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MOD 1 WIND TURBINE GENERATOR FAILURE MODES AND EFFECTS ANALYSIS

General Electric Company
Space Division

NASA-CR-159494

February 1979

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-20058

for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology

NOTICE

MOD 1 WIND TURBINE GENERATOR

FAILURE MODES AND EFFECTS ANALYSIS

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General Electric Company
Space Division
Advanced Energy Systems
Philadelphia, Pennsylvania 19101

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Cleveland, Ohio 44135
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For
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Office of Energy Technology
Division of Distributed Solar Technology
Washington, D.C. 20545
Under Interagency Agreement EX-77-A-29-1010

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FAILURE MODES AND EFFECTS ANALYSIS

Introduction

The following figures and tables present the results of a Failure Modes and Effects Analysis (FMEA) of the Mod 1 Wind Turbine Generator. This analysis was of limited scope, in accordance with Statement of Work NAS3-20058, and was directed primarily at identifying those critical failure modes that would be hazardous to life or would result in major damage to the system. As a result, the analysis was conducted from the "top down", minimizing the extent of analysis that would lead to trivial conclusions, had the analysis been approached from the "bottom up". For example, a component-by-component analysis of the lubrication system was not pursued, once it had been established that all lubrication system failures lead to the same, non-critical conclusion.

Evaluation Criteria

The criteria used for evaluation of the system is that none of the following injuries or damage shall occur because of a single failure or a single failure following an undetected failure of the wind turbine system.

Category I: Failures which would result in death or serious injury to the operator or general public.

Category II: Failures which would result in major or significant damage to the wind turbine system, extended outage, or damage to the connected utility.

All other failures are Category III. The failure categories are listed under Column 9 in the attached tables.

Task Approach

Figure 1 illustrates how the Mod 1 Wind Turbine Generator system was broken down for analysis. This organization corresponds roughly to the drawing system, defined by Drawing Tree 298E470. Since subsystem descriptions are beyond the scope of this report, reference should be made to the drawings that are identified on the Drawing Tree, should further details be required. Figures 2 through 10 provide an overview of each subsystem, with circled numbers corresponding to principal line items in the accompanying tables. Figures 8, 9 and 10 are simplified diagrams to further break down the Power Generation and Controls subsystems.

Each subsystem was approached from the top down, and broken down to successive lower levels where it appeared that the criticality of the failure mode warranted more detailed analysis. The attached tables, pages 1 through 55, were prepared as worksheets through several stages of review, including review by qualified GE specialists outside of the Mod 1 program and two reviews by knowledgeable NASA LeRC personnel. These summary tables were supplemented by analyses on topics of special interest that are included as appendices to this report covering:

- Unbalance Loads after Blade Separation
- Blade Interface Ring Flange Stress Analysis
- Blade Test Program
- Blade Quality Program
- Rotor Overspeed

Summary and Conclusions

The results of this study have been evaluated and the failure evaluation criteria have been met for all Category I failures, except for the blade and its attachment structure. Should a blade separate, as shown in Appendix A, no additional failures would propagate. Also, the probability of a blade separation is acceptably small based on the other information presented in the Appendices, i.e., the analysis of the interface ring flange, the design verifications to be achieved by the test program (especially the 1.7.4 tests of fatigue strength of welds), the inspections and checks of the quality program, and the redundancy built into the overspeed shutdown circuits.

A few Category II failures are also possible. These mainly involve conservatively designed items such as shafting, bearings, and gears where the possibility of failure, or premature failure, is acceptably small and it is not practical to completely avoid such failures. These items are discussed in more detail in the tables.

Some minor changes have been identified as a result of this study and are being incorporated. They are

- Pitch jam circuit redesigned to be fail-safe
- Overspeed reset redesigned to mechanically latch after power failure
- Software revised to check sensors in their non-active state
- Specific inspection points identified for checks during periodic maintenance

It may be necessary to incorporate additional changes later, if, for example, additional Category I or II failure modes are identified during the test and field check-out phases.

