaw drive system.

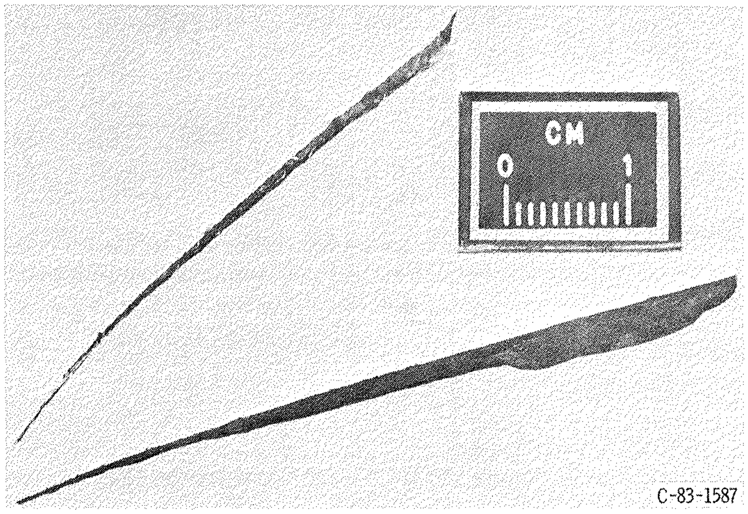


Figure 10. - Metal slivers removed from yaw ring gear.

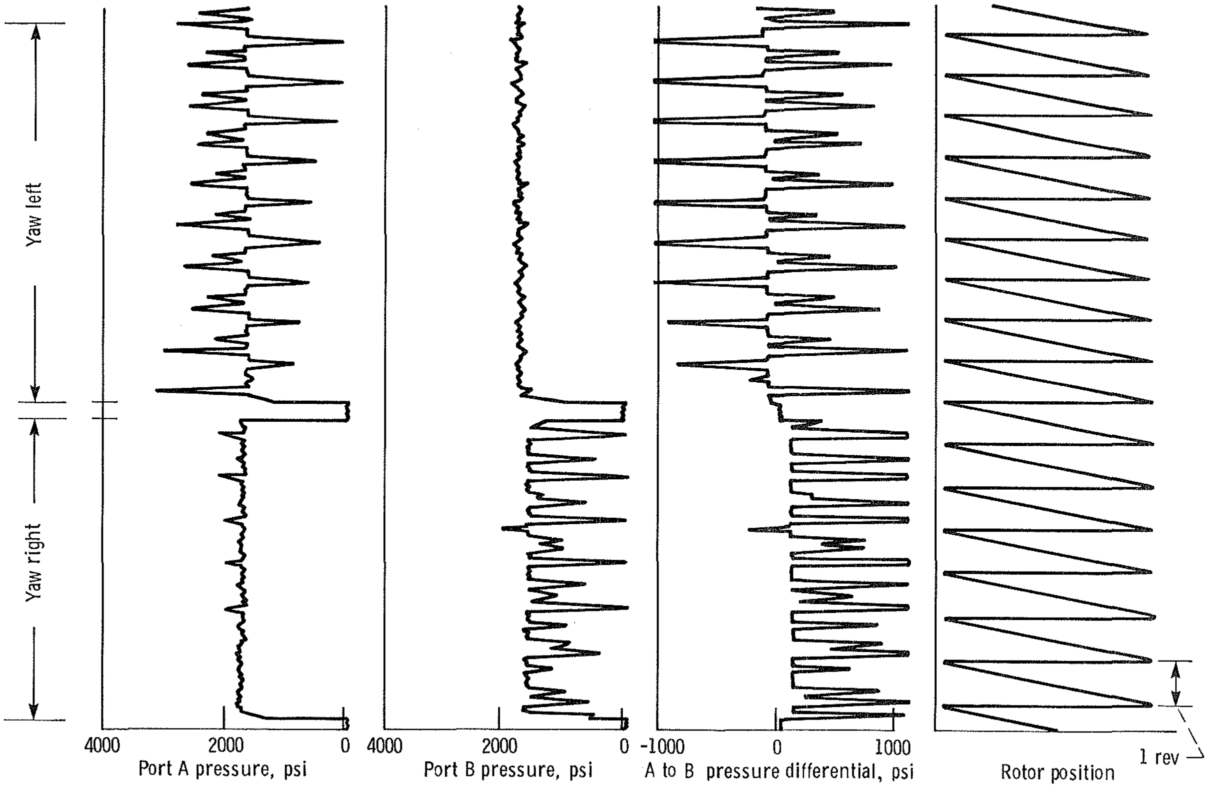


Figure 11. - Yaw drive motor pressures during yaw corrections. (Rotor speed = 17.5 rpm.)