Figure 1

FMEA SYSTEM DIAGRAM

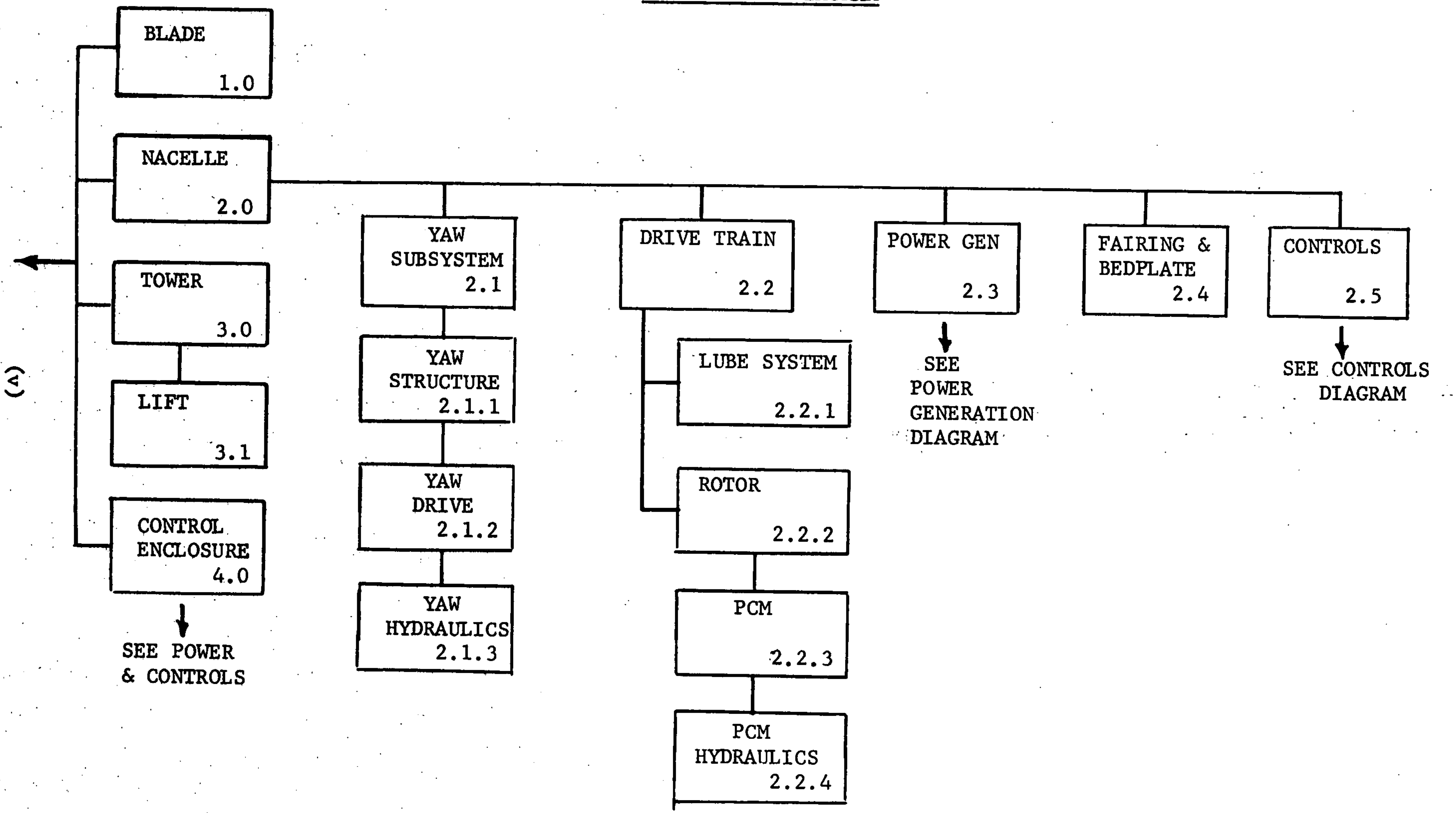


FIGURE 2

MOD-1 BLADE

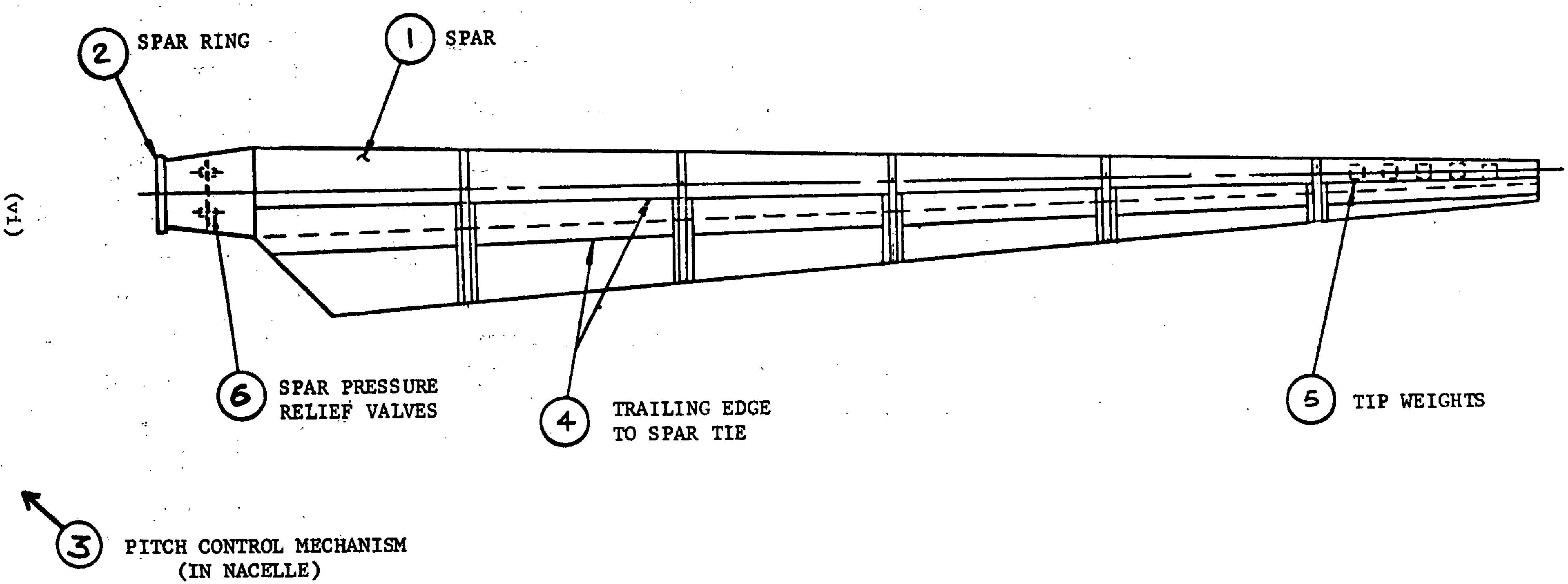


FIGURE 3

YAW MOTOR/DRIVE

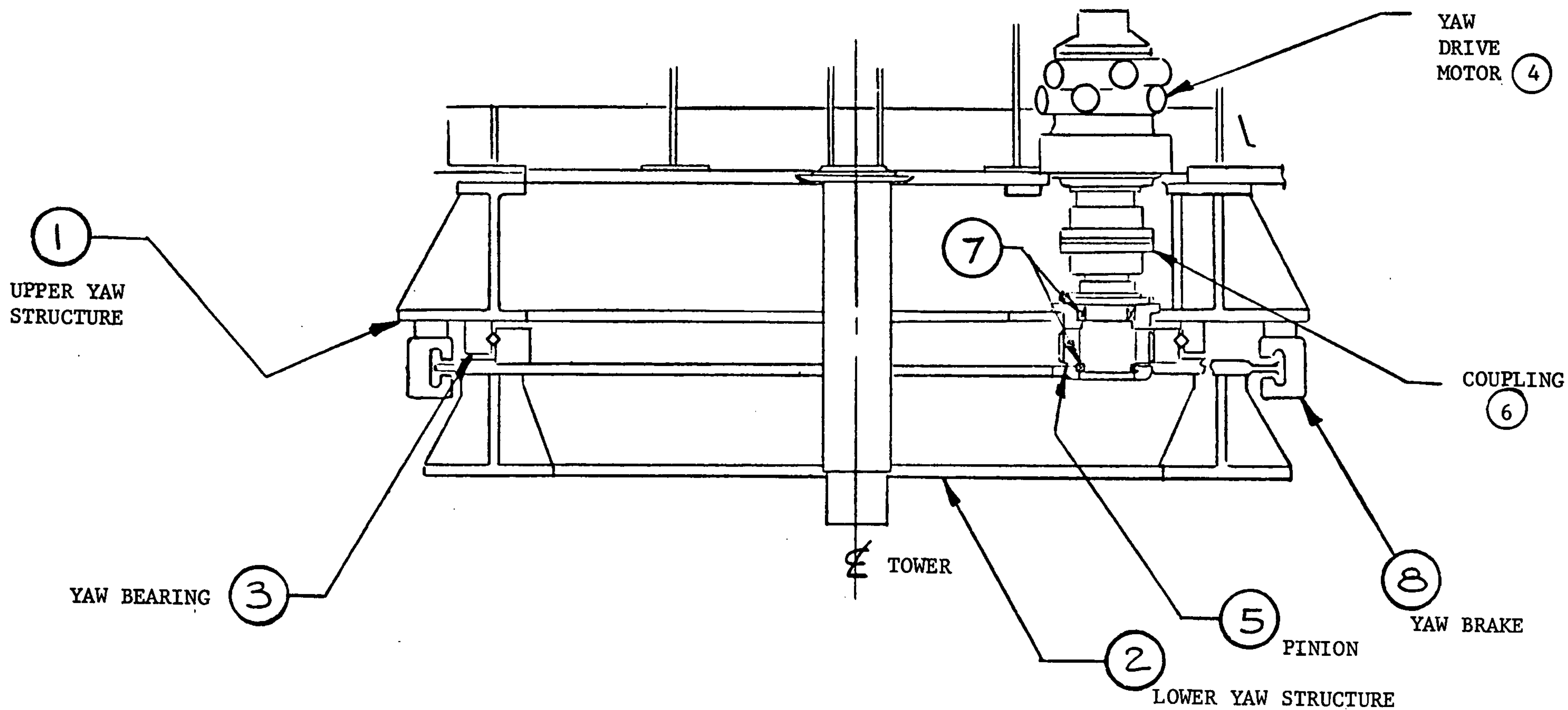


FIGURE 4

YAW HYDRAULICS

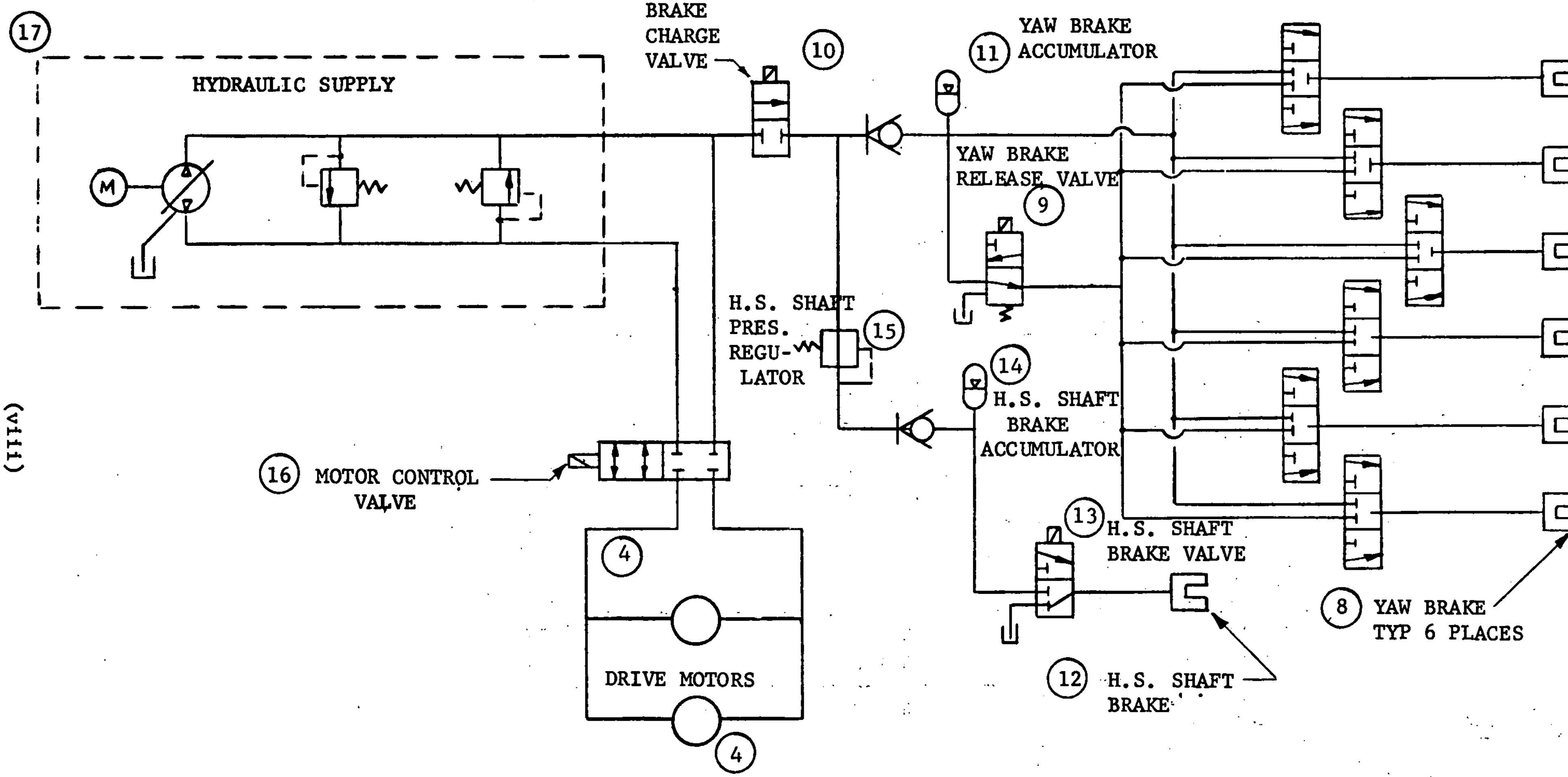


FIGURE 5

DRIVE TRAIN

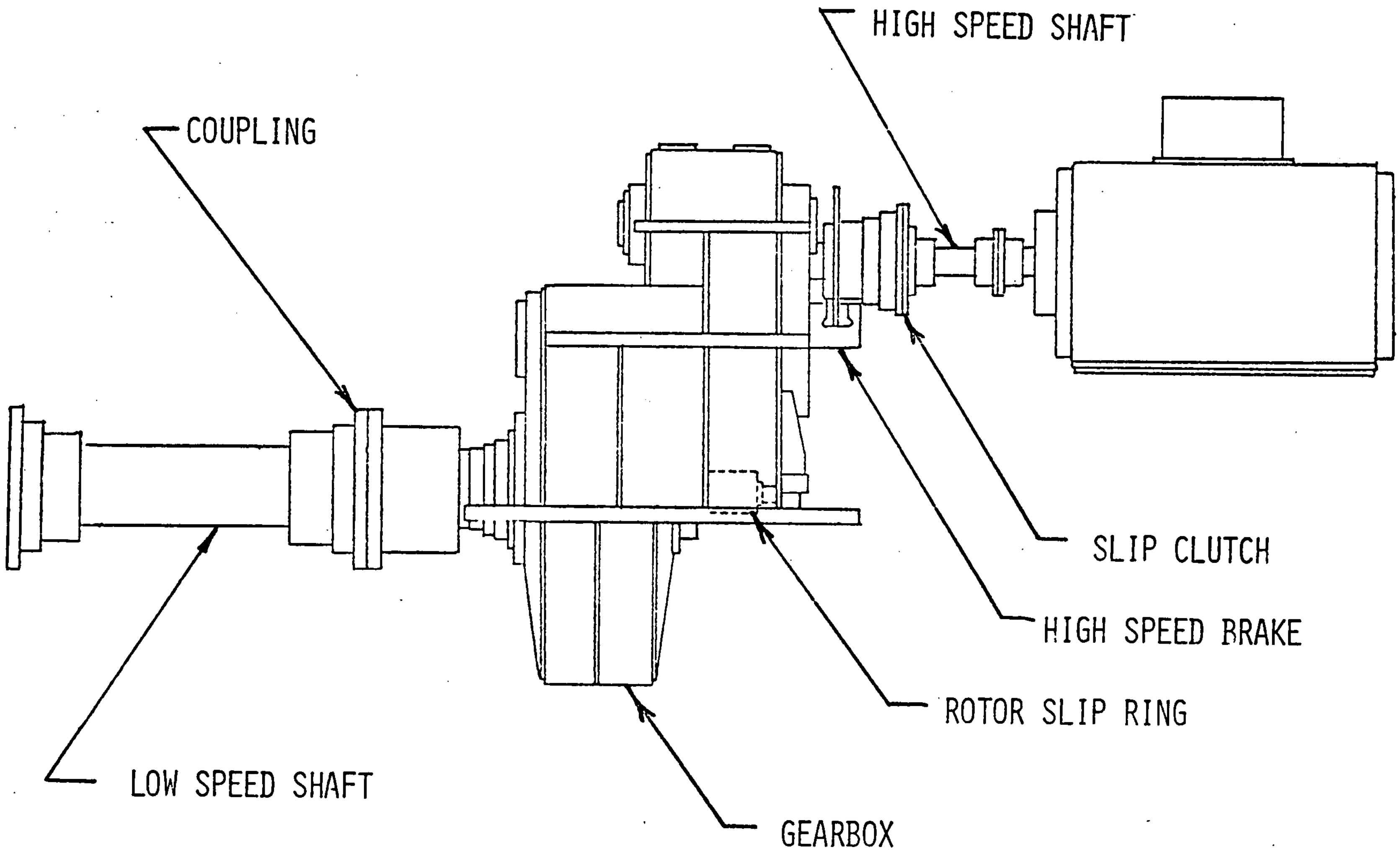


FIGURE 6

PITCH CHANGE MECHANISM

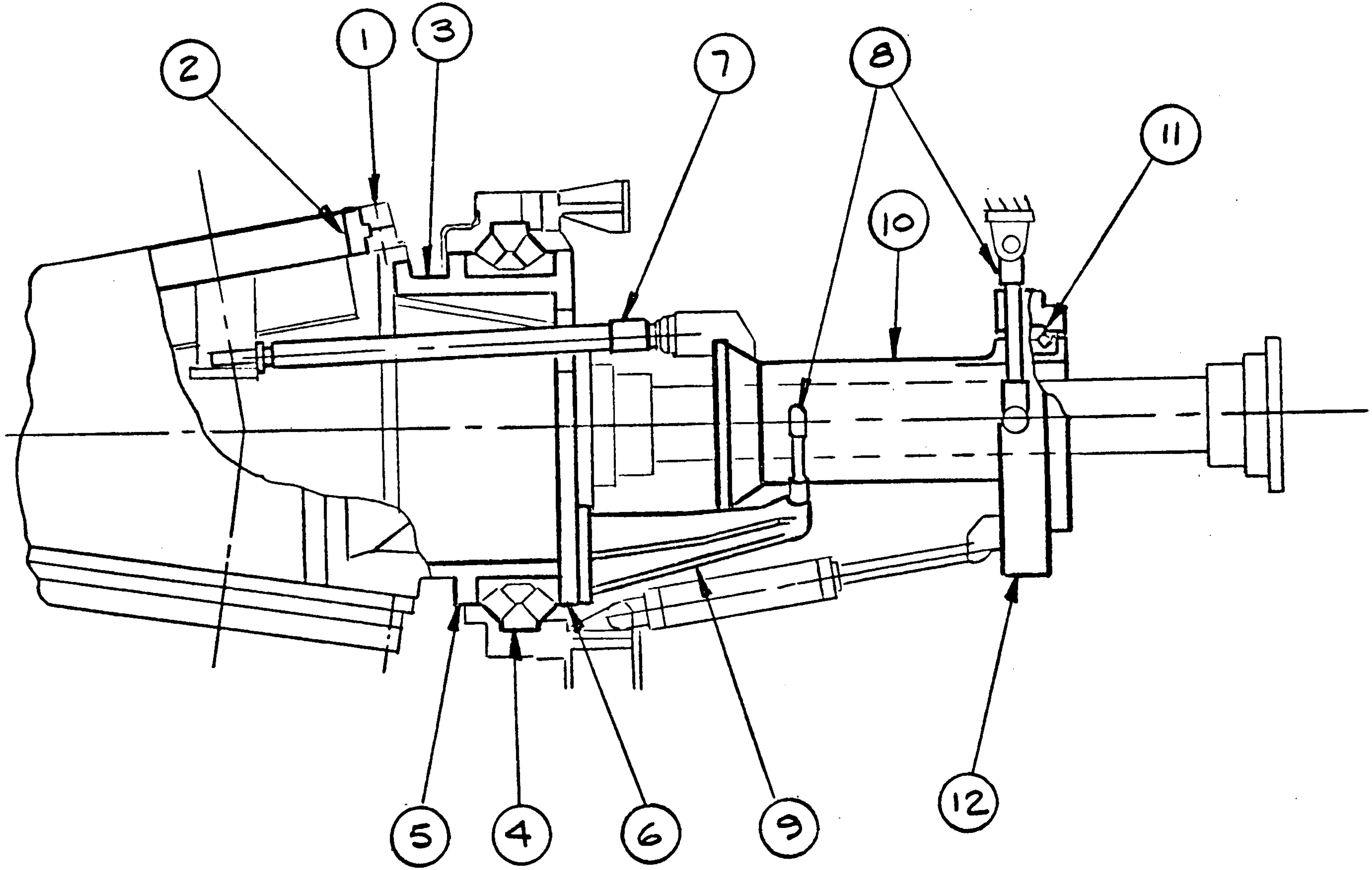
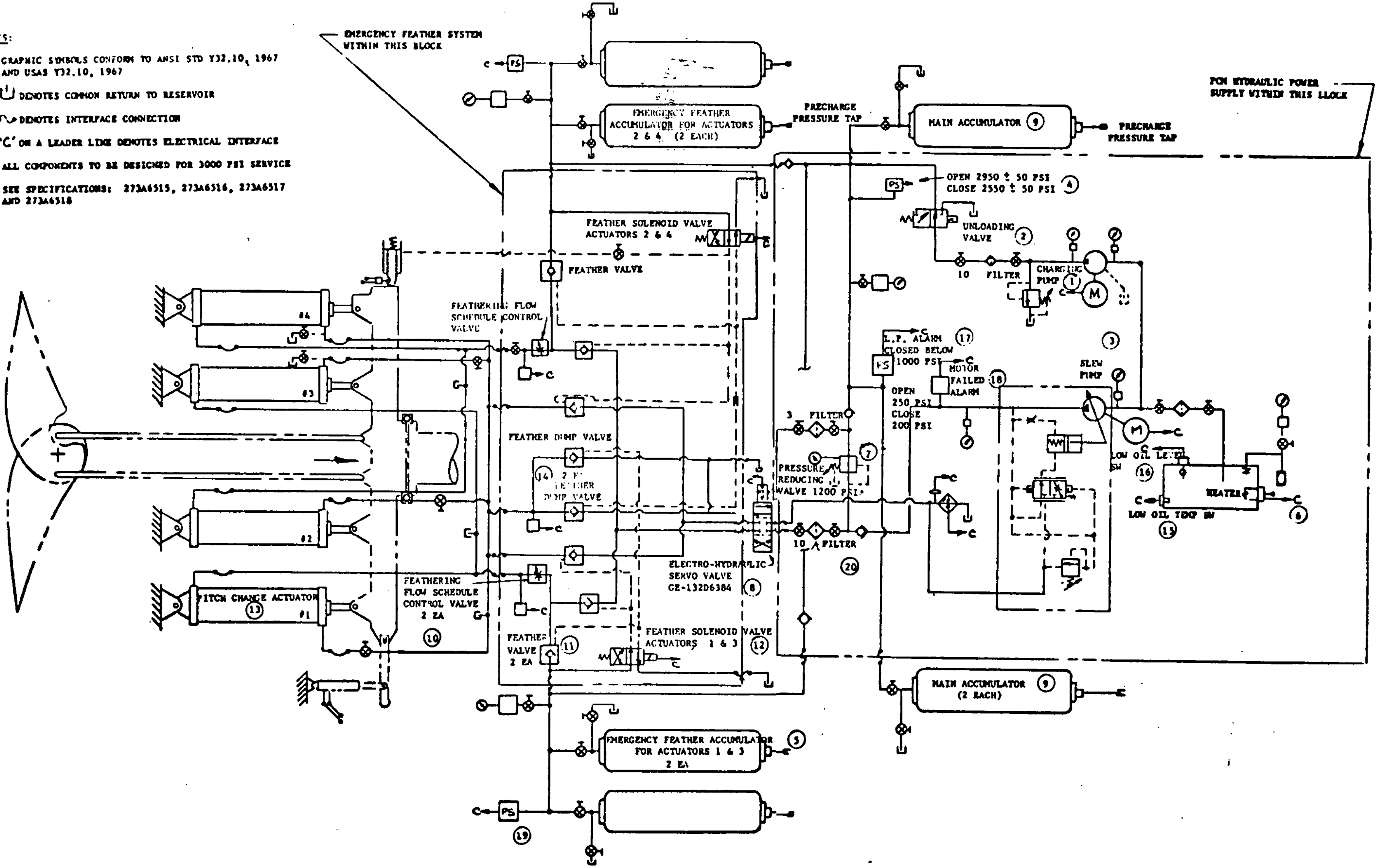


FIGURE 7

PCH HYDRAULIC PACKAGE



NOTES:

1. GRAPHIC SYMBOLS CONFORM TO ANSI STD Y32.10, 1967 AND USAS Y32.10, 1967
2. ⊔ DENOTES COMMON RETURN TO RESERVOIR
3. ⌒ DENOTES INTERFACE CONNECTION
4. 'C' ON A LEADER LINE DENOTES ELECTRICAL INTERFACE
5. ALL COMPONENTS TO BE DESIGNED FOR 3000 PSI SERVICE
6. SEE SPECIFICATIONS: 273A6515, 273A6516, 273A6517 AND 273A6518

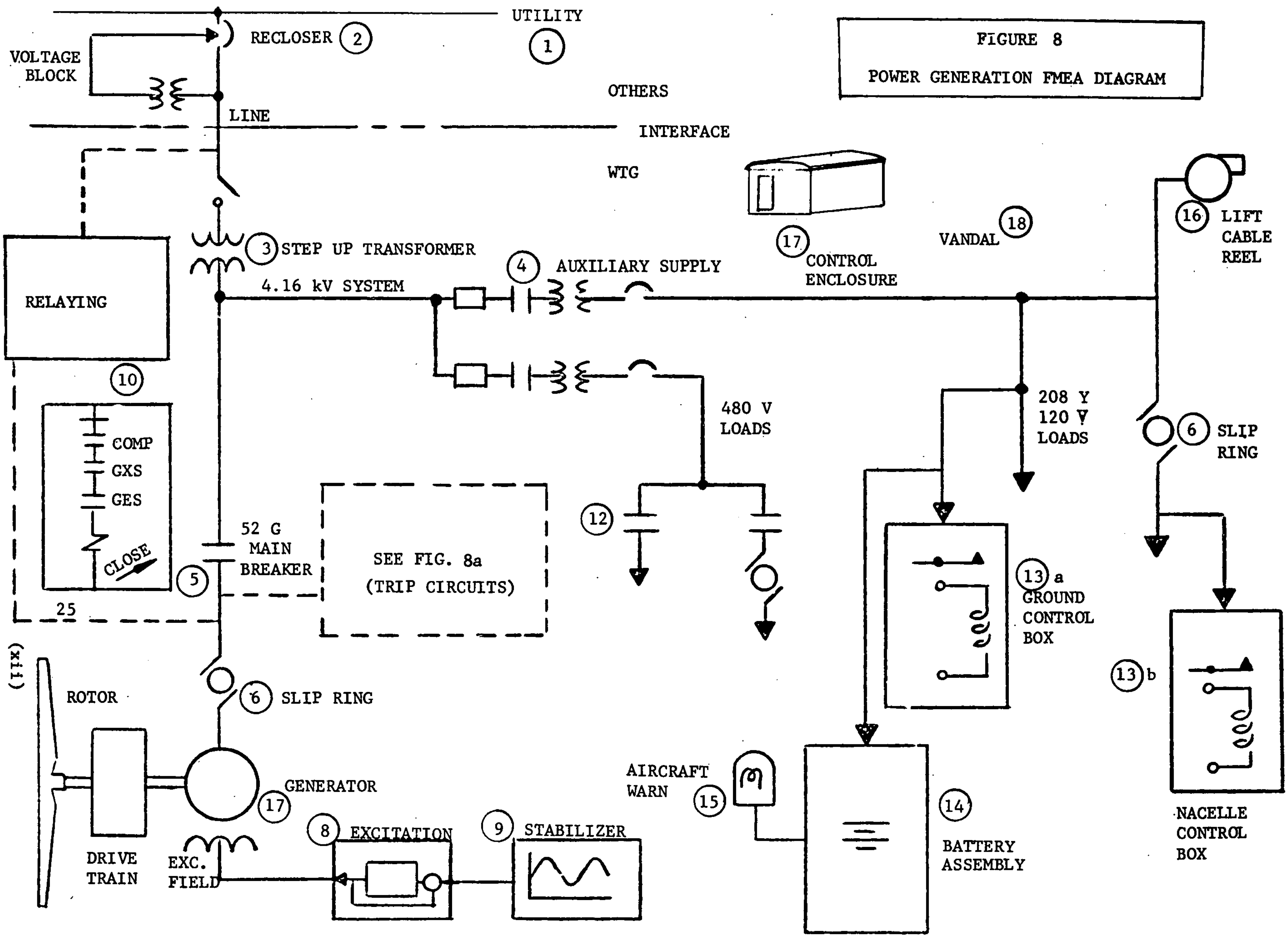
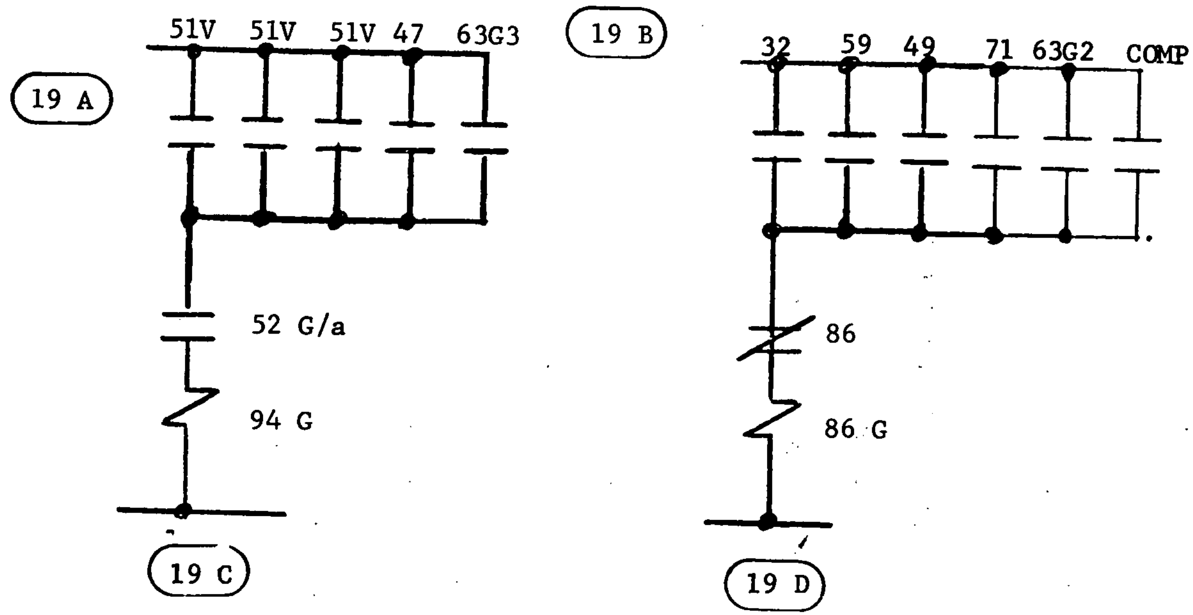