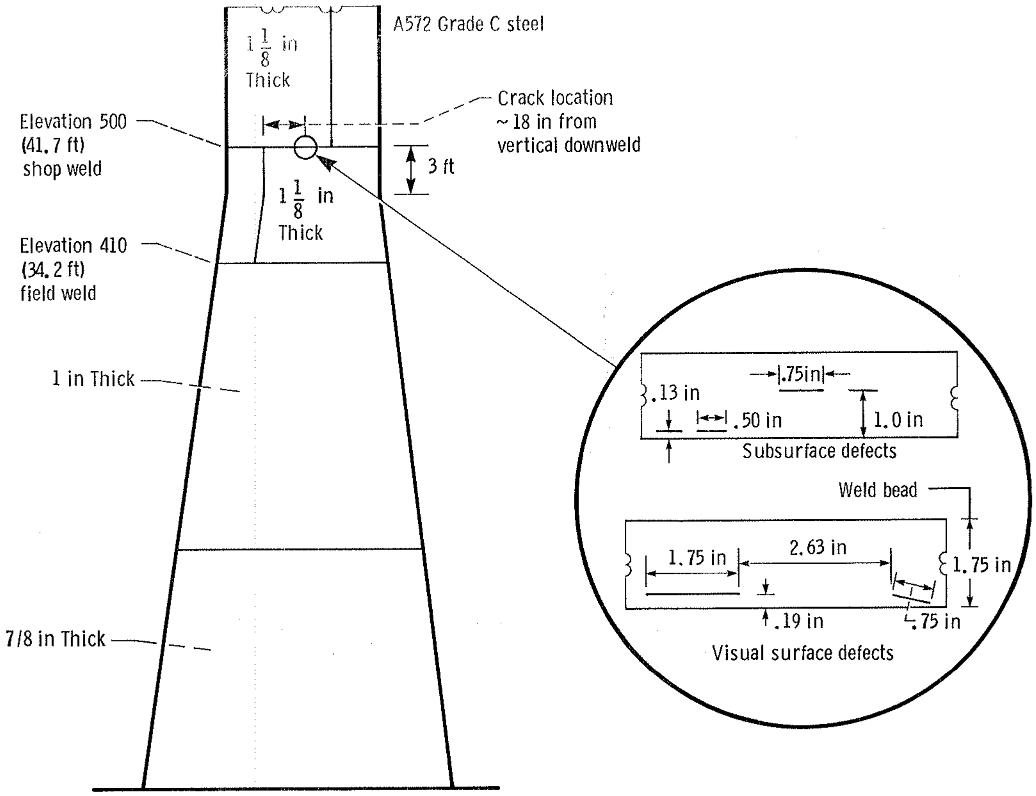


Figure 12. - Solano (WT5) tower crack, view looking east. (Subsurface defects are directly below surface defects.)

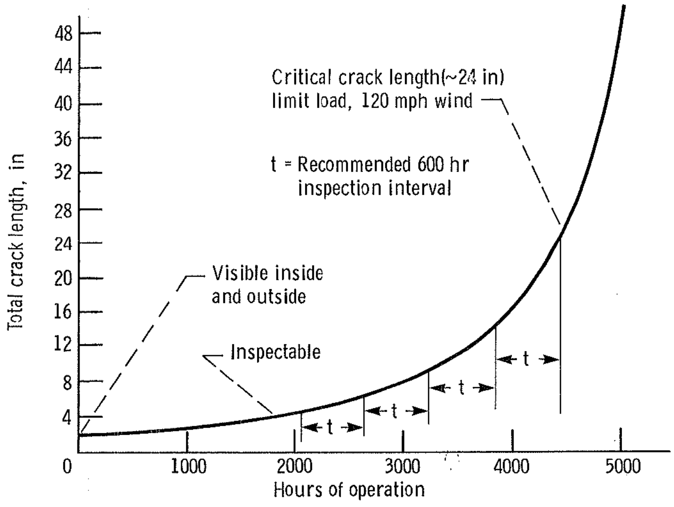


Figure 13. - Predicted tower crack growth rate.

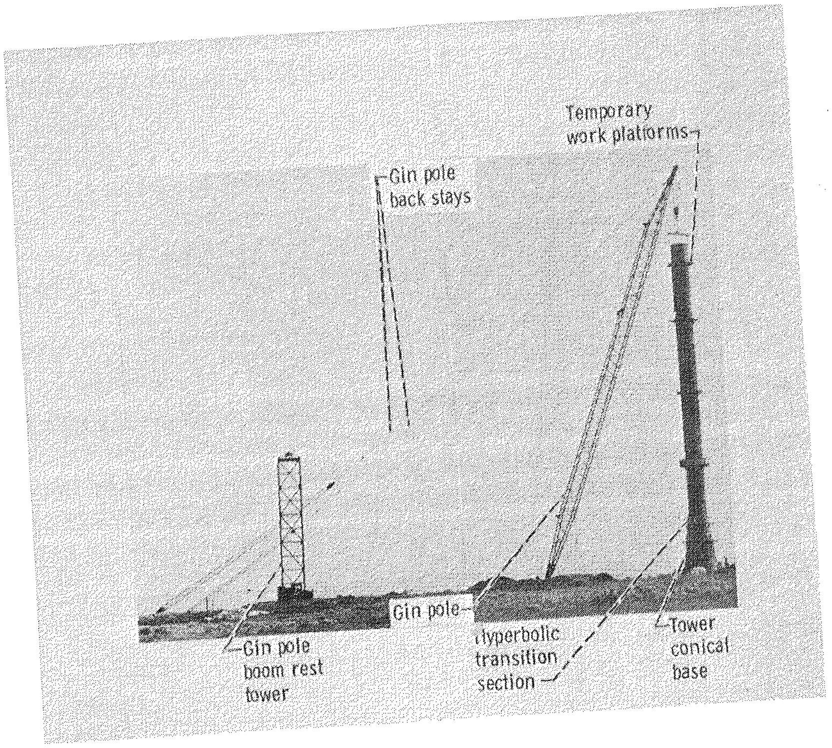


Figure 14. - Gin pole system.

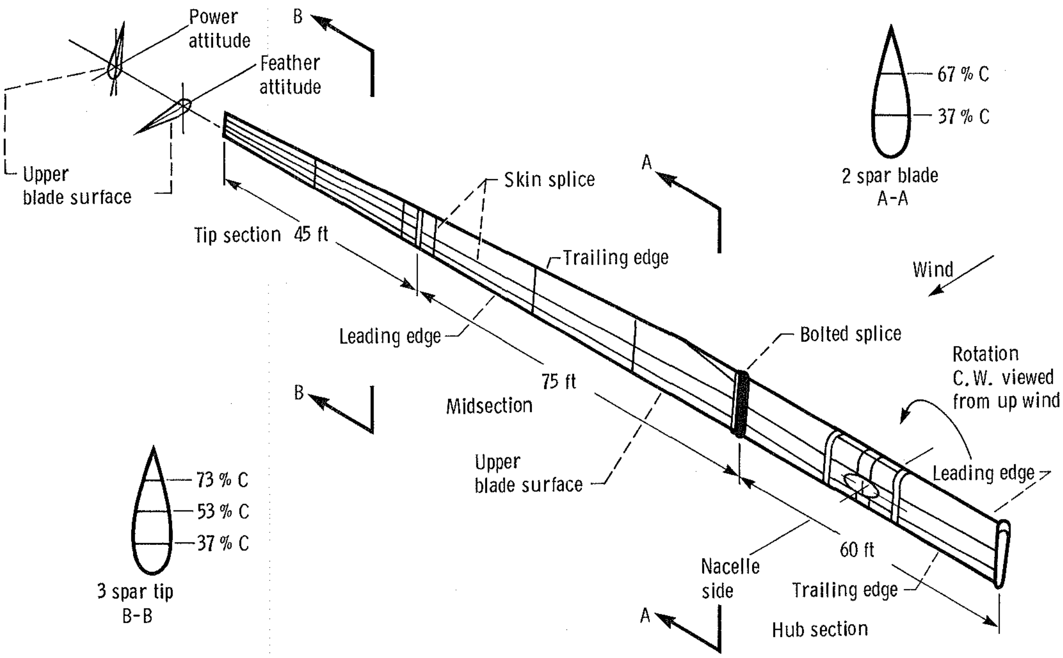


Figure 15. - Rotor configuration.