FIGURE 8

POWER GENERATION FMEA DIAGRAM



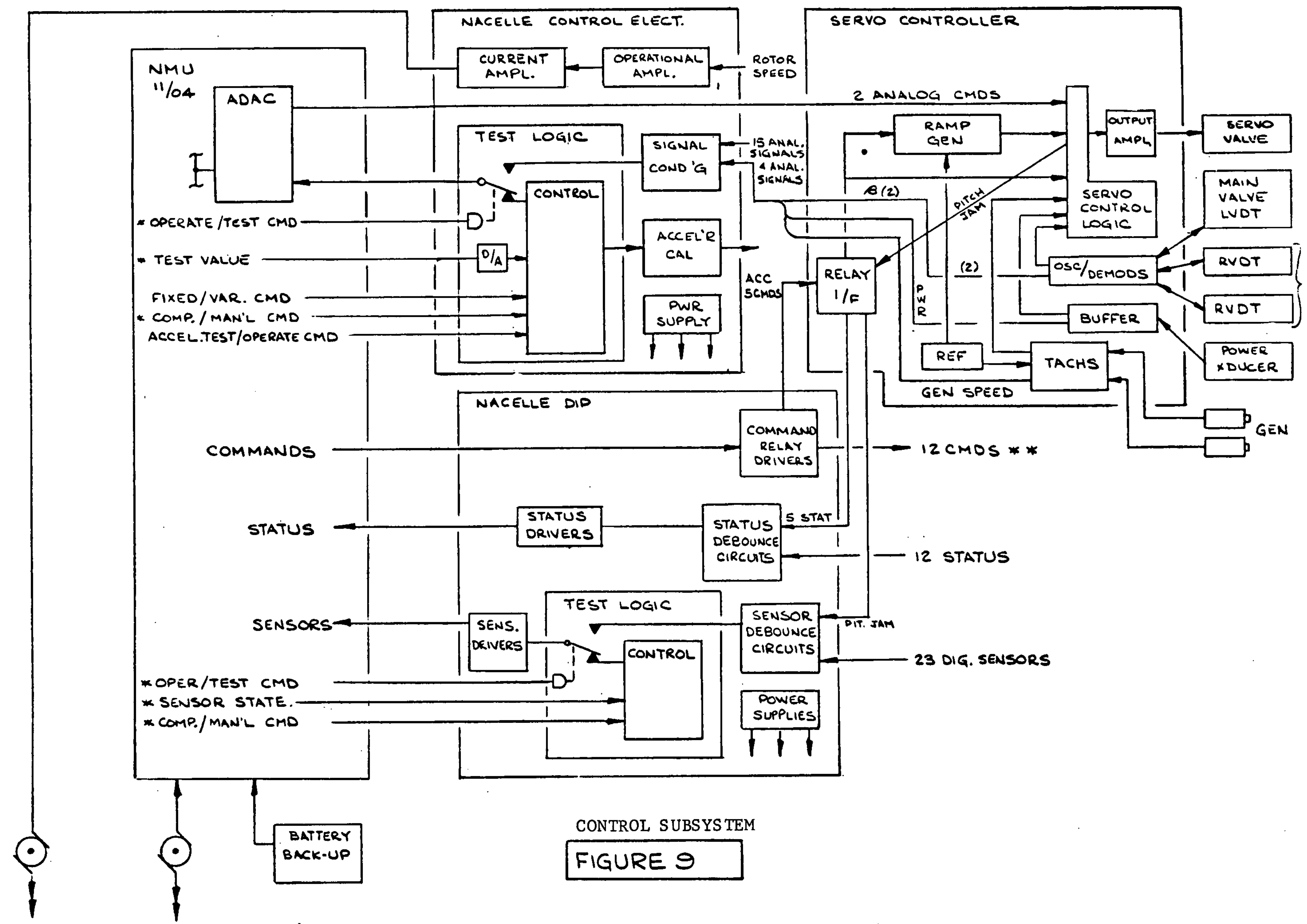
TRIP CIRCUITS

FIGURE 8a

POWER GENERATION FMEA

FMEA DIAGRAM/DRAWING CROSS REFERENCE

(1)	BLUE RIDGE ELECTRIC MEMBERSHIP CORPORATION	
(2)	TRANSFORMER ASM	273A6418
(3)	AUX SUPPLY	273A6509 (PART)
(4)	MAIN BREAKER	273A6509 (PART)
(5)	SLIP RING	273A6519
(6)	GENERATOR	273A6429
(7)	EXCITATION	273A6510 (REGUL. PART)
(8)	STABILIZER	265A7087
(9)	RELAYING	273A6510 (PART)
(10)	SYNC	273A6510 (PART)
(11)	MOTOR CONTROL	273A6431
(12)	GND. C.P.	848E893
(13a)	NAC. C.B.	132D6390
(13b)	BATTERY ASM	273A6432
(14)	WARN LAMP	273A6690
(15)	LIFT REEL	132D6046
(16)	CONTROL ENCLOSURE	273A6507
(17)	TRIP CIRCUIT RELAYS ONE-LINE DIAGRAM	298E475 REV. 3

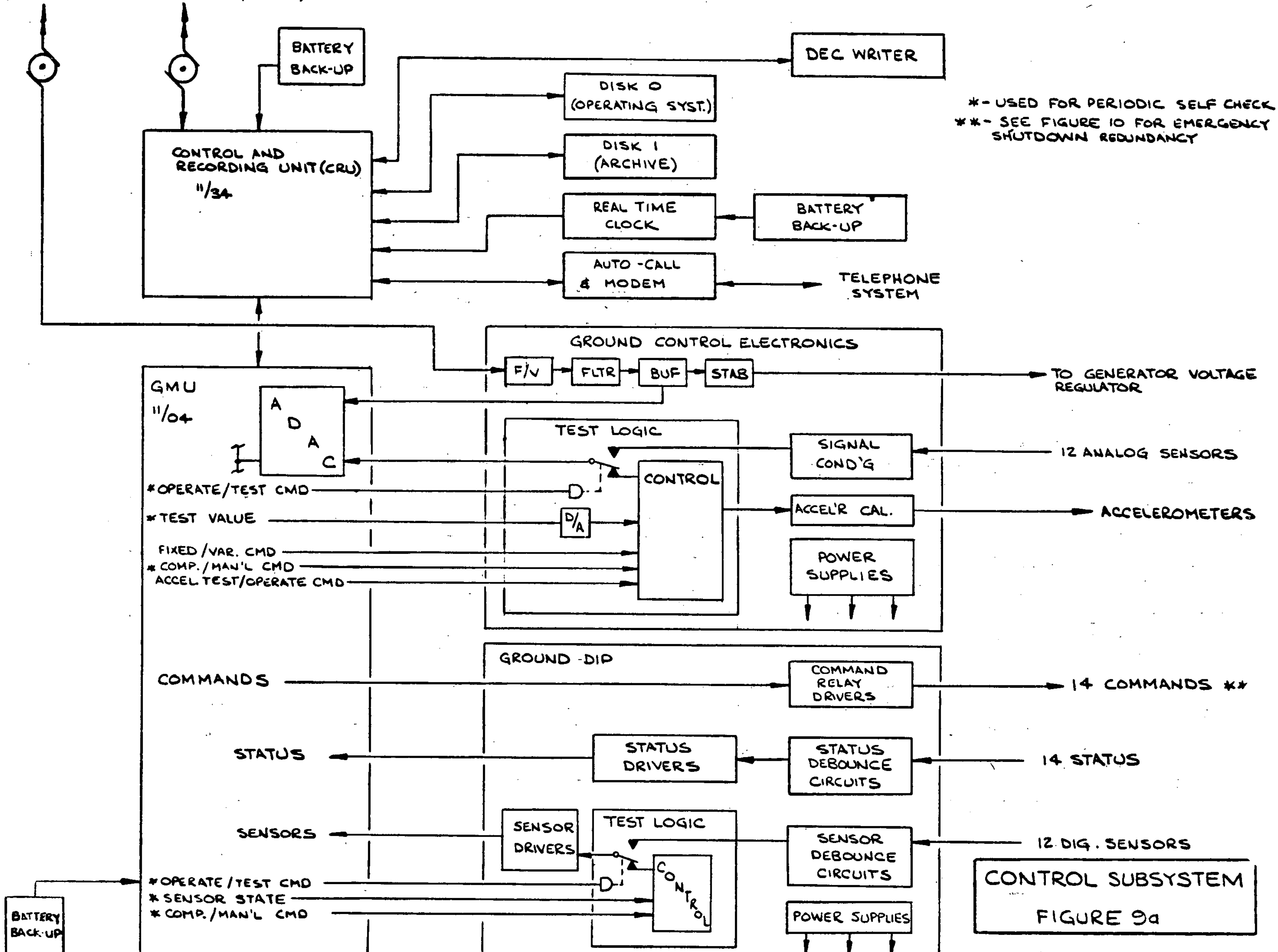


CONTROL SUBSYSTEM

FIGURE 9

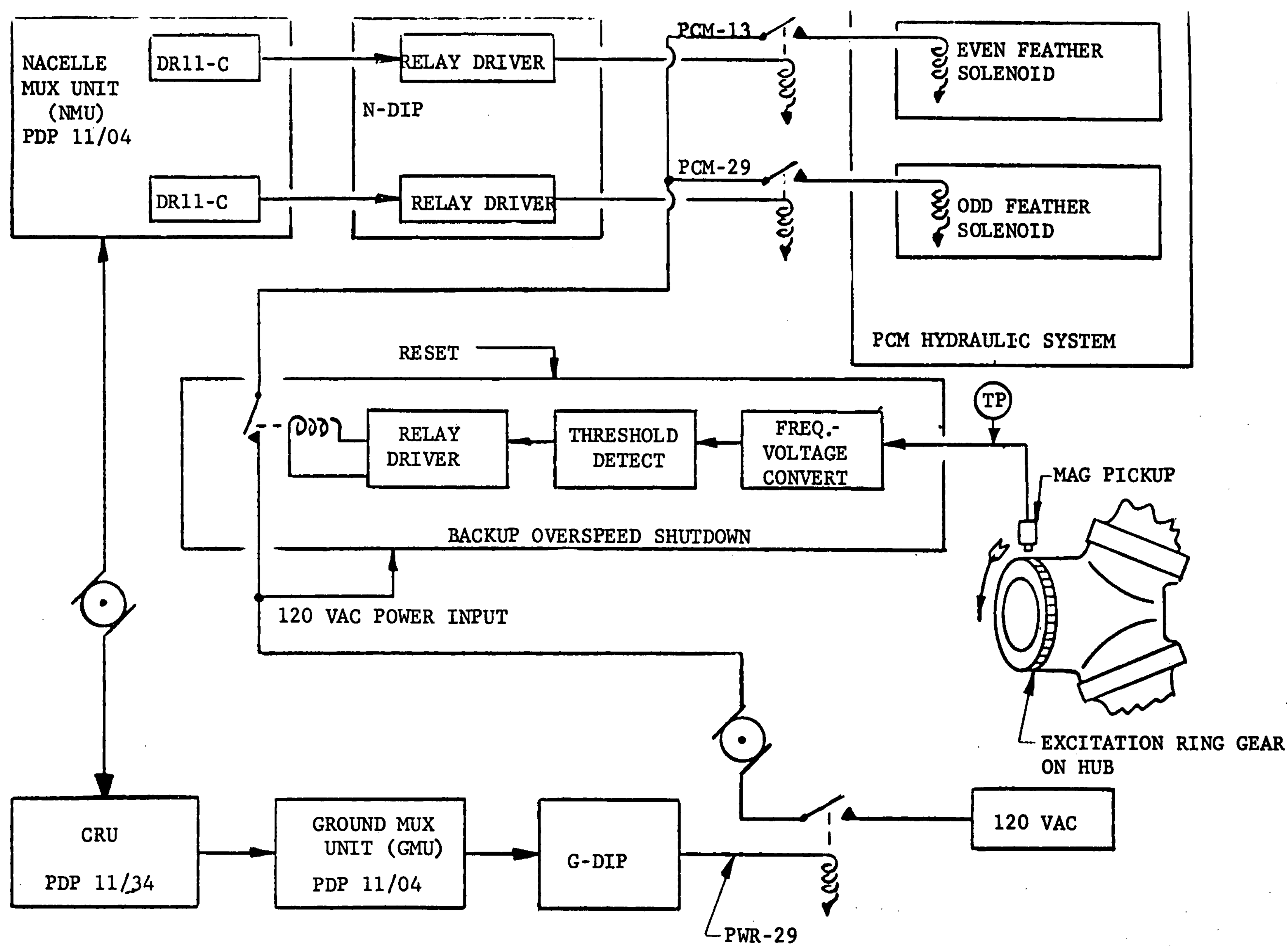
(FOR CONTINUATION SEE FIGURE 9a)

(FOR CONTINUATION SEE FIGURE 9)



CONTROL SUBSYSTEM
FIGURE 9a

FIGURE 10



EMERGENCY SHUTDOWN REDUNDANCY

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: ROTOR BLADE (1.0)
COMPONENT: BLADE DWG 276-10520
SUBASSEMBLY: ________

DATE: May 1978
PREPARED BY: F. Stearns

SEE FIGURE 2

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
SPAR DWG 276-10521 1	Carry Blade Aero-dynamic and dynamic loads	Crack in Spar	• Fatigue loads higher than anticipated • Undetected flaw which grew in fatigue stress environment • Spar struck or grazed by a hard foreign object (Bullet or rock)	Blade Separation	Excessively large rotor system unbalance and vibration High WTG vibration resulting in emergency shutdown	• Fatigue structural analysis performed. • Loads calculated with factors traceable to MOD-0 measured data. • Material certification provided by steel manufacturer. • Demonstrated QA capability of detecting flaws down to acceptable size. • Blades difficult to hit from a distance particularly when operating.	High stresses recorded by operating instrumentation. Excessive vibration sensed by rotor bearing accelerometer in hub. Emergency shutdown initiated automatically.	I	Analyses complete but documented results not available. It is recommended that inspection of the blades be performed at regular intervals.
SPAR RING DWG 276-10509 2	Retain Blade to Hub (via Hub/Ring attach. Bolts)	Crack in Ring Flange	• Fatigue loads higher than anticipated. • Undetected flaw which grew in fatigue stress environment	Blade Separation	Excessively large rotor system unbalance and vibration. High WTG vibration resulting in emergency shutdown.	• Fatigue structural analysis performed. • Loads calculated with factors traceable to MOD-0 measured data. • Material certification provided by steel manufacturer. Demonstrated QA capability of detecting flaws down to acceptable size.	High stresses recorded by operating instrumentation. Excessive vibration sensed by rotor bearing accelerometer in hub. Emergency shutdown initiated automatically.	I	

FMEA NOTES

1. These failures will be checked for during the periodic (6 month) maintenance activity to assure the protection or function is still working.

2. Software processing is used during appropriate WTG states to check for these latent failures.

SUBSYSTEM: ROTOR BLADE (1.0)
COMPONENT: BLADE DWG 276-10520
SUBASSEMBLY:

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: F. Stearns

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PRIMARY CONTROL SYSTEM (3)	Control Rotor System RPM	Primary control system failure resulting in an overspeed condition on the blades. Rotational velocity exceeds 48 RPM.	Excessive blade loads	Spar yielding/ failure in tension leading to deformed or separated blade.	Excessively large rotor system unbalance and vibration. High WTG vibration resulting in emergency shutdown.	Blade will yield decreasing effective cone angle. Requires multiple failures in control system sensing OR Failure of redundant hydraulic paths in the pitch control mechanism. (Ref. Hydraulic Sys. FMEA)	Excessive vibration sensed by rotor bearing accelerometer in hub. Emergency shutdown initiated automatically.	II	The spar will yield at approx. 48 RPM at the middle portion of the blade. Considering that the deformed blade will accumulate steady flap moment due to centrifugal force at a lower rate than undeformed, the blade failure RPM is $\geqq$ 60 RPM.
TRAILING EDGE TO SPAR TIE DWG 276-10524 (4)	Retain T.E. to Spar	Adhesive Bond Failure	Environment & premature fatigue failure of adhesive.	Blade unbalance	Excessive rotor sys. vibration resulting in emergency shutdown.	Belly Band will retain T.E. Section	Excessive vibration sensed by rotor bearing accelerometer in hub. Emergency shutdown initiated automatically.	II	Analyses complete but documented results not available It is recommended that inspection of the blades be performed at regular intervals.
TIP WEIGHT INSTALLATION DWG 276-10538 (5)	Balance Blades WRT each other. Control Frequency Placement	Separation of tip weight(s) from blade	Failure of tip wt. attach bolts	Blade unbalance	Excessive rotor sys. vibration resulting in emergency shutdown.	Cover over tip weight installation. Restrained with 55 bolts.	Excessive vibration sensed by rotor bearing accelerometer in hub. Emergency shutdown initiated automatically.	II	

SUBSYSTEM: ROTOR BLADE (1.0)
COMPONENT: BLADE DWG 276-10520
SUBASSEMBLY:

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: E. Stearns

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
SPAR PRESSURE RELIEF VALVES (6)	Control Spar Internal Pressure to ± 2 #/in^2	Valve stuck open	Foreign material on valve seat	Spar will no longer be sealed. As the spar internal press. tends to fluctuate due to external temp. and barometric pressure variations, the spar will ingest humid air, prematurely saturate the desiccant and will increase the possibility of internal spar corrosion.	NONE	Parallel redundant valves for both positive and negative pressure relief valves. Valves will actuate very infrequently -- approx. once per year. Spar internal surfaces are primed with MIL-P-23377	Visual inspection during regular maintenance period.	III	Valves will be inspected during normal maintenance periods.
		Valve stuck closed	Sticky fluid on seat, i.e., bugs or oily smoke which contaminated valve during time it was open.	Spar will remain sealed. Spar internal pressure might increase or decrease past design cracking pressure.	NONE				Failure of both positive pressure relief valves would not produce critical stresses in the spar unless the external temp. exceeded 241°F (not possible) Failure of both negative pressure relief valves would not produce critical stresses in the spar unless the external temp. greatly exceeded -58.5°F. (not likely in lower 48 states)

DATE: May 1978
PREPARED BY: R. Cockfield

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: YAW SUBSYSTEM (2.1)
COMPONENT: YAW STRUCTURE
SUBASSEMBLY: 47J240701

SEE FIGURE 3

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
UPPER YAW STRUCTURE (1)	Structural support and mounting for yaw drive	Fatigue cracks in weld (Web to flange joint)	Cyclic loads were underestimated Undetected flaw	Degraded stiffness (after extensive cracking) Distortion of yaw drive	Excessive vibration (after extensive cracking) Increased yaw drive power, reduced yaw bearing life	• Calculated range stress is below AISC limits • Weld has passed MT and UT inspection • Benefit of stress relief has not been accounted for • Yaw structure provides redundant load paths	Vibration sensors (after extensive cracking)	III	Inspection and repair of large cracks during periodic maintenance
LOWER YAW STRUCTURE (2)	Structural support and disk for yaw brake	Fatigue cracks in weld (Web to flange joint)	Cyclic load were under estimated	Degraded stiffness (after extensive cracking)	Excessive vibration (after extensive cracking)	• Calculated range stress is below AISC limits • Weld has passed MT and UT inspection • Benefit of stress relief has not been accounted for • Yaw structure provides redundant load paths	Vibration sensors (after extensive cracking)	III	Inspection and repair of large cracks during periodic maintenance.

DATE: May 1978
PREPARED BY: S. Onufreiczuk

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: YAW SUBSYSTEM (2.1)
COMPONENT: YAW DRIVE
SUBASSEMBLY: 47J240701

SEE FIGURE 3

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
YAW BEARING (3)	Enables the nacelle to rotate on the tower	Increased bearing friction	(a) cracked roller (b) galled surface (c) lack of lubrication	Increased power consumption	Sluggish yaw movement of nacelle	Bearing was designed using the latest analytical methods, and built and tested to stringent design specifications	Yaw error signal	III	Multiple roller failures are required before a significant loss of yaw torque to nacelle
YAW DRIVE MOTOR 2.1.2 (4)	To provide torque to impact yaw rotation to nacelle	No torque Insufficient torque	Internal leakage or valve failure	No yaw rotation Torque impacted to bull gear	Parallel motor will provide sufficient torque to yaw nacelle.	This motor has an extensive history and was selected based on the high performance capability. Motor tested and inspected.	Yaw position sensor	II	Two motors used in parallel. Limited level of redundance is available.
PINION 2.1.2 (5)	To transmit torque from motor to bull gear on yaw bearing. One pinion each per yaw drive motor.	(a) fails to move	Blockage or foreign object between gear teeth	No yaw rotation torque transmitted	No yaw rotation of nacelle - shutdown	Pinion was stress analyzed and produced to exacting fabricating process.	Yaw position sensor	II	" "
		(b) rotates without transmitting motion to bull gear	• Stripped teeth • Sheared shaft or cracked pinion housing and bearing	Reduced yaw capability if only one pinion failed. No yaw capability if both pinions failed	No yaw rotation of nacelle - shutdown				
GEAR COUPLING (6)	To connect the yaw drive pinion to the respective hydraulic yaw drive motor.	Stripped gear teeth	Overload Severe misalignment	Yaw maneuver can not be performed	Lack of yawing capability will cause shutdown	Coupling was extensively stress analyzed and proven to have adequate design margin.	Yaw position transducer	III	
		Sheared flange bolt	Overload	NONE	NONE	All bolts are torqued to prescribed levels using torque wrench.			Require multiple bolt failures before loss of yaw maneuver.
UPPER AND LOWER PINION BEARINGS (7)	To locate and facilitate rotation of pinion	Increased friction	Pitted or fractured rollers	Increased yaw motor torque, potential pinion-bullgear tooth misalignment	Progressive damage can lead to eventual shutdown	Bearings were selected for the radial and thrust forces expected with adequate design margins. Periodic maintenance will cause adequate lubrication in bearings.	NONE	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: Yaw SECTION (2.1)
COMPONENT: YAW DRIVE
SUBASSEMBLY:

SEE FIGURES 3 & 4

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
Yaw Brake Calipers and Disc (8)	To hold nacelle position and to provide drag forces during yawing	a. Drag Force high (yaw maneuver)	Puck/disc interface rough due to sand or other environment	Sluggish yaw movement	Sluggish yaw movement	Change in rates observed by existing yaw position instrumentation - clean up disc & pucks	Yaw Position Potentiometer	III	Yaw Drive Motor has sufficient torque to override increased drag
		b. Drag Force low (Yaw Maneuver)	Ice on Disc	Reduced Breaking Torque	Nacelle yaw excitation - increased moments and structural loads	Short Duration - Ice melts immediately under pressure between puck and disc.	Accelerometer and Strain Gauges		
Yaw Brake Release Valve 35 A (9) (see Figure 4)	Apply and release hydraulic pressure to yaw holding brake	a. Stuck in "POWER ON" position	Broken Return Spring	Holding Brakes remain "OFF"	Reduced Brake Holding Torque	Yaw Drive Motors provide Holding Torque	Yaw Drive Pressure Transducers	III	
		b. Stuck in "POWER OFF" position	Solenoid Circuit Open	Holding Brakes remain "ON"	No Yaw Maneuver Shutdown	None	Brake Status Pressure Switch	III	
		c. Internal leakage	Worn Seal	None	None	None		III	
Brake System charging valve 21 A (10)	To charge the brake accumulators on demand	a. Valve Open	Broken Return Spring	None	None	None			
		b. Valve Closed	Solenoid Circuit Open	Accumulators Fail to Charge	Lack of Braking Pressure Initiates Shutdown	Valve has extensive operating history Tested prior to installation	L.P. Alarm Switches	III	
Yaw Brake Accumulator (11)	To store hydraulic oil for yaw brakes	a. Lack of Pressure	• Aging of Bladder	Loss of all brake pressure	Shutdown		LP Alarm Switch	III	
		b. Leak in Bladder	• Pinching						
		c. External Leak	• Rupture • Crack						
High-Speed Shaft Brake (12)	To provide stopping and holding torque to hub during shutdown operation	a. Low brake torque	Environmental effect-ice, water on disc	None	None	Short duration-water ice quickly wiped off			
		c. Higher brake torque	Grit, sand on disc	Larger than normal torque on hub and drive train	Increased loads on blade	Very unlikely - puck drags on disc continuously keeping disc clean	Tachometer	III	
H. S. Shaft Brake Control Valve (13)	To control brake application and release	a. Valve failed in "ON" mode	Return spring broken	Brakes locked	• System will not start up • If running system shutdown occurs	Examine valve and fix as required	Pressure Switch at brake	III	
		b. Valve failed in "OFF" mode	Solenoid coil circuit open	No braking or holding torque	Cannot use brake to stop blade rotation during shutdown	Use feather system to stop	Pressure switch at brake		

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: YAW SECTION (2.1)
COMPONENT: YAW HYDRAULICS 2.1.3
SUBASSEMBLY:

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 4

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
H.S. SHAFT BRAKE ACCUMULATOR (14)	To store hydraulic oil for h.s. shaft brake	(a) lack of pressure	Leak in compressed air side	Hydraulic supply motor	Power consumption increases	This unit is a passive device with few failure prone elements. Testing prior to installation will ensure high quality component.		III	
		(b) requires frequent re-charging - gets progressively worse	Leak in bladder	Duty cycle increase					
		(c) external leak	• Rupture • Crack	Loss of brake pressure	Shutdown		LP Alarm switch	III	
H.S. SHAFT BRAKE PRESSURE REGULATOR (15)	To regulate inlet pressure to accumulator	(a) Fails closed	Contamination Broken feed-back spring	Cannot recharge accumulater	Eventual shutdown	Component selected has extensive operating history. Will be tested prior to installation.	LP Alarm switch	III	
		(b) Fails open	Broken spring	Accumulator will be charged to pump capability	NONE	Yaw brake recharge cycle will recharge h.s. shaft brake accumulator		III	
MOTOR CONTROL VALVE (16)	To connect the yaw motors to, or isolate from, the yaw hydraulic supply	(a) Failed closed	Electrical lead broken Contamination on spool	No hydraulic fluid admitted to motors	Non yaw rotation possible WTG shuts down	Valve selected has an extensive operating history and will be tested prior to installation.	Yaw position potentiometer	III	
		(b) Failed open	Broken return spring Contamination on spool	Motor always connected to power supply	Will attempt to yaw when broken accumulators are recharging.	Since all six yaw brakes are engaged, no unscheduled yaw motion will result.		III	
HYDRAULIC SUPPLY (17)	To provide hydraulic fluid under pressure to the yaw motors and the brake accumulators on demand.	Lack of pressure	(a) Failed electrical motor (b) sheared coupling (c) damaged charge pump (d) failed cross-over relief valve (e) loss of hydraulic fluid	Accumulators not re-charged. Yaw drive motors inoperative	Yaw Drive disabled WTG shutdown required.	Sundstrand pump has a long history of reliable service. Extensive testing prior to installation.	Pump failed alarm Low oil level switch	III	
		Pump fails to shut off	Control signal problem	Temperature of hydraulic fluid will increase	Shut down WTG		High oil temp. switch.		

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: DRIVE TRAIN (2.2)
COMPONENT: DWG 298E464
SUBASSEMBLY:

DATE: May 1978
PREPARED BY: R. Cockfield

SEE FIGURE 5

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
DRIVE SHAFT (1)	Transmit Torque at 34.7 RPM	Fracture	(a) Fatigue loads underestimated (b) Operation of WTG at Off design conditions (c) Material properties below specs	Rotor overspeed initiates emergency shutdown High speed brace does not stop rotor at 3-9	Shut down but with rotor not at 3-9 Excessive vibration	(a) Conservative factors applied to fatigue analysis, infinite life calculated (b) Slip clutch provides over torque protection. Stresses low at operating torque. Normal shutdown above 35 MPH (c) Material certs available. No failure, even with improper heat treatment	LS speed sensor OR Bearing Vibration Sensor	II	
LS COUPLINGS (2)	Transmit torque at 34.7 RPM Permit angular misalignment	Slip at tapered fit with shaft	(a) Improper installation (b) Load in excess of design load	Fracture of shaft if occurring frequently.	Excessive vibration if shaft fractures.	(a) Fit verified by dimensional check. (b) Slip clutch		III	
		Bolt Failure	(a) Overtorquing (b) Load in excess of design load (c) Wrong bolt or material (d) Stress corrosion, hydrogen embrittlement of cadmium plating	None, due to number of bolts	None	(a) Calibrated torque wrench used. Torque below yield strength. (b) Design stresses conservat (c) Standard bolt with identification on head (d) Stresses low, embrittlement reduced by proper plating techniques		III	
		Internal Gear Failure	(a) Fatigue loads underestimated (b) Load in excess of design load	Same as shaft failure, above	Same as shaft failure, above	(a) Conservative calculation of fatigue life (b) Slip clutch protects against overload	LS speed sensor OR Bearing Vibration Sensor	II	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: DRIVE TRAIN (2.2)
COMPONENT: DWG 298E464
SUBASSEMBLY:

DATE: May 1978
PREPARED BY: R. Cockfield

SEE FIGURE 5

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
GEARBOX (3)	Transmit torque with speed increase from 34.7 RPM to 1800 RPM	Internal Gear Tooth Failure	(a) Fatigue loads underestimated (b) Load in excess of design load (c) Improper material or hardening (d) Loss of lubricating oil	Increased noise level, vibration	None, initially. Gearbox life may be reduced.	(a) Multiple teeth, failure of several adjacent teeth required before performance lost. Split load path of gear train provides redundancy. Spalling of gear surface would be seen long before fracture. Conservative fatigue analysis. (b) Conservative strength analysis. Slip clutch provides overload protection (c) Material certs & process records available (d) Emergency shutdown initiated with rise in oil temp. or drop in level	Vibration sensor (d) Oil Level Sensor Oil Temp Sensor	III	Periodic maintenance will include tooth inspection on critical gear. Failure initiates as surface pitting. See Note 1
		Bearing Failure	(a) Fatigue loads underestimated (b) Loads in excess of design loads (c) Loss of lubricating oil	Increased noise & vibration	None, initially gearbox life may be reduced Excessive vibration will initiate shutdown	(a) Conservative life estimates (b) Slip clutch (c) Emergency shutdown	Vibration Sensor Bearing Temp Sensor OR Oil Level Sensor	III	Bearing failure initially as surface pitting. See Note 1

FMEA NOTES

1. These failures will be checked for during the periodic (6 month) maintenance activity to assure the protection or function is still working.
2. Software processing is used during appropriate WTG states to check for these latent failures.

SUBSYSTEM: DRIVE TRAIN (2.2)
COMPONENT: DWG 298E464
SUBASSEMBLY:

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: R. Cockfield

SEE FIGURE 5

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
LUBRICATION SYSTEM (2.2.1)	Lubricate Gearbox and rotor bearing	Loss of oil	(a) Pump failure (b) Leakage (c) Blocked Orifice (d) Clogged Filter	Reduced bearing & Gear life	Shutdown	(a) Emergency shutdown initiated by lack of flow (b) Emergency shutdown initiated by drop in oil level	Oil Flow Switch	III	Oil filter cleaned during periodic maintenance
		Oil Overheating	(a) Diverting valve failure (b) Leakage (c) Ambient Temperature above design conditions (d) Excessive Friction Losses	Reduced Bearing life Breakdown of oil	Shutdown	Emergency shutdown initiated by overtemp condition	Oil temp Sensor	III	Oil sample tested during periodic maintenance
		Oil under temperature	(a) Diverting valve failure (b) Heater failure (c) Ambient temperature below design conditions (d) Nacelle vent fan fails on	Excessive pumping power Reduced bearing life	Failure to start if not operating	Emergency shut down initiated by under temp. condition, or low flow to rotor bearing	Oil Temp Sensor Air temp Sensor Oil flow switch	III	
HS BRAKE (4)	Hold rotor when parked Place blades in 3-9 position	Fails "ON"	(a) Controls error (b) Stuck puck	Excessive puck wear, overheating of disk	(a) shutdown	(a) Data link anomoly causes shutdown (b) Pressure bleed on caliper releases brake	(a) Controls self-check (b) Rotor position sensor	III	
		Fails "OFF"	(a) Controls error (b) Caliper friction (c) Hydraulic leak (d) Worn pads		Blade not parked in 3-9 position, may rotate when not operating				

DATE: May 1978
PREPARED BY: R. Cockfield

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: DRIVE TRAIN (2.2)
COMPONENT: DWG 298E464
SUBASSEMBLY:

SEE FIGURE 5

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
SLIP CLUTCH (5)	To protect drive train from torque overload	Fails to slip	(a) Improper adjustment (b) Mechanical jam or bearing seizure	Shaft or coupling failure if overload occurs	Shutdown if overspeed occurs as a result of shaft or coupling failure	(a) Torque limited by springs with limited range. Visual indication of proper adjustment checked statically. (b) Anti-friction bearing, grease packed	Speed sensor	III	Torque setting verified during periodic maintenance.
		Slips as too low a torque	(a) Improper adjustment (b) Cyclic loading underestimated (c) Degradation of facing material	Excessive clutch plate wear Overheating Overspeed if very low torque	None Shutdown if overspeed occurs	(a) Same as above (b) Clutch life conservatively designed Plates are replaceable	Speed sensor	III	Clutch wear measured during periodic maintenance. Torque setting verified. Plates easily replaced.
HS SHAFT ASSY (6)	Transmit torque at 1800 RPM & permit angular misalignment	Fracture of shaft	(a) Fatigue loading underestimated (b) Load in excess of design loads (c) Improper material or heat treatment	Rotor overspeed Local damage if shaft shaft parts are thrown	Shutdown	(a) Conservative fatigue analysis, infinite life calculated (b) Slip clutch Stresses low at operating torque Normal shutdown above 35 MPH (c) Material certs available	Speed sensor	II	No critical systems in path of fractured shaft (i.e., hydraulic lines)

SUBSYSTEM: ROTOR HUB (2.2.2)
COMPONENT:
SUBASSEMBLY: 848E885G1

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: F. Mamrol

SEE FIGURE 6

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
BLADE RETENTION BOLTS 197B2589P2 BEARING RETENTION STUDS 197B2590P1 (1)	Hold Blade to Bearing and Bearing to Hub	Bolt failure	Excessive preload Loads in excess of design loads. Stress corrosion	NONE	NONE	Hydraulic tensioning device cannot yield bolt at max. capacity • Preload is below stress corrosion threshold • Face and threads sealed to corrosive environment.	Periodic inspection for loose or missing bolts.	III	Bolts are fatigue rated. Rolled threads and head fillet. At least half the bolts can be missing before ultimate strength of remaining bolts is reached. Several bolts can be missing before fatigue endurance limit is reached on remaining.
BLADE RETENTION BEARING 164D6401P1 (2)	Allow pitch change of blade.	Breakup of rollers and raceway surfaces.	Loads in excess of design loads	Roughness in pitch change mechanism operation	NONE	• Periodic inspection • Bearings do not usually fail catastrophically. • Calculated B_{10} lite is adequate. • Calculated Margin of Safety non Brinell is adequate		II	See Note 1
		Structural failure of inner race shoulder	Loads greatly in excess of design loads	Decreased root restraint of blade	Shutdown	Shoulder on hub and pitch mount captivate inner race.	Rotor brg. accelerometer	II	
HUB ASSEMBLY 848E946 (3)	Transmit torque from blades	Structural failure	Loads in excess of design loads	One or both blades separate. Extreme vibration.	Shutdown	Finite Element Analysis shows positive margins*. Flaw size limited by NDT.	Rotor brg. accelerometer.	I	
		Bolt failure	Excessive preload Loads in excess of design loads Stress corrosion	NONE	NONE	Hydraulic tensioning device cannot yield bolt at max. capacity • Preload is below stress corrosion threshold • Face and threads sealed to corrosive environment	Periodic inspection for loose or missing bolts.	III	Bolts are fatigue rated. Rolled threads and head fillet. At least one bolt can be missing before ultimate strength or fatigue endurance limit is reached on remaining.

* Minimum Margin of Safety (M.S.) = 0.29 on tensile yield strength for Emergency Feather condition, worst case, 2 places.