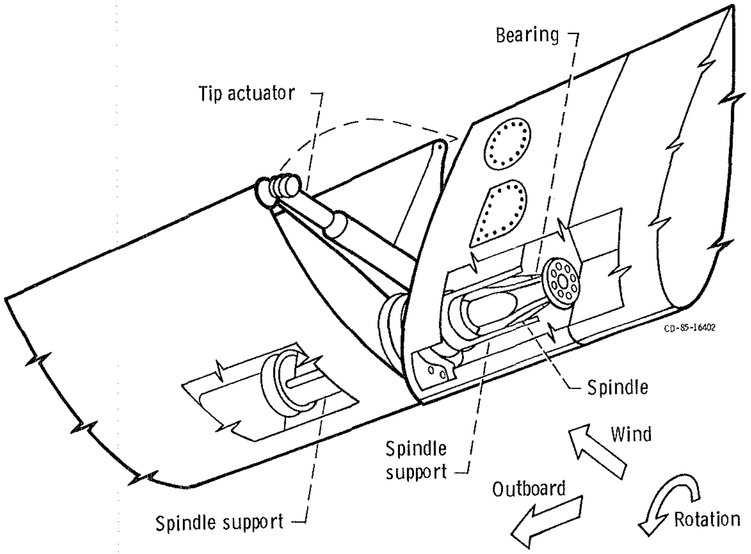


Figure 16. - Rotor spindle assembly.

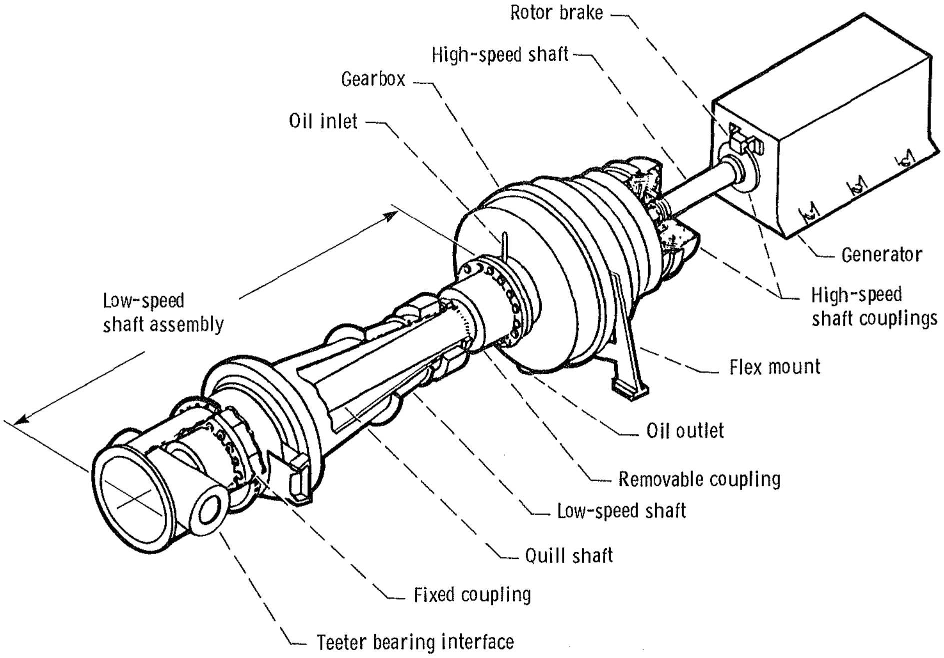


Figure 17. - Drive train assembly.

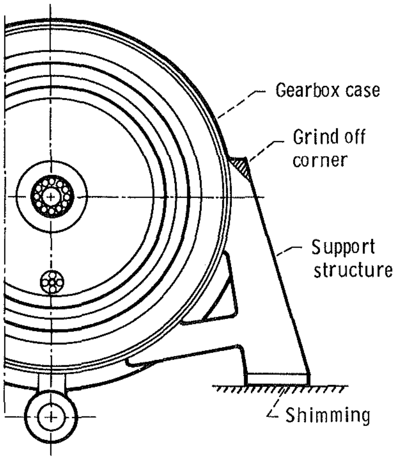


Figure 18. - Gearbox details.