SUBSYSTEM: ROTOR HUB (2.2.2)
COMPONENT:
SUBASSEMBLY: 848E885G1

DATE: May 1978
PREPARED BY: F. Mamrol

SEE FIGURE 6

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
MAIN ROTOR BEARING 132D6044P1 (4)	Support rotor	Breakup of rollers and raceway surfaces	Loads in excess of design loads	Vibration	Excessive vibration will initiate emergency shutdown	• Periodic inspection • Bearings do not usually fail catastrophically • Calculated B_{10} life adequate • Calculated Margin of safety non Brinell is adequate	Magnetic Plug in Lube line	II	See Note 1
OIL SEALS 197B2586P1 P2 (5)	Retain oil in main bearing housing; exclude foreign matter	Cut or wear in lip	Installation damage Wear	Depletion of transmission oil	Shutdown	• Usually evident at checkout • Periodic inspection Initial leakage rate is low	Low oil switch	III	See Note 1
TORQUE PLATE 848E937G1 (6)	Clamp main bearing	Structural failure	Loads in excess of design loads	Decreased hub restraint	Shutdown	Calculated margin of safety = large	Rotor Accelerometer	II	
	Transmit torque to rotor shaft	Loss of bolt torque							
		Bolt failure	Excessive preload	NONE	NONE	Hydraulic tensioning device cannot yield bolt at max. capacity	Periodic inspection for loose or missing bolts	III	
			Loads in excess of design loads						
			Stress corrosion			• Preload is below stress corrosion threshold • Face and threads sealed to corrosive environment • Margin of safety (torque) = .46 Several bolts can be loose or failed			

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: PITCH CHANGE MECHANISM (2.2.3)
COMPONENT: Pitch Rod Assy 132D6422G1
SUBASSEMBLY: Link Assy 132D6423G1

SEE FIGURE 6

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
ROD END BEARING 132D6418P1 (7)	Transmit Axial Load allowing rotation	Liner Wear	Loads in excess of design loads Contamination	Shock & vibration in PCM linkage	NONE	Low bearing pressure increases useful life Environment moderated inside hub & nacelle	Periodic inspection	III	NOTE 1
		Structural failure of eye or shank	Loads in excess of design loads	Uncontrolled pitch of blade - unbalanced forces - vibration	Shutdown	Low stress level Margin of Safety (Fatigue) = .80 Margin of Safety (limit) = .68	Rotor brg. Accel.	II	NOTE A
ROD 132D6397P1 (8)	Transmit axial load	Structural failure	Excessive induced load	Uncontrolled pitch of blade - unbalanced forces - vibration	Shutdown	Low stress level Margin of Safety (Fatigue) = large Margin of Safety (limit) = large	Rotor brg Accel.	II	NOTE A
ADJUSTING NUT 132D6420P1	Blade pitch change (maintenance)	Change adjustment	Loosening of locking studs	Differential blade pitch variation	Shutdown (if severe)	Differential threads of same hand cannot turn enough to come out of engagement	Periodic inspection	III	NOTE 1
STUD 197B2576P1	Preload & lock adjusting nut	Loose preload	Vibration	NONE	NONE	• Locking tab washer • Studs engage in holes in adjacent part	Periodic inspection	III	NOTE 1
ROD END BEARING 132D6419P1	Transmit axial load allowing rotation	Liner Wear	Loads in excess of design loads Contamination	Shock & vibration in PCM linkage		Low bearing pressure increases useful life Environment moderated inside hub & nacelle	Periodic inspection	III	NOTE 1
		Structural failure of eye or shank	Loads in excess of design loads	Differential blade pitch vibration	Shutdown (if severe)	• Actuator sleeve contained by shaft • Link limited by clevis-see "support beam"	Rotor brg Accel. Pitch change brg accel.	II	NOTE A, B

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SEE FIGURE 6

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
LINK 132D6348P1	Support & guide actuator sleeve	Structural failure	Loads in excess of design loads	Differential blade pitch vibration	Shutdown (if severe)	• Actuator sleeve contained by shaft • Link limited by clevis-see "support beam"	Rotor brg accel. Pitch change brg. accel.	II	NOTE A,B
JAM NUT 197B2578P1	Preload Threads	Lose Preload	Vibration	Fretting	NONE	Bolts safety wired	Periodic inspection	III	NOTE 1 -
SUPPORT BEAM 848E889 (9)	Support aft end of PCM	Structural failure	Loads in excess of design loads	Actuator sleeve has lateral freedom Small differential pitch between blades may produce sensible vibration Unrestrained parts will impact at least lower actuators, which may inhibit complete feathering.	Shutdown	Low stress level Margin of safety (fatigue) = 1.0 Margin of safety (limit) = .16 Displacement of actuator sleeve is limited by shaft or by pitch rods in torque plate holes.	Rotor Accelerometer	II	NOTE A,B
ACTUATOR SLEEVE 848E933 (10)	Transmit actuator force to pitch rods	Structural failure of link lugs	Loads in excess of design loads	Same as for support beam	Shutdown	Low stress level MS (fatigue) = MS (limit) = Displacement of actuator sleeve is limited by shaft or by pitch rods in torque plate	Rotor Accelerometer	II	Note A,B
		Structural failure of pitch rod clevis	Loads in excess of design loads	One blade pitch uncontrolled - differential pitch-vibration	Shutdown	Low stress level MS (fatigue) = large MS (limit) = .12	Rotor Accelerometer	II	Note A
		Structural failure of sleeve	Loads in excess of design loads	Pitch of both blades uncontrolled	Rotor overspeed without shutdown	Low stress level MS (fatigue) = .60 MS (limit) = .28		I	Note A

DATE: May 1978
PREPARED BY: F. Mamrol

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: PITCH CHANGE MECHANISM (2.2.3)
COMPONENT:
SUBASSEMBLY:

SEE FIGURE 6

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PITCH CHANGE BEARING 132D6045 (11)	Transmit actuator force to pitch rods	Breakup of rollers and raceway surface	Loads in excess of design loads	Roughness in pitch change mechanism	NONE	• Periodic inspection • Bearings do not usually fail catastrophically		II	See Note 1
THRUST RING 848E934G1 (12)	Transmit actuator force to pitch change bearing	Structural failure of forward link lugs	Loads in excess of design loads	Same as support beam	Shutdown	Low stress level MS (fatigue) = large MS (limit) = large	Rotor Accelerometer	II	NOTE A
		Structural failure of actuator lugs	Loads in excess of design loads	Upper actuators may fall into rotating PCM. Lower actuators will fall clear	Shutdown	Low stress level MS (fatigue) = large MS (limit) = large Redundant actuators (2 pair) MS is still large with one pair of actuators	Rotor Accelerometer	II	

NOTES

A. SINGLE POINT CRITICAL FAILURE ELEMENTS ARE SUBJECT TO NON-DESTRUCTIVE TESTING (MAG. PARTICLE, RADIOGRAPHIC, ULTRASONIC). ACCEPTANCE CRITERIA BASED ON MINIMUM SIZE DEFECT THAT WILL PROPAGATE CRACK.

B. FAILURE OF THIS ITEM MAY NOT CAUSE EFFECTS THAT WILL HAVE IMMEDIATE RESULTS ON NEXT HIGHER ASSEMBLY, NOR IS THE RATE OF DAMAGE THAT MAY RESULT ASSESSABLE. THE RATE MAY BE GREATER THAN WHAT CAN BE SAFELY DETECTED AT PERIODIC INSPECTION.

C. MARGIN OF SAFETY (M.S.) = $\left[\frac{\text{ALLOWABLE STRESS}}{\text{CALCULATED STRESS}} - 1\right]$. ALLOWABLE STRESS IS 60% OF MINIMUM YIELD STRENGTH (42 KSI MEASURED) PER AISC UNLESS OTHERWISE NOTED. WHEN INDICATED M.S. = LARGE, M.S. IS GREATER THAN 1.0.

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
ACCUMULATOR CHARGING PUMP (1)	To change the main and emergency feather accumulator	Lack of flow or pressure	(a) Electric motor failed (b) Shaft/coupling sheared (c) Contamination binding gears	Reduced slewing flow rate UNTIL main accumulator discharged	Blade pitching rate limited to 1½ deg/sec until SHUTDOWN occurs when accumulators are discharged	Pump is tested prior to installation. Extensive operating history exists for this pump.	Main accumulator low pressure alarm switch	III	
CHARGE PUMP UNLOADING VALVE (2)	To direct charging flow to accumulators on demand, or to return to reservoir as required.	(a) Failed in "ON" position	Return spring broken or contaminated on spool	Pump relief valve will open	NONE	Valve tested prior to assembly. Has extensive operating history.	Oil temp. sensor	III	Hydraulic fluid temp will rise
		(b) Failed in "OFF" position	Solenoid circuit open, or contaminant on spool	Main accumulator will be discharged	• Shutdown • Blade pitching rate limited to 1½ deg/sec		Blade Pitch Potentiometer L.P. alarm switch	III	
SLEW PUMP (3)	To provide the hydraulic power supply for blade pitch control	Lack of flow/pressure	Electrical motor failed. Shafts/coupling sheared Pressure compensation in pump leaks or has broken feedback spring	Slewing system is disabled	• Blade pitch control disabled • Shutdown	Pump tested prior to installation. Has extensive operating history behind it.	Blade angle Potentiometer Pump alarm switch	III	
		Excessive pressure	Jammed spool valve in pressure compensation	High power consumption by motor -- overhead possible RELIEF VALVE OPENS	Blade pitch control impaired		Oil temp. sensor	III	Relief valve in circuit

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
UNLOADING VALVE CONTROL SWITCH (4)	To cycle unloading valve on-off to maintain accumulator pressure above 2500 psig	(a) Stuck in open position	Broken spring, contaminant on contacts	Main Accumulator depleted	Blade pitch rate limited to 1½ deg/sec. System shuts down.	Proven device -- extensively tested	Blade Pitch Potentiometer	III	
		(b) Stuck in closed position	Welded contacts, leaky diaphragm	Relief valve will open as pressure builds up	NONE	Switch tested prior to installation	Oil temp. switch	III	Hydraulic fluid temp. will rise
EMERGENCY FEATHER ACCUMULATOR (5)	To store sufficient hydraulic fluid at 3000 psi to permit full stroking of actuators in the event the pumps are deactivated.	(a) Leakage of air valve	Contaminant on seat	Loss of feathering pressure	NONE -- the redundant set can provide feathering flow	Failure can be detected before it becomes catastrophic. Feather accumulators are arranged in two mutually redundant pairs. Each pair alone can accomplish feathering maneuver.	L.P. alarm switch	III	During periodic maintenance, accumulators should be discharged (hydraulic oil only) and the residual gas pressure checked. Pressure should not fall below 1000 psi.
		(b) Piston seal leakage	Contaminant under piston seal. Scratched piston seal	Air entering hydraulic fluid	Reduction of system stiffness.				
PCM HYDRAULIC FLUID HEATER (6)	To heat the hydraulic fluid when its temperature drops below 20°F. Keeps viscosity in the desired range.	Open circuit	Burned out heating element	PCM slew pump and charge pump will not start up if ambient temp. is below 0°F.	System can not start up below 0°F.	Heaters will be tested thoroughly to assure high reliability	Low temp. switch	III	
MAIN ACCUMULATOR FLOW PRESSURE REGULATOR (1200 PSI) (7)	To limit the slew control pressure to 1200 psi	(a) Stuck open	(a) Contaminant in spool	(a) Slightly higher slew rates	NONE	Regulator tested prior to installation	Blade pitch Potentiometer	III	
		(b) Stuck closed	(b) Broken feedback spring	(b) Slewing flow rate limited to slew pump flow	Blade pitching rate limited to 1½ deg/sec.		Blade pitch Potentiometer	III	
		(c) Body leakage	(c) Damaged body seal	(c) Progressive depletion of stored fluid	Eventual shutdown		Low level switch in oil tank	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PCM SERVO VALVE (3)	To meter the hydraulic fluid to the actuators in response to a command signal	(a) Fails to respond to signal (b) Slews to one side	Open command signal circuit Contamination in flapper valve	Unscheduled movement of actuators	Undesired blade pitch angle causes SHUTDOWN	Servo valves are a high reliability item. High degree of filtration provided to assure reliable operation.	Blade pitch angle potentiometer	III	
PCM MAIN ACCUMULATORS (9)	To store sufficient hydraulic fluid to assist the slew pump during gust conditions	Loss of pressure on compressed air side	(a) leaky fill valve (b) leaky body seal (c) leaky piston seal	Slew rate limited/ max. pumping rate = 30 gpm	NONE	Accumulators tested prior to installation	Blade pitch angle potentiometer	III	
FEATHERING FLOW CONTROL VALVE (10)	To schedule flow into actuators during feathering	Flow does not vary	Blocked spool movement Metering valve (a) Block open (b) Block closed	Blade pitch rate is constant	High blade stresses <u>may</u> cause blade to buckle	Feather system will be tested and calibrated Fluid is filtered through 10 micron filter and periodically checked to eliminate contaminants that can cause silting.	If blade is bent, bearing vibration sensors will detect excess vibration & shut down system	III	This failure would only occur during an emergency shutdown caused by another failure. See Note 1
FEATHER VALVE (11)	To admit fluid to actuators from emergency feather accumulators	Valve stuck in closed position	Poppet held in place by contaminant	Two of four actuators are not pressurized during feather mode.	NONE -- potential reduced feather rate	This valve is one of two mutually redundant valves	Pitch increase pressure transducer	III	
		Valve stuck in open position	SAME	Two of four actuators will remain pressurized after feather signal is removed.	Will prevent start-up	Valves tested before installation.	Pitch increase pressure transducer	III	This failure is effective when the WTG is down, therefore it will not adversely affect operation -- can be repaired.
		Inadvertant open	Loss of pilot pressure	Pressure applied to two pitch change actuators	Feather blade and system shutdown	Extensive testing Proven device	Blade angle position indicator	III	

DATE: May 1978
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SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
FEATHER SOLENOID VALVE (12)	To control pilot pressure to feather valves, block check, feather dump, and pitch lock valves. Deliberate de-energizing, or power failure will cause system to go to feather mode	(a) Stuck in energized position	Broken return spring	NONE - Feather control is redundant	NONE - Feather control is redundant	Two, mutually redundant valves are provided driving mutually redundant piloted check valves.	Emergency Accumulator pressure switch	III	Exercise units during maintenance.
		(b) Stuck in de-energized position	Open solenoid coil circuit	(a) If failure occurs while operating, feather control system will be activated (b) If failure occurs while system is inoperative, start up will be impossible.	System will automatically shutdown				
PITCH CHANGE ACTUATOR (13)	To provide motive force to pitch change mechanism	(a) Internal Leakage	• Contaminant in fluid caused scoring of ID or "O"-ring	NONE	NONE	In-process flushing and filtration provided to minimize contaminant inclusion			Servo valve opens more than usual to compensate for internal leakage.
		(b) External leakage	• Contaminant in fluid causes scoring of rod or rod seals	Gradual loss of fluid in reservoir	System shuts down when liquid level trips level switch in tank		Low level switch	III	
		(c) Binding of piston or rod	• Misalignment or excessive side loads			Actuator designed to eliminate side loading			
		(d) Binding of sphere rod bearings	• Contaminant in sphere rod bearing			Sphere-rod is made of self-lubricated materials.			

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

DATE: May 1978
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SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
FEATHER DUMP VALVE (14)	To provide an unrestricted drain path for the rod end of all four actuators when in feathering mode.	Fails to open	Contamination blocked poppet	Backpressure in rod-end manifold slightly higher than normal.	NONE	Two valves in parallel	Decrease pitch pressure transducer	III	
		Fails to close	SAME	Blade stuck in feather mode.	Cannot startup	Valves tested before installation. Liquid filtered to eliminate particles that can cause this failure.		III	
		Inadvertent opening	Loss of pilot pressure	Depressurize rod end of all pitch change actuators	Shutdown	Extensive testing Proven device	Blade angle position indicator	III	
LOW OIL TEMP SWITCH (15)	To provide an indication of safe operating temperature in PCM fluid reservoir. Temp. must be above 20°F for start-up	Switch fails to open	Broken thermostat Broken spring	PCM power supply will not start up	System will not start up	Switch tested prior to assembly. Has a long operating history	NONE	III	
		Switch fails to close		Pumps may cavitate, if startup is at low temp.	Sluggish system operation may cause shutdown		Motor failed alarm switch will close if condition becomes severe.	III	This would be a temporary condition. Circulation of fluid will cause temp. to rise.
LOW OIL LEVEL SWITCH (16)	To prevent operation of system with low oil level.	Switch fails closed	Broken spring	Prevents startup of PCM hydraulics	Prevents system startup	Switch tested fully before installation		III	This failure is most likely to occur when the tank is being filled, but the switch indicates it to be empty.
		Inadvertent closure	Broken spring	False indication of low oil level	Shutdown	Switch tested fully before installation			Signal can be ignored until new switch replacement is provided.
		Switch fails OPEN	Broken spring Loose wire	NONE	NONE	Switch tested fully before installation	L.P. alarm & slew pump failed alarm will warn of low system pressure	III	This failure is critical only if a tank leak develops simultaneously

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
L.P. ALARM SWITCH (17)	To warn of charging pump failure	Switch fails closed	Broken spring or leakage pressure capsule	Prevents startup of PCM hydraulics	Prevents system startup	Switch tested fully before installation	NONE	III	
		Inadvertent closure	"	False indication of pump failure	Shutdown			III	
		Switch fails open	Broken spring	NONE	NONE	Switch tested fully before installation	NONE	III	Failure of this switch in open position will not effect operation unless accompanied by motor or pump failure. In that case, emergency feather accumulator pressure switches will indicate any problem.
PUMP FAILED ALARM SWITCH (18)	To warn of slewing pump failure	Switch failed closed	Broken spring or leaky pressure sensing element	NONE	Will shutdown or prevent startup of system.	Switch tested before installation	NONE	III	Failure of switch to close alone will not affect operation unless accompanied by simultaneous pump failure.
		Switch failed open	Broken spring	NONE	NONE		NONE	III	
EMERGENCY FEATHER ACCUMULATOR PRESSURE SWITCH (19)	To warn of low pressure condition in emergency accumulators	Switch failed open	Broken spring or leaky diaphragm	NONE	NONE	Switch tested prior to installation	Periodic check out	III	There are two sets of accumulators, each with its own switch. Since both sets are mutually redundant, adequate protection against failure exists
		Switch failed closed	Broken spring	NONE	Prevents startup of system				
		Inadvertent switch closure	Shock, vibration or random failure	NONE	Will cause shut down of system				

SUBSYSTEM: PCM
COMPONENT: PCM Hydraulics 2.2.4
SUBASSEMBLY: 884E810

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: S. Onufreiczuk

SEE FIGURE 7

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
FILTERS (20)	To extract and hold all particulate contaminants from hydraulic fluid	Case Leakage	Damage to case or seals	Depletion of oil in reservoir	Eventual shutdown of system	Filter tested and inspected prior to installation	Low oil Level switch	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:
See Diagram 8

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(1) Utility	Supply/accept power (Not part of WTG system)	No voltage at line interface	• Fault • Switching	No power interchange	Power loss causing shutdown with re-start	None	No power or voltage	III	Infrequent 5 hrs/yr typical
		Loss of a phase	• Line down • Fuse	Auxiliary motors may overheat	Phase unbalance causing shutdown Lockout after time delay	None	Neg. seq. relay		
(2) Utility Recloser	Protect line (Not part of WTG system)	Close out of sync. with WTG running	Voltage block failure	Current & torque surges at generator	Varies: Loss of fatigue life on drivetrain Shutdown with re-start on over-current	Slip coupling protects drivetrain	Relays Archive	III	Unlikely occurrence
(3) Step-up Transf.	Voltage match	• Overheat • Internal fault • Tank rupture	• Low oil • Overload • Blocked cooling • Lightning • Leak	• Pressure in tank from fault • Decreased insul. life	Shutdown with lock-out on temp. or low oil	• Fuses • Pressure relief vent • Maintenance • Lightning arrestors	Oil level & temp. alarms Visual leak	III	Remote fire possible if lightning ruptures tank. Inspection of cooling tubes airflow req'd SEE NOTE 1
		Loss of Phase	• Fuse • Open winding	Auxiliary motors may overheat	Phase unbalancing causing shutdown with lockout after time delay	None	Neg. seq. relay	III	
(4) Auxiliary Supply	Voltage match WTG auxiliary systems	• Overheat • Fault	• Overload • Lightning Damage	• Decreased insul. life	Shutdown on loss of phase or no power	• Fuses • Lightning arrestors		III	Periodic inspection
		Loss of phase	• Line down • Fuse	• Motor overheat • Loss of some power	Shutdown if computer loses power	Starter overload devices	Archive	III	Secondary loss of phase protection not provided Periodic inspection and test