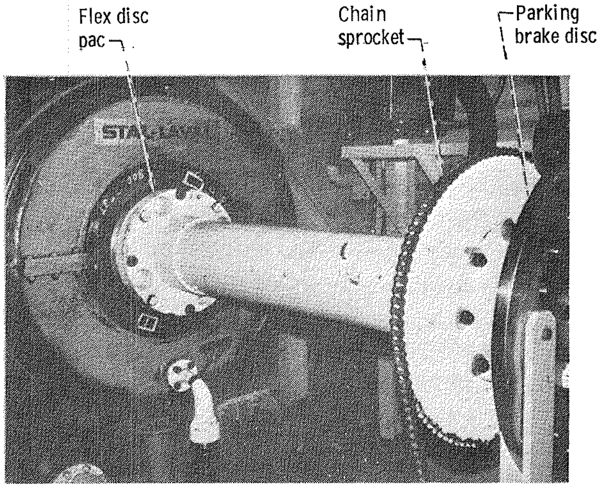


Figure 19. - High-speed shaft.

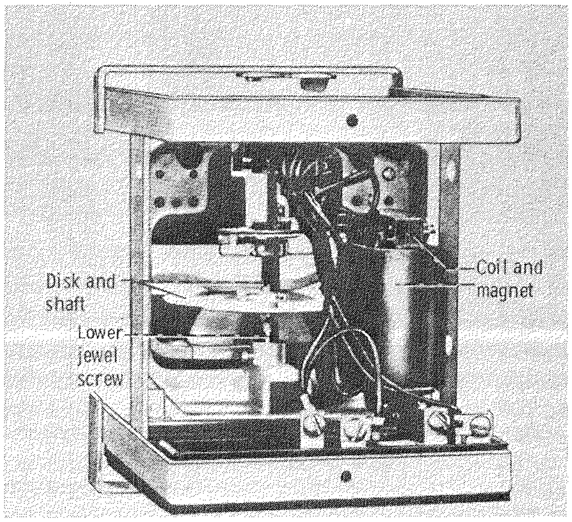


Figure 20. - Typical induction disk relay.

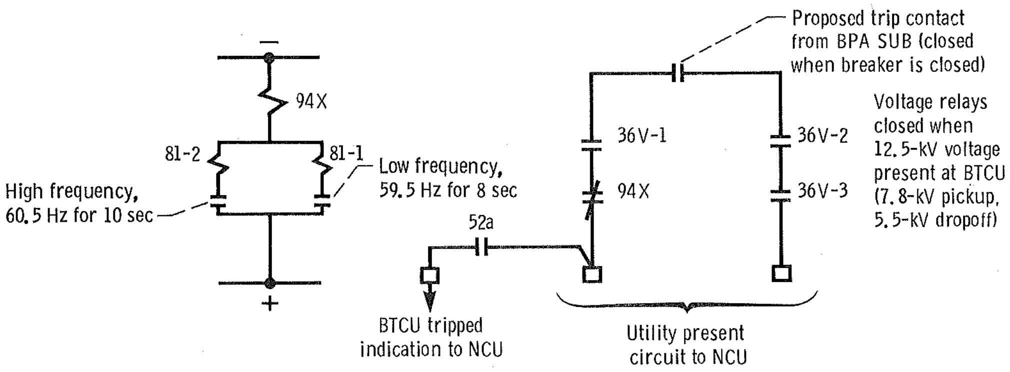


Figure 21. - Loss of utility power relay trip circuit.

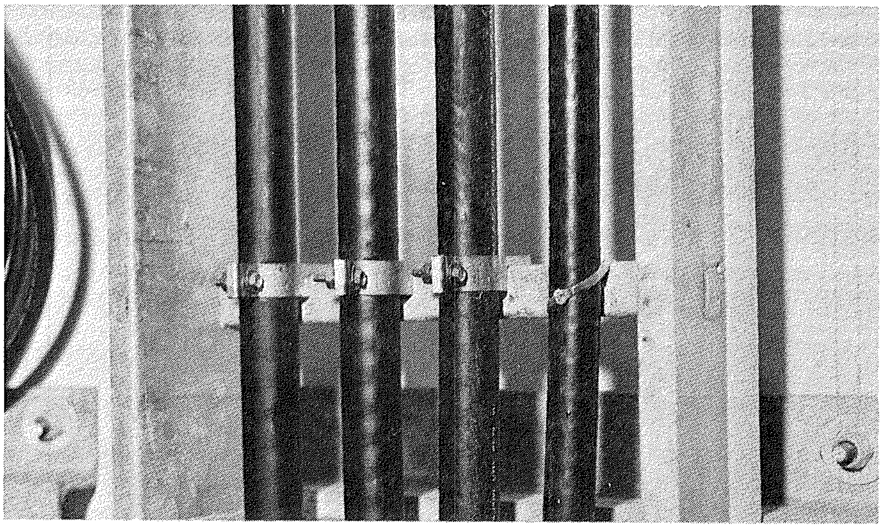


Figure 22. - Phase conductor (4.16-kV) cable ladder clamps.

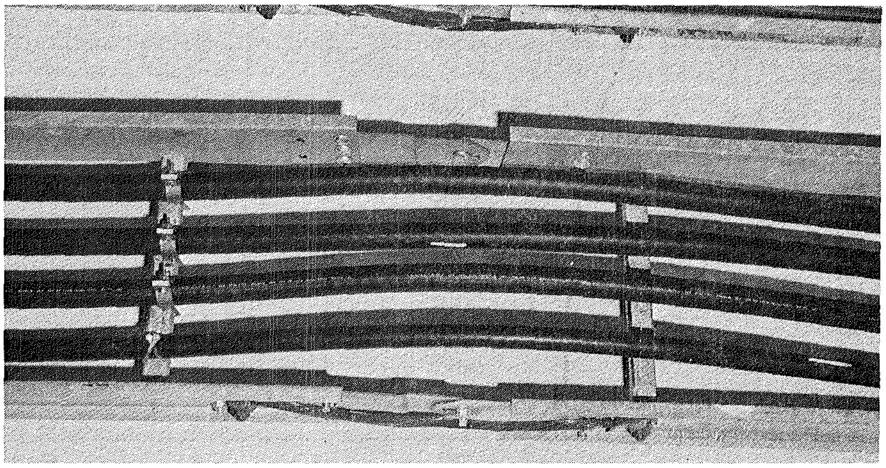


Figure 23. - Power cable ladder extension joints.

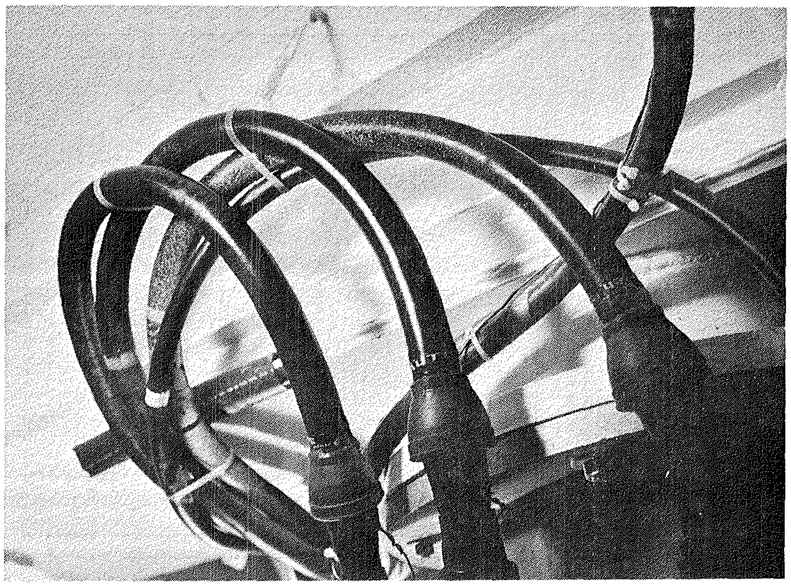


Figure 24. - Wind turbine HV cable suspension at yaw slipring.