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:
See Diagram 8

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(5) Main Breaker	Connect/disconnect generator, clear faults	No close	• No close signal • Jam	Cannot complete start-up	Shutdown after time out	None	Archive	III	Periodic inspection
		No open or no interruption	• No trip signal • Jam • No trip power See 14 and 19	• Cannot disconnect generator from line • Slip coupling overheats	• Shutdown against torque load • Generator insulation or drive damage • Fire if slip coupling continuously running	• DC trip • Parallel circuits • Conservative rating • Field removed from generator • Manual operation to trip if attended • Line recloser trip on high current	Archive	II	Reliable control over disconnection from line requires periodic test and maintenance on main breaker.
		Close at wrong time	Circuit failure See 11 Manual operation	Generator connected to line	Shutdown and breaker open via overcurrent	Requires multiple failure in close circuit. Slip coupling protects drive train.	Protective relays Archive	III	Manual control on close will be disabled
		Open at wrong time (Loss of load)	• Circuit failure • Latch failure • Manual operation	Generator disconnected	Shutdown via breaker open and overspeed	None	Protective relays Archive	III	Safe failure mode Periodic maintenance required on mechanism.
(6) Slipring	Transfer power/control across the yaw bearing (rotor S.R. only for engrg. data)	Will not turn	• Bearings Stuck • Misalignment	Slightly higher yaw torque	None	Yaw drive will move even badly jammed bearing.	None	III	Assembly care needed to prevent misalignment
		Fault	• Lightning • Dirty insultion	Breaker opens	Probable shutdown by current relays	H.V. circuit has ground shield rings to reduce damage.	Archive	II	Major repair if internal slipring damage
		Open or noisy signal	Dirty ring or brush or burnt spot	• Bad signals • Loss of power	Shutdown by computer	Dual communication lines	Archive Test	III	Realign 90° or repair burnt spots

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:
See Diagram 8

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(7) Generator ASM	Generate electric power	Overheat	• Blocked air • Overload • No excitation • Unbalance	Decreased insul. life	Shutdown with lock-out through winding temp. relay	Most of operating time below rating	Protective relays	III	Fan on shaft is not directional. Periodic inspection of air flow path is required.
		Fault	• Wet insulation • Lightning	• Fire damaged insul	Shutdown with lock-out through current relay	Space heaters, lightning arrestors & surge capacitors	Protective relays	II	Major repair if stator or rotor winding damage
		Jammed bearing while not rotating	• Bearings • Misalignment • No lube	Will not rotate in low winds	Shutdown after time out	None	Archive	III	Periodic visual lube check required
		Bearing seizure while running	• No lube • Mechanical failure • Fatigue	• Journal damage • Scoring	Shutdown on temp. or vibration with repair	High reliability sleeve bearing with oil ring	RTD in control or vibration	III	Bearing replacement does not require major disassembly
		Overspeed (more than 125% rated)	Loss of drivetrain control	• Rotor winding distortion • Metal to metal on stator	Shutdown with lock-out on overspeed possible repair	Redundant detection and powerful control elements	Computer or backup overspeed detection	III	Unlikely due to multiple redundant speed shutdown means. Actual speed where damage occurs is unknown.
		RTD sensors open/short Incorrect reading	Piece part failure	Incorrect signal to protective relay	Shutdown with lock-out or no thermal protection	None Computer has current and power sense of overload	Test Prot. relays	III	Embedded spares Manual reset req'd
(8) Excitation (Exciter & Regulator & VAR Control)	Control output voltage and reactive power	No or full output	• No power • Circuit failure	• Full output overheats generator rotor circuits	Shutdown with lock-out through over-voltage or power factor relays or exciter field current	None - except for multiple sensing devices	Prot. relays Comp. sensor Archive	III	Manual reset req'd Periodic inspection req'd
		Incorrect output	Age or circuit deterioration	Low output reduces stability					

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:

See Diagram 8

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(9) Stabilizer Circuit See 8 also	Modify drivetrain damping to increase stability via excitation system	No or incorrect signal	• No power • Speed sensor circuitry failure	Larger variations in drivetrain torque & power Possible loss of synchronization	• Slip coupling thermal damage • Decreased drivetrain fatigue life • Excessive voltage variations	None Vibration may cause shutdown for severe oscillations	Test Prot. relays Customer complaints about voltage Archive	III	Periodic inspection of circuit and slip coupling required. Index marks on coupling to indicate motion should be provided.
(10) Protective Relays See 19 also	Detect electrical problems	No or incorrect operation	• Jam • Loose connection • No power • Circuit failure	Main breaker fails to open when req'd Main breaker open	Shutdown or reduced protection	Highly reliable devices Periodic adjustment Overlapping function	Test History	III	Critical items are covered in detail under 19 See Note 1
(11) Synchronizer (2) 25 on 298E275 Rev. 3	Closes main breaker when generator output is in sync. with utility, under correct frequency and phase	No output	• Potential circuit • No enable signal • No power	Cannot complete startup	Shutdown after timeout	None	Test	III	Slip coupling thermal rating adequate to accommodate asynchronous closing with no drivetrain damage.
		Output at wrong time	Mechanism failure	Current & torque surges at generator	Shutdown with restart decreases drivetrain fatigue life	• 2 vote redundancy • Slip coupling limits torque	Test Archive	III	
(12) Motor Control	Start, stop Protect motors	No output	No power No signal	Motor will not start	Cannot start-up system	Reliable devices used extensively in industry	Visual	III	Routine preventative maintenance
		Overload inoperative	Jammed relay	No motor overload protection and overheat	Shutdown from final parameter such as pressure	Reliable devices	Test	III	

DATE: May 12, 1978
PREPARED BY: R. Barton

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:
See Diagram 8

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(13) A & B Control Boxes	Interface computer output with power circuits	No output	No power No signal	Load not energized	Shutdown by control	Sealed relays Main feather circuits are dropout relay action independent of box	Computer status feedback	III	
		Output at wrong time	Contact weld Circuit failure	Energized at wrong time or remain on					
(14) Battery Assembly	Supply D.C. (125V) for breaker trip & aircraft warn lamps	Loss of DC voltage	• Loose connection • Bad battery cells	Trip power lost if voltage below 70%	Shutdown by control	DC loads supplied thru charger	Alarm on DC to control	III	Periodic battery maintenance required
		No charger output	Circuit failure	Battery charge not maintained	Shutdown by control	DC loads supplied by battery	Alarm on DC to control	III	Periodic maintenance
(15) Aircraft Warning Light	Warn pilots of tower hazard	No light	• Filament burnout • No DC • Mechanical damage	Reduced warning	Issues warning notice to dispatcher	• Dual lamps on independent circuits (one should be on) • Met tower lighting	Current sensing Visual	III	Dispatcher notification of local aviation authorities until repair recommended
(16) Lift Cable Reel	Wind up & pay out lift cable	Does not wind up	• Jam • Ice • Broken spring	Cable lies on ground	None	None - Repair		III	
		Does not pay out	• Jam • Ice	Cable jerk or break	Lift inoperative	Switch on cable stops lift		III	Personnel can lower lift or use escape device
		Skip spot on ring	• Burnt ring • Cold weather	Opens power circuit	Lift may not operate in one position	None - Replace ring			

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:
See Diagram 8 and 8a

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
(17) Control Enclosure	House ground equipment	No heating or cooling	• Air cond. • Heater thermostat • No power • External AC damage	No or less environment control - will go hot or cold	None - until out of computer band, then shutdown initiated by computer	Redundancy (3) A/C (2) Htrs.	Temp. sensor	III	
(18) Security	--	Unauthorized entry	• Vandal • Thief • Curiosity seeker	Power & interface equipment spurious operation	Shutdown on door Entry Alarm	No windows on C.E. Low probability Door locks	Door sensor	II	Potential hazard to people; a fence should be considered
(19A) Phase over current relay circuit Quan.(3) & Phase Balance 51V and 47 on 298E475 Rev. 3 (See Diagram 8a)	Detect overcurrent or phase unbalance and trip main breaker	a) Output fails open b) Output fails closed when operating c) Output fails closed when not operating	Loss of CT or PT signal Mechanical or electrical failure of relay	a) Tripping relay not actuated b) Tripping relay actuated c) None until close of main breaker attempted, then tripping relay actuated	a) No overcurrent protection on one phase or phase balance b) System shutdown due to breaker trip c) Same as b)	a) Other (2) phase relays will operate on phase to phase faults or over power b) None c) None	Test Visual (no flag)	III	Periodic test and maintenance required to insure proper operation of relays. Trip relay pickup circuit blocking close-May be added for C)
(19B) Line Ground Current Relay Circuit 64G3 on 298E475 Rev. 3 (See Diagram 8a)	Detect line neutral current indicating phase to ground fault and trip main breaker	a) Output fails open b) Output fails closed when operating c) Output fails closed when not operating	• Loss of CT signal • Relay mechanical or electrical failure	Same as 19A, a,b,c	a) No line fault protection by 64G3 and WTG will continue operating b) System shutdown due to trip c) Same as b)	a) Frequency drift or phase overcurrent or phase unbalance relays will operate depending on current value and cause main breaker trip and system shutdown. Utility voltage block on recloser b),c) None	Test Visual (flag)	III	Same as 19A See Note 1

SUBSYSTEM: Power Generation (2.3)
COMPONENT:
SUBASSEMBLY:

See Diagram 8a

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 12, 1978
PREPARED BY: R. Barton

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
(19C) Tripping Relay 94G on 298E475 Rev. 3	Trip main breaker (non lockout)	a) Output fails open b) Output fails closed when operating c) Output fails closed when not operating	a) No DC, open coil or output circuit b),c) circuit failure or welded contact	a) Breaker will not be tripped when required b) Breaker trips c) Startup sequence blocked	a) No protection from phase current, line ground current, phase balance relays b) System shutdown due to breaker trip c) No start	a) Utility voltage block on recloser Computer can operate lockout relay which has parallel function on detection of frequency drift, overpower or unbalanced currents b),c) None	Test	III	Same as 19A See Note 1
(19D) Lockout Relay 86G on 298E475 Rev. 3 and 32, 64G2, 57, 55, 71, 49 supplying 86G	Trip main breaker (lockout)	a) Output fails open b) Output fails closed when operating c) Output fails closed when not operating	a) No DC, open coil or output circuit, jam on latch release b),c) Circuit failure, latch failure	Same as 19C, a,b,c	a) No protection from reverse power, gen. ground current, overvoltage, power factor, transformer temp. or oil level b) System shutdown due to breaker trip c) No start up	a) Computer can operate tripping relay which has parallel function on detection of frequency drift, reverse power, or unbalance b), c) None	Test	III	Same as 19A See Note 1

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: NACELLE (2.4)
COMPONENT: FAIRING 298E461
SUBASSEMBLY:

DATE: May 1978
PREPARED BY: R. Cockfield

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
SIDE PANELS	Protection of Nacelle-mounted equipment from environment	Structural Failure	Loads in excess of design conditions (150 MPH wind)	Collapse or complete loss of fairing	Loss of wind sensor, causing normal shutdown Loss of obstruction lights (2), causing normal shutdown Under or over temperature of temp. sensitive systems, causing normal shutdown	• Conservative and detailed stress analysis was performed • Aluminum structure can yield without collapse	Temp. sensors, Wind sensor	II	Inspection during periodic maintenance and after known hurricane conditions
EXHAUST FAN	Cooling air for Nacelle-mounted equipment	(a) Fan fails to operate (b) Louvers jammed shut	• Electrical short or open • Mechanical failure of fan • Thermostat failure • Louver bearing failure • Bird strike	Over temperature within nacelle	Overtemperature in NMU, causing normal shutdown Overtemperature in lube oil, causing normal shutdown	• Some air circulation even with exhaust closed • High ambient temperatures improbable	Temp. sensors	III	
		(c) Fan does not shut down (d) Louvers jammed open	• Thermostat failure	Under temperature within nacelle	Under temperature in NMU, causing shutdown Under temperature in lube oil, causing continuous heater operation or shutdown	• Air velocity within nacelle is limited by intake louvers • Low ambient temperatures improbable • Lube system and gearbox provide heat to nacelle	Temp. sensors	III	

SUBSYSTEM: NACELLE (2.4)
COMPONENT: BEDPLATE 298E471
SUBASSEMBLY: ______

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: R. Cockfield

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
JOINT AT STA. 256, UPPER FLANGE	Structural support and rigid mounting for drive train	Fatigue cracks in weld *	Cyclic loads were underestimated Undetected flaw	Degraded stiffness (after extensive cracking)	Excessive vibration (after extensive cracking)	• Calculated range stress is below AISC limits • Cyclic torque reaction at gearbox was conservatively overestimated by a factor of 2 • Weld has passed MT and UT inspection • Bedplate structure provides redundant load paths	Vibration sensors (after extensive cracking)	III	Inspection and repair of large cracks during periodic maintenance Analysis based on bedplate finite element model and local hand calculations
		Yielding	(a) Unusual loads not anticipated (b) Transients during start-up and shut-down	Distortion of gearbox mounting (after extensive yielding)	Excessive vibration (after extensive distortion)	• Calculated stress is below 60% of yield • Weld has passed MT and UT inspection • Certification of material mechanical properties available	Vibration sensors (after extensive distortion)	III	Inspection during periodic maintenance

*Calculated stress range is 6852 psi. Allowable stress range is 7000 psi, based on AISC stress category D and loading condition 4 (more than 2×10^6 cycles)

$$MS = \frac{7000}{6852} - 1 = +0.02$$

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: CONTROL & RECORDING UNIT (CRU) AND PERIPHERAL RACK
SUBASSEMBLY: CONTROL & RECORDING UNIT (CRU) WITH BATTERY BACKUP

DATE: 6 April 1978
PREPARED BY: R. T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
CRU (DEC PDP 11/34)	Central processing unit for WTG. 64K parity memory. Phone line control, local operator control, real time process control, archive control	No output	• Power supply failure • Unibus failure	• Remote MUXs are not commanded • Decwriter interface lost • Real time clock interface lost • Modem interface lost • Disk interface lost	Complete loss of system control and data acquisition both local and dispatcher	GMU and NMU issue Emergency Shutdown Lockout commands instantly upon loss of Signal	GMU and NMU looking for loss of signal	III	
		Confused or scrambled output	• Circuit failure	Same as above	Same as above	GMU and NMU issue Emergency Shutdown Lockout commands instantly upon loss of Parity	GMU and NMU looking for parity	III	
CRU BATTERY BACKUP (DEC H775CA)	To retain data in MOS memory through power interrupt	No output	• Open circuit, breaker interrupt, etc.	None until power interrupt, then CRU goes down	None until power interrupt, then complete loss of system control and data acquisition both local and dispatcher	GMU and NMU issue Emergency Shutdown Lockout commands instantly upon loss of signal	GMU and NMU looking for loss of signal	III	
TERMINAL (DEC LA36)	Operator Interface: contains keyboard for operator commands and printer for messages	Fails to print	• Circuit failure • Mechanical failure • Ribbon or paper	NONE	Operator			III	Spare ribbons & paper on site
		Fails to respond to command inputs	• Circuit failure • Keyboard failure	CRU would not receive commands	Loss of operator control	Software Processing shuts down system	DPM Time out	III	
			• Operator error	CRU would receive wrong command	NONE	Software first checks for validity of input command. If command is invalid it is ignored and message is sent to operator.	Software Processing	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: CONTROL & RECORDING UNIT (CRU) AND PERIPHERAL RACK
SUBASSEMBLY: DISK DRIVE

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
DISK DRIVE "0" (DEC RK05)	Non-volatile mass storage of the operating software system 2.5 Megabytes	Will not write	Circuit failure	None - not used	None	None	None	III	Should be cleaned and checked every six months
		Will not read	Circuit failure	Operating software would not "boot" after next-power interrupt	Fails to restart	None	Dispatcher would not receive hourly message	III	
DISK DRIVE "1" (DEC RK05)	Diagnostic archive for sensor, CMD, status, and state values 2.5 Megabytes	Will not read	Circuit failure	None - not used until system is off	None	Data can be reviewed using another drive	None	III	Should be cleaned and checked every six months
		Will not write	Circuit failure	Archive data is lost	Diagnosis of failure must be performed without the insight provided by data.	None	Playback	III	

DATE: 6 April 1978
PREPARED BY: R. T. Hedges

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: CONTROL & RECORDING UNIT (CRU) AND PERIPHERAL RACK
SUBASSEMBLY:

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
REAL TIME CLOCK WITH 60-HOUR BATTERY BACKUP (DATUM 9100)	Time tag data	No output or wrong time	Circuit failure or extended power interrupt	None	Data will be time tagged with erroneous time and flagged as such	None	Playback of archive	III	Front panel lamp indicates battery failure
AUTOCALL AND MODEM (VADIC)	Dial dispatcher, phone number modulate outgoing data, de-modulate incoming data	No output	Circuit failure	None	Dispatcher communications interrupted	None	Hourly message and solicited communication not present	III	
ISOLATION TRANSFORMER AC INPUT PANEL	Line noise attenuation	Short circuit	Insulation breakdown	Circuit breaker opens after overcurrent, interrupting CRU power	Complete loss of system control and data acquisition both local and dispatcher	NMU and GMU issue Emergency Shutdown Lockout commands instantly upon loss of signal	GMU and NMU looking for loss of signal	III	
		Open circuit	Connection or wiring parts	CRU power lost	Same as above	Same as above	Same as above	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NACELLE MULTIPLEXER UNIT (NMU) RACK
SUBASSEMBLY:

DATE: 6 April 1978
PREPARED BY: R. T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
NACELLE MULTIPLEXER UNIT (NMU) (DEC PDP 11/04)	Data multiplexer, issue commands, data compression, sense link with CRU, issue Emergency Shutdown Lockout independently, 32K MOS memory	No output to CRU	• Power supply failure • Unibus failure • Other circuit failure	Data not sent to CRU, commands not issued to user subsystems, ESD cannot be issued to nacelle user subsystems	Loss of control and data acquisition of nacelle user subsystems	GMU issues Emergency Shutdown Lockout command instantly upon CRU detection of loss of Signal	CRU looks for loss of signal	III	
		Confused or scrambled output	Circuit failure	Same as above	Same as above	GMU issues Emergency Shutdown Lockout command instantly upon CRU detection of loss of Parity	CRU looks for parity	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NACELLE MULTIPLEXER UNIT (NMU) RACK
SUBASSEMBLY: NACELLE DIGITAL INTERFACE PANEL (N-DIP)