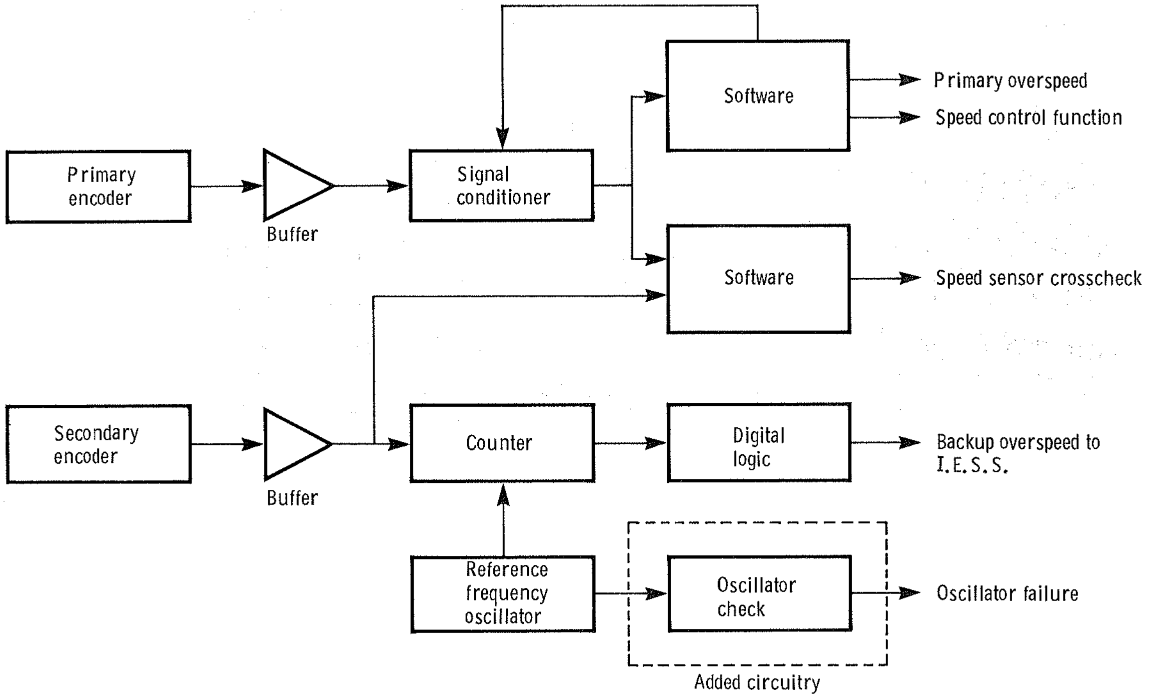


Figure 25. - Overspeed sensing circuitry.

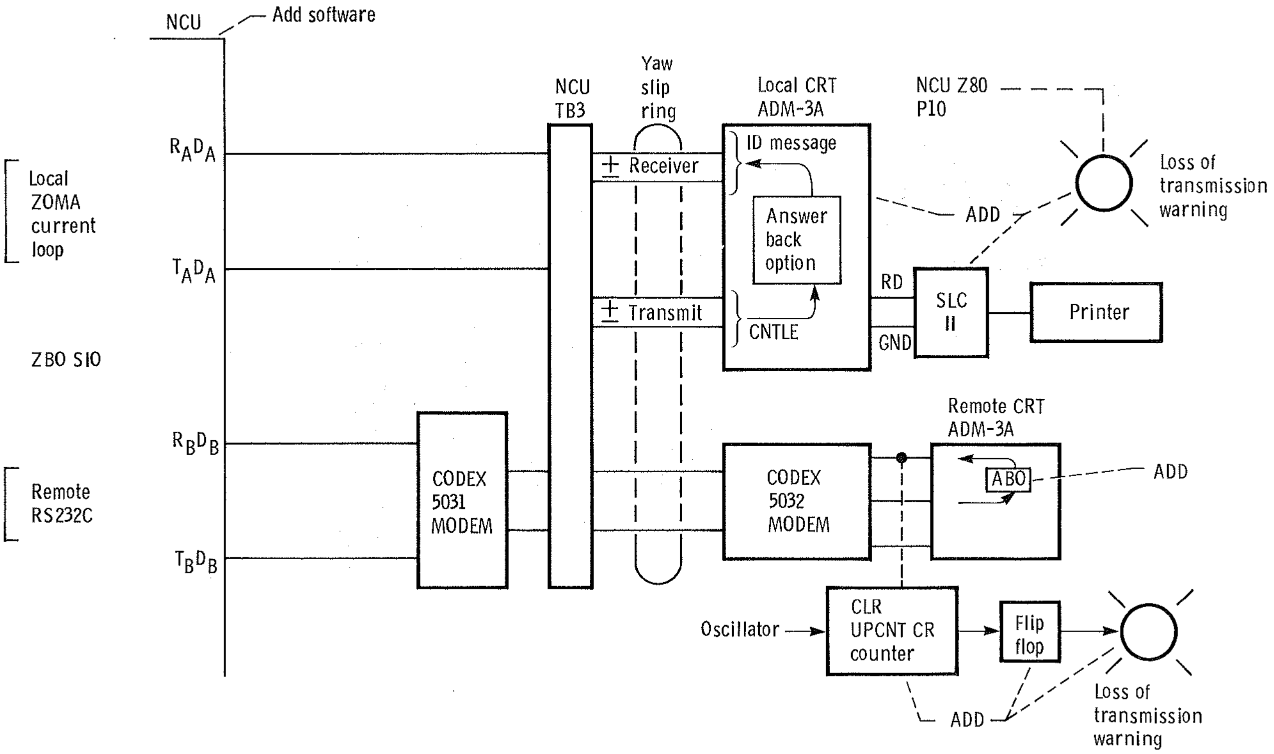


Figure 26. - Wind turbine control communications link.

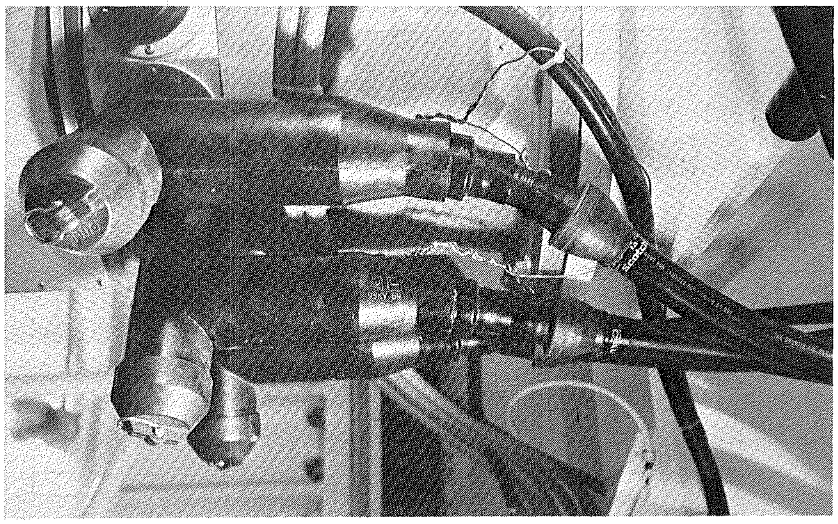


Figure 27. - Wind turbine yaw slipring HV molded cable terminations.

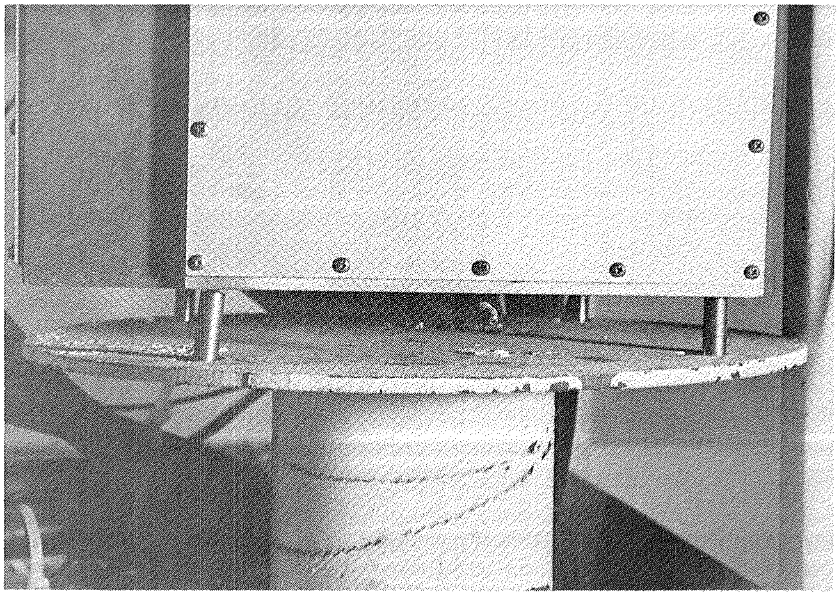


Figure 28. - Wind turbine yaw slipring anti-rotation restraint.

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16. Abstract

This report documents the findings and recommendations of the Government committee formed to conduct an as-built review of the three Mod-2 wind turbine units at Goldendale, Washington. The purpose of the review was to identify any critical deficiencies in machine components that could result in failure, and to recommend any necessary corrective action before resuming safe machine operation. The review concluded that none of the deficiencies identified would preclude planned attended or unattended operation, provided that certain corrective actions were implemented.

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