DATE: 14 April 1978
PREPARED BY: R. T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
STATUS DEBOUNCE CIRCUITS, DRIVERS, OR ANY OTHER IN LINE STATUS CIRCUIT	Remove signal ambiguity and drive PDP 11/04 DR11C interface	Any combination "on" when it should be "off"	Circuit failure	"On" status indicated to MUX	None	MUX only samples when command is "active"	None	III	
		Any combination "off" when it should be "on"	Circuit failure	"Off" status indicated to MUX	Corresponding command indicated to be failed	Shutdown is commanded in response	MUX measures response time	III	
COMMAND RELAY DRIVERS OR ANY OTHER IN LINE COMMAND CIRCUIT	Boost signal to drive relay coils	Fails to change command state when required	Circuit failure	User device is not commanded	Corresponding function does not respond	Shutdown is commanded in response to timeout	MUX measures response time	III	
COMMANDS PCM-13	Emergency feather even on/off	"On" when not requested	Circuit failure	Actuators 2 & 4 are pressurized	Blades are driven to feather	ESD is commanded	Pitch jam signal	III	See Figure 9
PCM-14	PCM Auto on/off	"On" when not requested	Circuit failure	Pitch ramp is initiated in servo controller	PCM slider pushes against feather latch	ESD is commanded	Pitch jam signal	III	
		"Off" when it should be on	Circuit failure	Output relay opens	Blades begin to drift toward feather	ESD is commanded	Pitch jam	III	
PCM-15	PCM Manual on/off	"On" when not requested	Circuit failure	In "SPEED" mode reference is removed. In "POWER" mode no effect	Shaft RPM will decrease	ESD is commanded	Pitch jam or timer time out	III	
		"Off" when it should be on	Circuit failure	Output relay opens	Blades begin to drift toward feather	ESD is commanded	Pitch jam	III	
PCM-32	Speed schedule on/off	"On" when not requested	Circuit failure in manual mode	None	None	None	None	III	
			Circuit failure in auto mode	Step input	Step from 0 to 1800 RPM	ESD is commanded	Pitch jam	III	
		"Off" when it should be on	Circuit failure	Ramp generator disabled in servo controller	Rotor shaft attempts to go to zero speed	ESD is commanded	Pitch jam on Δt	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NACELLE MULTIPLEXER UNIT (NMU) RACK
SUBASSEMBLY: NACELLE DIGITAL INTERFACE PANEL (N-DIP)

DATE: 11 May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
YAW-22	Yaw accum. flow enable on/off	"On" when not requested	Circuit failure	Yaw rate increases by 50%	None	None	None	III	
		"Off" when not requested	"	Valve closed	Terminates accum. charging	NSD, AR	Pressure sensors	III	
PCM-29	Emergency feather odd on/off	"On" when not requested	"	Actuators 1 & 3 are pressurized	Blades are driven to feather	ESD is commanded	Pitch jam signal	III	See Figure 9
		"Off" when not requested	"	1 & 3 are shut off	None	Redundant set	None	III	
YAW-12	Yaw drive CW/off	CW when not requested	"	Yaw accumulator charge rate increases by 200%	None	None	None	III	
		"Off" when not requested	"	Valve closed	Yaw terminated	NSD	Δt	III	
YAW-13	Yaw drive CCW/off	CCW when not requested	"	Cannot charge yaw accumulator	No yaw brake No shaft brake	NSD shutdown	Accumulator alarm	III	
		"Off" when not requested	"	Valve closed	Yaw terminated	NSD	Δt	III	
YAW-16	Yaw drive on/off	"On" when not requested	"	Yaw drive solenoid valve actuates	If in accumulator charge mode, nacelle will attempt to yaw	NSD is commanded	DPM 24 senses YAW-16 status	III	
		"Off" when not requested	"	Valve closed	Yaw terminated	NSD	Δt	III	
YAW-15	Yaw brake	Disable "on" when not required	"	Brake solenoid actuates	Yaw brakes released	NSD is commanded	DPM 24 senses YAW-16 status	III	
		"Off" when not requested	"	Brake solenoid release	Yaw brakes apply	NSD is commanded	Same as above	III	

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NACELLE MULTIPLEXER UNIT (NMU) RACK
SUBASSEMBLY: NACELLE DIGITAL INTERFACE PANEL (N-DIP)

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
DRT-25	Shaft brake	"On" when not requested at 1800 RPM	Circuit failure	Generator shaft brake is applied causing overheating	Shaft slows slightly	ESD is commanded in response to main breaker open	Switchgear protective relaying & software processing	II	Brake would require rework
		"Off" when not requested	"	Gen shaft brake releases	Shaft is free to turn	None	None	III	
PCM-34	Power mode	Speed-to-power when not requested	"	Servo controller transfers modes from speed to power	Rotor RPM decreases smoothly back to 0 RPM	ESD is commanded	CRU DPM is counting time to reach full speed	III	
	Power mode power/speed	Power-to-speed when not requested	"	Servo controller transfer to speed control at RPM setting for previous synchronization	If utility frequency significantly different front gen, synchronization is lost	Breaker will be commanded open and ESD will follow	Protective switchgear	III	
YAW-14	Charge accum. on/off	"On" when not requested	"	Charge accumulator solenoid actuated	Accumulators will attempt to overpressure	Relief valves will dump fluid	Relief valves	III	
		Failed off	"	Valve closed	Terminates accum. charging	NSD, AR	Pressure sensors	III	
DRT-27	Hub backup overspeed reset on/off	"On" when not requested	"	Backup overspeed device will be reset	None	Momentary reset circuit does not inhibit next shutdown action	None	III	See Figure 9
		Failed off	"	Overspeed detector remains tripped	Cannot restart	None	None	III	See Figure 9
PCM-38	Wind feed forward on/off	"On" when not requested	"	Servo controller switches "On" wind feed forward	Larger drive train variational torques & decrease in fatigue life	Slip clutch trims torque peaks	None	III	
		Failed "off" when requested "on"	"	Servo controller switches out wind feed forward	Larger drive train variational torques & decrease in fatigue life	Slip clutch trims torque peaks	None	III	

DATE: 11 May 1978
PREPARED BY: R. T. Hedges

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: N-DIP

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
ENV-17	Video camera disable on/off	"On" when not requested	Circuit failure	Video camera turns off	None	None	None	III	
		Failed off	Circuit failure	Video camera won't turn off	None	None	None	III	
ENV-24	Video pan disable on/off	"On" when not requested	Circuit failure	Video pan turns off	None	None	None	III	
		Failed off	Circuit failure	Video pan won't turn off	None	None	None	III	
TEST LOGIC	Reconfigure signal paths to accommodate computer driven self check or front panel switch positions	Oper/test fails in "test"	Circuit failure	DIP will output erroneous "sensor" states	CRU will receive inconsistent data	Shutdown is commanded when incorrect state is detected	Software processing	III	
SENSOR DEBOUNCE CIRCUITS or any other in-line sensor circuit or the sensor itself	Remove signal ambiguity, drive 11/04, DR11C interface, etc.	Any failure which indicates WTG failure	Short or open circuit	Computer receive false indication of failure	Shutdown	None	Software processing	III	
ROT-01	Rotor bearing oil flow	Ind. flow	Short circuit	None	None	None	None	III	See Note 2
PCM-06	Odd feather accum. alarm	Alarm off	Open circuit	None	None	None	None	III	See Note 1
PCM-07	Even feather accum. alarm	Alarm off	Open circuit	None	None	None	None	III	See Note 1
PCM-08	Main accum. alarm	Alarm off	Open circuit	None	None	None	None	III	See Note 1
PCM-10	PCM hyd low oil level	Level high	Short circuit	None	None	None	None	III	See Note 1
PCM-09	Feather latch pos.	Either way	Short or open circuit	False indication of failure	Shutdown	None	Software processing	III	All combinations are continuously monitored

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU Rack
SUBASSEMBLY: NACELLE DIP

DATE: 17 April 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
PCM-17	Pitch jam	No pitch jam	Open circuit	None	None	None	Software processing	III	Signal presence is checked at every shutdown
PWR-43	Gen htr. monitor	Htrs on	Short circuit	None	None	None	None	III	
YAW-02	Yaw hyd oil level	Level high	Short circuit	None	None	None	None		See Note 1
YAW-03	Yaw hyd pump fail alarm	No output	Open circuit	None	None	None	None	III	See Note 2
DRT-01	Shaft brake accum low	Pressure normal	Open circuit	None	None	None	None	III	Has backup alarm
DRT-02	Shaft brake alarm	Pressure normal	Open circuit	None	None	None	None	III	See Note 1
YAW-04	Yaw brake accum low	Pressure normal	Open circuit	None	None	None	None	III	Has backup alarm
DRT-13	Xmission oil level	Level high	Open circuit	None	None	None	None	III	See Note 1
PCM-28	Slew pump failed alarm	No output	Open circuit	None	None	None	None	III	See Note 2
DRT-26	Shaft brake pressure	Either way	Short or open circuit	None	None	None	None	III	See Note 2
YAW-05	Yaw brake alarm	Pressure normal	Open circuit	None	None	None	None	III	See Note 1

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: NACELLE DIP

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: 5-16-78
PREPARED BY: T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
Sensors and their circuits (cont.)									
YAW-07	Yaw Brake ON/OFF	Either Way	Short or Open Circuit	None	Shutdown	None	None	III	See Note 2
DRT-22	Lube Oil Temp.	Indicates Warm	Short circuit	None	None	None	None	III	See Note 1
YAW-10	Yaw Drive ON/OFF	Either Way	Short circuit	None	None	None	Software Processing	III	All combinations are continuously monitored
YAW-11	Charge Accum. ON/OFF	Either Way	Short circuit	None	None	None	Software Processing	III	All combinations are continuously monitored
PWR-06	Obs. Lite #1 ON/OFF	ON	Short circuit	None	None	None	None	III	See Note 1
PWR-42	Obs. Lite #2 ON/OFF	ON	Short circuit	None	None	None	None	III	See Note 1

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: NACELLE CONTROL ELECTRONICS (NCE)
SEE FIGURE 9

DATE: May 1978
PREPARED BY: R.T. Hedges

ANALOG SENSORS. The following failures could occur either in the sensor itself or somewhere in the signal conditioning or test logic circuitry. Each sensor and its associated circuitry provides a proportional analog signal indicating value of function being monitored.

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PCM-01	Blade pitch angle #1	No output or incorrect value	Sensor or conditioning circuitry failure	Servo Cont'r. sets wrong blade angle	Possible overspeed	Shutdown is commanded if incorrect angle is detected.	2nd RVDT is compared to 1st.	III	
PCM-02	Bladepitch Angle #2	No output or incorrect value	Sensor or conditioning circuitry failure	CRU receives different angle	NONE	Shutdown is commanded if incorrect angle is detected.	2nd RVDT is compared to 1st	III	
PWR-30	Generator power transducer	No output or incorrect value	Sensor or conditioning circuitry failure	Servo Cont'r. sets wrong power	Possible overstress	Shutdown is commanded if incorrect power is detected.	Ground power sensor is compared to nacelle unit in CRU	III	
DRT-06	Rotor Shaft Position	No output or incorrect value	Sensor or conditioning circuitry failure	Blade Position software receives wrong angle	Blade stowed to other than 3-9 position after shutdown.	NONE	NONE	III	See Note 1
DRT-07	Gen. Shaft Speed (0-1900 RPM)	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect Shaft Speed	Unable to synchronize. Shutdown	NONE	Tach signals are compared in comp	III	
DRT-29	Gen. Shaft Speed (1400-2200 RPM)	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect Shaft Speed	Unable to synchronize. Shutdown	NONE	Δ t to synchronize	III	
ENV-01	Wind Speed #1	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect wind regimes	Overstress Shutdown & message	NONE	2nd sensor compared to first	III	
ENV-02	Wind Speed #2	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect wind regimes	Overstress Shutdown & message	NONE	2nd sensor compared to first	III	
ENV-03	Wind Direction #1	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect yaw position setting	Loss of energy collection. Shutdown & message	NONE	2nd sensor compared to first	III	
ENV-04	Wind Direction #2	No output or incorrect value	Sensor or conditioning circuitry failure	Incorrect yaw position setting	Loss of energy collection. Shutdown & message	NONE	2nd sensor compared to first	III	

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: NACELLE CONTROL ELECTRONICS (NCE)

SEE FIGURE 9

ANALOG SENSORS

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
ROT-04 PCM-03 PCM-04 PCM-05 PWR-01 PWR-04 PWR-05 DRT-08 PCM-27 DRT-14 ENV-05	Rotor Bearing Vib. ODD Increase Pressure EVEN increase pressure Decrease pressure Gen. Winding Temp ØA Gen. Bearing Temp. Shaft Gen. Bearing Temp. aft Gen. shaft vib. Pitch change Bearing Vib. Transmission Hi spd. brg. temperature Nacelle temperature	Any failure which falsely indicates WTG failure	Sensor or circuit malfunction	Receives false indication of failure	Shutdown	NONE	Software processing	III	
ROT-04	Rotor Bearing Vib.	Low output	Sensor or circuit malfunction	NONE	NONE	NONE	NONE	III	See Note 1
PWR-01 PWR-04 PWR-05 DRT-14	Gen. Winding Temp. ØA Gen. Bearing Temp. Shaft Gen. Bearing Temp. aft Transmission Hi spd. brg. temp	Low temp.	Sensor or circuit malfunction	NONE	NONE	NONE	NONE	III	See Note 1
Analog Command PCM-30	Power Reference to Servo Controller	Incorrect Value	D/A converter or interface circuitry failure	Servo controller sets wrong blade angle	Wrong generator output power in the range of 0 to 2000 kilowatts	NONE	NONE	III	
Analog Command PCM-16	Speed Trim to Servo Controller	Incorrect Value	D/A converter or interface circuitry failure	Servo Controller set wrong shaft speed	Possible overspeed Shutdown.	NONE	Software & hardware overspeed detection	III	See Figure 9
					Under speed - synchronization will not occur Shutdown	NONE	Software processing Δ t	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: SERVO CONTROLLER

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
OUTPUT AMPLI-FIER	Linear Drive Ampl. for servo valve coil	No output	Circuit failure	No valve coil current	No blade angle control	Hydraulic bias in servo valve toward feather and emergency shutdown	pitch jam	III	
		Full on toward feather	Shorted CE on output transistor	Full rate valve coil current	Blade goes to feather Emergency shutdown	NONE	Pitch jam	III	
		Full on toward full power	Shorted CE on output transistor	Full rate valve coil current	Blade angle attempts to go to full power. Emergency shutdown	NONE	Pitch jam	III	
SERVO CONTROL LOGIC	Closed loop servo control and compensation for speed and power modes.	No output	Circuit failure	No valve coil current	No blade angle control	Hydraulic bias in servo valve toward feather and emergency shutdown	Pitch jam	III	
		Full on toward feather	Shorted CE on output transistor	Full rate valve coil current	Blade goes to feather Emergency shutdown	NONE	Pitch jam	III	
		Full on toward full power	Shorted CE on output transistor	Full rate valve coil current	Blade angle attempts to go to full power. Emergency shutdown	NONE	Pitch jam	III	
		Unstable	Piece part open or short changing compensation network	Valve coil current oscillatory	Loss of blade control. Emergency shutdown	NONE	Pitch jam	III	
OSCILLATOR/ DEMODULATOR, POWER TRANSDUCER BUFFER, & TACHOMETERS	Condition sensor input signals	No output	Open connection or piece part	Loss of feedback in servo loop	No blade angle control. Emergency shutdown.	NONE	Pitch jam	III	
		Full scale output	Shorted amplifier	Incorrect feedback in servo loop	No blade angle control. Emergency shutdown	NONE	Pitch jam	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: NMU RACK
SUBASSEMBLY: SERVO CONTROLLER (CONT.)

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
RAMP GENERATOR	Generator speed ramp signal for startup & shutdown	No output when ramp function is called for	Open connection or piece part failure	Loss of ramp	Blade goes to feather. Emergency shutdown.	NONE	Pitch jam or Δ time	III	
SPEED REFERENCE	Common voltage ref. for servo speed loop and tachometers	HI voltage LO voltage (speed mode)	Open connection or failed piece part	Servo controls to wrong speed	Will not synchronize with utility line. Normal shutdown	NONE	Δt time out to synchronize	III	
RELAY INTERFACE	Same as the following command circuits under Nacelle DIP: PCM-14 PCM-15 PCM-32 PCM-34 PCM-38								

FAILURE MODE EFFECTS AND CRITICALITY ANALYSI

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: Ground Multiplexer Unit (GMU) Rack
SUBASSEMBLY:

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
GROUND MULTIPLEXER UNIT (GMU) (DEC PDP 11/04)	Data Multiplexer, issue commands, data compression, sense link with CRU, issue ESD, LO independently, 32 K MOS memory	No output to CRU	• Power supply failure • Unibus failure • Other circuit failure	Data not sent to CRU, commands not issued to user subsystems. ESD cannot be issued to Ground user subsystems.	Loss of control & data acquistion of Ground user subsystems.	NMU issues ESD, LO commands instantly upon CRU detection of loss of signal.	CRU looks for loss of signal	III	
		Confused or Scrambled output	Circuit failure	Same as above	Same as above	NMU issues ESD, LO commands instantly upon CRU detection of loss of parity.	CRU looks for parity	III	

SUBSYSTEM: CONTROL (2.5)
COMPONENT: GMU RACK
SUBASSEMBLY: G-DIP

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
TEST LOGIC	Switch signal paths to suit computer driven test or panel switch positions	OPER/TEST fails in "TEST"	Circuit failure	DIP will output erroneous "sensor" states.	CRU will receive inconsistant data.	Shutdown is commanded when incorrect state is detected.	Software Processing	III	
Status debounce circuits, drivers, or any other in-line status ckt.	Remove signal ambiguity and drive "104,DR11C 1/F	Any combination "ON" when it should be "OFF"	Circuit malfunction	"ON" status indicated to MUX	NONE	MUX only samples when command is "ACTIVE"	NONE	III	
		Any combination "OFF" when it should be "ON"	Circuit malfunction	"OFF" status indicated to MUX	Corresponding command indicated to be failed.	Shutdown	MUX measures response time	III	
Command relay drivers or any other in line command circuit	Boost signal to drive relay coils	Fails to change state when required	Circuit malfunction	User device is not commanded	Corresponding function does not respond	Shutdown	MUX measures response time	III	
CMD PWR-23	Sync Enable ON/OFF	ON	" "	Switchgear is enabled	NONE	Synchronizer will not close breaker	NONE	III	
CMD PWR-24	Main Breaker OPEN ON/OFF	ON (OPEN)	" "	Breaker opens	Attempted overspeed	Emergency shutdown	Software processing	III	
CMD PWR-25	Voltage Reg. RAISE/OFF	ON (RAISE)	" "	Full Excitation motor pot to limit	Overvoltage	Shutdown	Protective relaying	III	
CMD PWR-26	Voltage Reg. LOWER/OFF	ON (LOWER)	" "	Minimum excitation motor pot limit	Lagging power factor	Shutdown	Protective relaying	III	
CMD PWR-31	Voltage Reg. PWR ON/OFF	OFF	" "	Loss of excitation power	Lagging power factor	Shutdown	Protective relaying	III	In Gen. state
CMD PWR-27	Power Factor RAISE/OFF	RAISE	" "	Full excitation motor pot to limit	Overvoltage	Shutdown	Protective relaying	III	
CMD PWR-28	Power Factor LOWER/OFF	LOWER	" "	Minimum excitation motor pot limit	Lagging power factor	Shut down	Protective relaying	III	
ENV-09	SAIR DISABLE ON/OFF	ON	" "	SAIR is disabled	Data is not recorded	NONE	NONE	III	

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: GMU RACK
SUBASSEMBLY: G-DIP

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

COMMANDS

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
PCM-22	Slew Pump ON/OFF	OFF	Circuit Malfunction	Pump Stops	PCM hydraulic flow capability is reduced	NSD (Normal Shut Down)	Pump failed alarm	III	
PCM-23	Charge Pump ON/OFF	OFF	" "	" "	"	"	Main Accum. Alarm	III	
PWR-29	Aux Power Disable ON/OFF	OFF	" "	Loose power to Emergency feather valves	Blades Feather	ESD	Valves are "dead man" connected	III	See Figure 9
DRT-23	Oil Lube Pump ON/OFF	OFF	" "	Pump stops	Loss of lube oil flow	NSD	Flow is measured	III	
ENV-13	Security alarm ON/OFF	OFF	" "	No alarm and message if breakin	Vulnerable to Breakin	NONE	NONE	III	
YAW-17	YAW Pump ON/OFF	OFF	" "	Pump stops	Yaw stops	NSD	Pump failed alarm	III	

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: GMU RACK
SUBASSEMBLY: G-DIP

DATE: Maly 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

DIGITAL SENSORS & CKTS

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
SENSORS & THEIR CIRCUITS	Provide sensor signals to multiplier	Any failure which indicates WTG failure	Circuit malfunction	False indication of failure	Shutdown	NONE	Software Processing	III	
PWR-17	XFMR Temp Alarm	OFF	" "	NONE	NONE	NONE	NONE	III	
PWR-18	XFMR Oil level alarm	OFF	" "	"	"	"	"	III	
PWR-19	XFMR Ground Current Alarm	OFF	" "	"	"	"	"	III	
PWR-20	Main Breaker Position	Either way	Short or open ckt	"	Shutdown	NONE	Software Processing	III	All combinations are continuously monitored
PWR-32	Battery low voltage alarm	Normal voltage	Circuit malfunction	"	"	NONE	NONE	III	Note 1
PWR-41	Main Breaker Lockout	Not locked out	" "	Computer does not detect lockout	Allows system startup	Main Breaker will not respond to command	NONE	III	Hourly message will indicate repeated startup attempts
ENV-12 & ENV-19	Encl. Door Alarms	OFF	" "	No alarm & message if breakin	Vulnerable to breakin	NONE	NONE	III	
PCM-24	Slew Pump ON/OFF	OFF	" "	NONE	NONE	ESD	Software Processing	III	All combinations with pump failed alarm are continuously monitored
YAW-18	Yaw Pump ON/OFF	OFF	" "	NONE	NONE	NSD	Software Processing	III	"
ENV-14	Entrance Alarm ON/OFF	OFF	" "	No alarm and message if breakin	Vulnerable to breakin	NONE	NONE	III	
ENV-15	Lift Interlock	WTG Enabled	" "	Can use lift	Operation is not inhibited. Potential safety hazard	Procedure requires reading message on DEC writer to verify shutdown.	NONE	III	2nd FAILURE or one procedural failure causes safety hazard.

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: CONTROLS (2.5)
COMPONENT: GMU RACK
SUBASSEMBLY: GCE

DATE: May 1978
PREPARED BY: R.T. Hedges

SEE FIGURE 9

ANALOG SENSORS: The following failures could occur either in the sensor itself or in signal conditioning or test logic circuitry

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PWR-07 PWR-08 PWR-09 PWR-10 PWR-11 PWR-12 PWR-13 PWR-16 PWR-22 DRT-05	Gen. Current ØA " " ØB " " ØC " Volt ØA - ØB " PWR KW " " KVAR Utility Volt. ØA -ØB " Freq. Exciter Fld Curr. Rotor Shaft Spd.	Any failure which indicates WTG failure	Sensor or circuit malfunction	False indication of failure	Shutdown	NONE	Software Processing	III	
PWR-10	Gen. Volt ØA - ØB	Wrong Value	Circuit Malfunction	Exciter voltage set wrong	Δ V between gen. and utility too large at synchronization	NONE	NONE	III	Max. effective control range is ± 10%
PWR-11	Gen. Power KW	Wrong Value	Circuit Malfunction	NONE	NONE	Shutdown	Compared with nacelle power sensor	III	
PWR-13	Utility Voltage ØA - ØB	Wrong value	Circuit Malfunction	Exciter voltage set wrong	Δ V between gen. and utility too large at synchronization	NONE	NONE	III	Max. effective control range is ± 10%
PWR-22	Exciter field current	Wrong value	Circuit Malfunction	NONE	NONE	Shutdown	Software Processing	III	
DRT-05	Rotor Shaft Speed	Wrong value	Circuit Malfunction	NONE	NONE	Shutdown	Compared with DRT-07	III	

DATE: May 1978
PREPARED BY: R. Cockfield

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: TOWER (3.0)
COMPONENT: STRUCTURE 848E834
SUBASSEMBLY:

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
PINTLE, JOINT 17 OR LEG, JOINT 1	Structural support	Fatigue cracks in weld	Cyclic loads were under estimated Undetected flaw	Degraded stiffness (after extensive cracking)	Excessive vibration (after extensive cracking)	• Calculated range stress is below AISC limits • Benefit of stress relief has not been accounted for • Weld area exceeds minimum required • Weld has passed MT and VT inspection • Loads are largely compressive (no crack growth likely)	Vibration Sensors (after extensive cracking)	III	Inspection and repair of large cracks during periodic maintenance Analysis based on tower finite element model and local hand calculations.
		Yielding of weld	(a) Unusual loads not anticipated (b) Transients during start-up and shut-down	Distortion of nacelle mounting (after extensive yielding)	Excessive vibration (after extensive distortion)	• Calculated stress is below 60% of yield • Weld area exceeds minimum required • Weld has passed MT and UT inspection • Truss structure provides redundant load paths	Vibration sensors (after extensive distortion)	III	Inspection during periodic maintenance.
BRACE, MEMBER 20 - 26	Structural support	Buckling	(a) Unusual loads not anticipated (b) Transients during start-up and shut-down (c) Ice shed from blade	Distortion of tower (after extensive buckling)	Excessive vibration (after extensive distortion)	• Calculated stress is below critical buckling • Truss structure provides redundant load paths • Rugged section is immune to all but massive ice projectile	Vibration sensors (after extensive distortion)	III	Inspection during periodic maintenance.

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

SUBSYSTEM: TOWER (3.1)
COMPONENT: LIFT DEVICE 273A6500
SUBASSEMBLY: ______

DATE: May 1978
PREPARED BY: R. Cockfield

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON		COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
				NEXT HIGHER ASSEMBLY	SYSTEM				
LIFT DEVICE	Transfer personnel & material to top of tower	Broken cable	(a) Overload (b) Stress corrosion (c) Fatigue (d) Vandalism (e) Wear (f) Wrong material	NONE	NONE. System can continue to operate with lift inoperative	(a) Factor of safety of 8 on each drive cable • Drive cables are redundant • Posted weight limit • Safety cable with factor of safety of six if both drive cables break • Small floor area limits inadvertant overload • Check out by Mfg. prior to use (b) Cables are stainless steel aircraft type Periodic inspection & lubrication (c) Low stress, low no. of cycles in 30 yrs. (d) Fenced area (e) No rubbing loads Smooth surfaces at all contacts (f) Material certs available	Loss of tension switch Over-tension switch	III	Loss of tension in cable will cause power to be cut to both motors in down direction and will apply brakes. Tension exceeding 125% of normal will cut power to both motors in up direction See Note 1

SUBSYSTEM: TOWER (3.1)
COMPONENT: LIFT DEVICE 273A6500
SUBASSEMBLY:

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: R. Cockfield

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
LIFT DEVICE		Fracture of anchor points for cables	(a) Overload (b) Fatigue (c) Vandalism (d) Improper material or installation	NONE	NONE. System can continue to operate with lift inoperative.	(a) See (a) above (b) Low stress, low no. of cycles in 30 yrs. (c) Fenced area, critical anchor points are at top of tower & not accessible (d) Check out by Mfg prior to use	Loss of tension switch Overtension switch	III	Periodic inspection will include anchor bolts & support structure
		Slipping of drive	(a) Mechanical failure of drive mechanism (b) Failure of cable termination on drive drum (c) Brake failure (d) Icing	NONE		Grip will engage on safety cable	Loss of tension	III	Brake force is sufficient to break or melt ice on cable
		Loss of electrical power	(a) Electrical short (b) Loss of Utility power (c) Overtension of power cable (d) Relay, switch or component failure	NONE	NONE	• Power supply on independent circuit • Fused terminal box located at ground level • Emergency descent with "Rescumatic" • All wiring is weathertight (NEMA type 4) • If cable is overtensioned, over-ride switch enables operation "Down" only	Overtension switch on power cable	III	
		Electrical short resulting in shock hazard	(a) Insulation failure (b) Component failure (c) Moisture in enclosures	NONE	NONE	• Power supply is fused • All structure grounded • Weathertight enclosures (NEMA type 4) • Check out by Mfg.		III	Check out of wiring will include ground resistance on all structure

SUBSYSTEM: TOWER (3.1)
COMPONENT: LIFT DEVICE 273A6500
SUBASSEMBLY:

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

DATE: May 1978
PREPARED BY: R. Cockfield

UNIT OR ASSEMBLY	FUNCTION	FAILURE MODE	PROBABLE CAUSE	FAILURE EFFECT ON: NEXT HIGHER ASSEMBLY	FAILURE EFFECT ON: SYSTEM	COMPENSATING PROVISIONS	FAILURE DETECTION METHOD	CRIT CAT.	REMARKS
LIFT DEVICE GATE	To keep personnel from falling through opening in railings	Gate open during operation	(a) Mechanical failure of gate or hinges (b) Latch not secure (c) Intentional disabling of safety switch & opening of gate	NONE	NONE	(a) Gate is rugged construction (b) Gate opens inward only. • Gate is self-closing & self-latching • Latch requires positive, double motion to unlatch; cannot be unlatched inadvertantly • Switch on gate enables power only when closed* (c) Requires double failure or double overt action	Gate open switch	III	
RAILING	To keep personnel from falling from lift or tower	Structural failure of rails or attachments	(a) Overload (b) Improper material or installation	NONE	NONE	(a) No. of people in lift is limited by available floor area as well as posted limit. Construction of railings is to OSHA standards (b) Checkout by manufacturer prior to operation Periodic inspection		I	Periodic inspection will include security of railings.

APPENDIX A - BLADE

Unbalance Loads after Blade Separation

Interface Ring Flange

Test Program

Quality Program

I-1 UNBALANCED LOADS AFTER BLADE SEPARATION

A loads analysis was performed to determine the loads on the major items of structure resulting from the loss of a blade. These loads are presented on Table I-1. For comparison purposes, the maximum infrequent loading condition of emergency feather - 15% overspeed is presented. Effects on major items are:

The remaining blade has loads imposed which are within its capacity and should suffer no damage.

The blade retention bearing in the hub also will be subjected to loads which are within its capacity and will suffer no degradation.

The hub bearing on the bedplate side will be subjected to loads which are substantially higher than the emergency feather condition. The bearing has the capacity to carry these loads for the few cycles they will be imposed with a small reduction in life.

The bedplate will experience local yielding but no failure due to loads somewhat in excess of design values.

The yaw bearing will be subjected to bending moments which approach the maximum moment capability of the bearing. For the few cycles this loading occurs, there should be no damage to the rollers or races. The yaw brake, however, will slip due to the high yawing moment.

The tower base will experience overturning bending moments approaching 50×10^6 ft-lbs. This will result in local yielding of some of the tower secondary members; however, the 4 corner legs have the inherent stability in buckling and as a column to carry the higher loads.

I-2 BLADE INTERFACE RING FLANGE

A three-dimensional finite element stress was performed for the WTG blade ring adapter (Boeing DWG #276-10509, Rev. B, 5/11/78, transmitted via Datafax). It was performed to verify the design and analysis submitted by Boeing.

The ring adapter was analyzed using the latest worst case loads for both fatigue conditions and emergency feather conditions. The equivalent axial load at the blade attachment section was 1,404,000 pounds (7,152 psi) for the fatigue case, and 4,379,130 pounds (22,310 psi) for the emergency feather case. The bolt preload was given as 110,340 pounds (-31,022 psi).

RESULTS

As expected, the peak stresses in each case occurred at the root of the elliptical transition section on the outer surface of the ring, immediately adjacent to the bolt head location. For the fatigue case, the peak principal tensile (cyclic) stress was found to be 20,200 psi. For the emergency feather case, the peak principal tensile stress was found to be 50,000 psi. The margins of safety were found to be +.416 and +.26, respectively. Also, the preload applied by the attachment bolts was not exceeded.

ALLOWABLE STRESSES

The allowable stresses in the ring adapter material are given as

$MAX_{FATIGUE}$ = 28,600 psi [Ref: Blade Spec. 273A6684]

$MAX_{FEATHER}$ = 63,000 psi

MARGINS OF SAFETY

The margins of safety were determined using the peak stresses obtained from the finite element run.

For the fatigue case: $M.S. = \frac{28,600}{20,200} - 1 = .42$

For the emergency feather case: $M.S. = \frac{63,000}{50,000} - 1 = +.26$

ANALYSIS

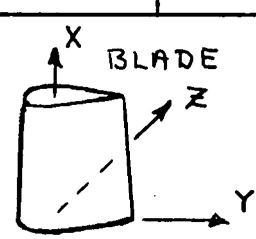
A sketch showing the modelling approach is presented on Figure I-2.

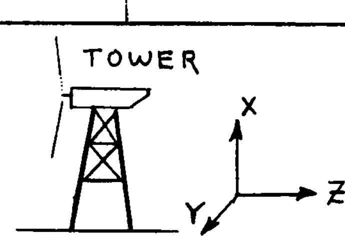
The stress distribution within the WTG blade ring adapter was determined by using the finite element method, due to the non-uniform geometry of the ring cross-section. The SAP V finite element computer program was used for the actual numerical determination. This code was developed at the University of California, Berkeley, and is well documented and accepted throughout the technical community. Using the initial geometry of Figure I-2, a three-dimensional finite element model was developed for the 1/112 section. This model consisted of 765 elements and 1185 nodes.

Table I-1
DYNAMIC & GRAVITY LOADS

LOAD (LBS FOR SHEAR, FT-LBS FOR MOMENT)		Two Blades, 50 MPH 40.25 RPM REV F BLADE: MEAN	Two Blades, 50 MPH 40.25 RPM REV F BLADE: CYCLIC (+)	One Blade, 35 MPH 35 RPM REV E BLADE: MEAN	One Blade, 35 MPH 35 RPM REV E BLADE: CYCLIC (+)
BLADE RET BRNG (BLADE SIDE)*	V_X	396,130	7,518	293,050	26,138
	V_Y	-25,435	18,956	-12,830	19,434
	V_Z	65,021	22,400	31,943	12,154
	M_X	5,968	17,769	8,399	16,195
	M_Y	-3,107,330	1,021,300	-1,485,420	523,030
	M_Z	-1,043,770	792,160	-59,430	733,800
BLADE RET BRNG (HUB SIDE)+	V_X	396,130	7,518	293,050	26,138
	V_Y	-2,576	20,684	-5,884	19,693
	V_Z	69,130	23,843	32,522	12,810
	M_X	5,968	17,769	8,399	16,195
	M_Y	3,207,870	1,126,200	-1,556,400	670,340
	M_Z	10,940	869,910	-141,498	604,410
HUB BRNG (HUB SIDE)+	V_X	-52	66,225	276,610	833,230
	V_Y	35	86,466	6,846	69,698
	V_Z	-2,359	18,680	-13,432	10,363
	M_X	106	606,630	-50,535	266,490
	M_Y	2,639	2,339,700	-3,187,200	769,480
	M_Z	66,386	184,210	-194,540	628,260
HUB BRNG (B/P SIDE SIDE)**	V_X	-91,795	13,970	-66,665	52,678
	V_Y	-5,286	21,627	-4,333	156,720
	V_Z	-2,359	18,680	-13,432	10,363
	M_X	82,336	507,490	-3,964	2,167,700
	M_Y	1,311,000	1,051,600	749,170	1,933,900
	M_Z	66,386	184,210	-194,540	628,260
YAW BRNG**	V_X	-339,830	17,162	-318,650	219,810
	V_Y	18,220	60,879	-8,156	268,110
	V_Z	-6,105	34,807	-13,586	57,064
	M_X	-5,369	636,680	57,842	5,285,900
	M_Y	842,030	947,600	103,970	2,210,700
	M_Z	-35,132	454,260	-326,310	1,351,600
TOWER BASE**	V_X	-680,180	22,181	-662,290	382,840
	V_Y	-23,166	80,510	-1,227	348,320
	V_Z	-6,779	45,747	-9,793	71,981
	M_X	-4,539	807,110	143,550	6,073,900
	M_Y	1,168,500	5,539,300	2,305,400	5,279,500
	M_Z	-3,149,500	10,766,000	-797,300	47,697,000

*Ref. to blade angle @ 3/4 R
+Blade coord (rotating)
**Tower coord (stationary)





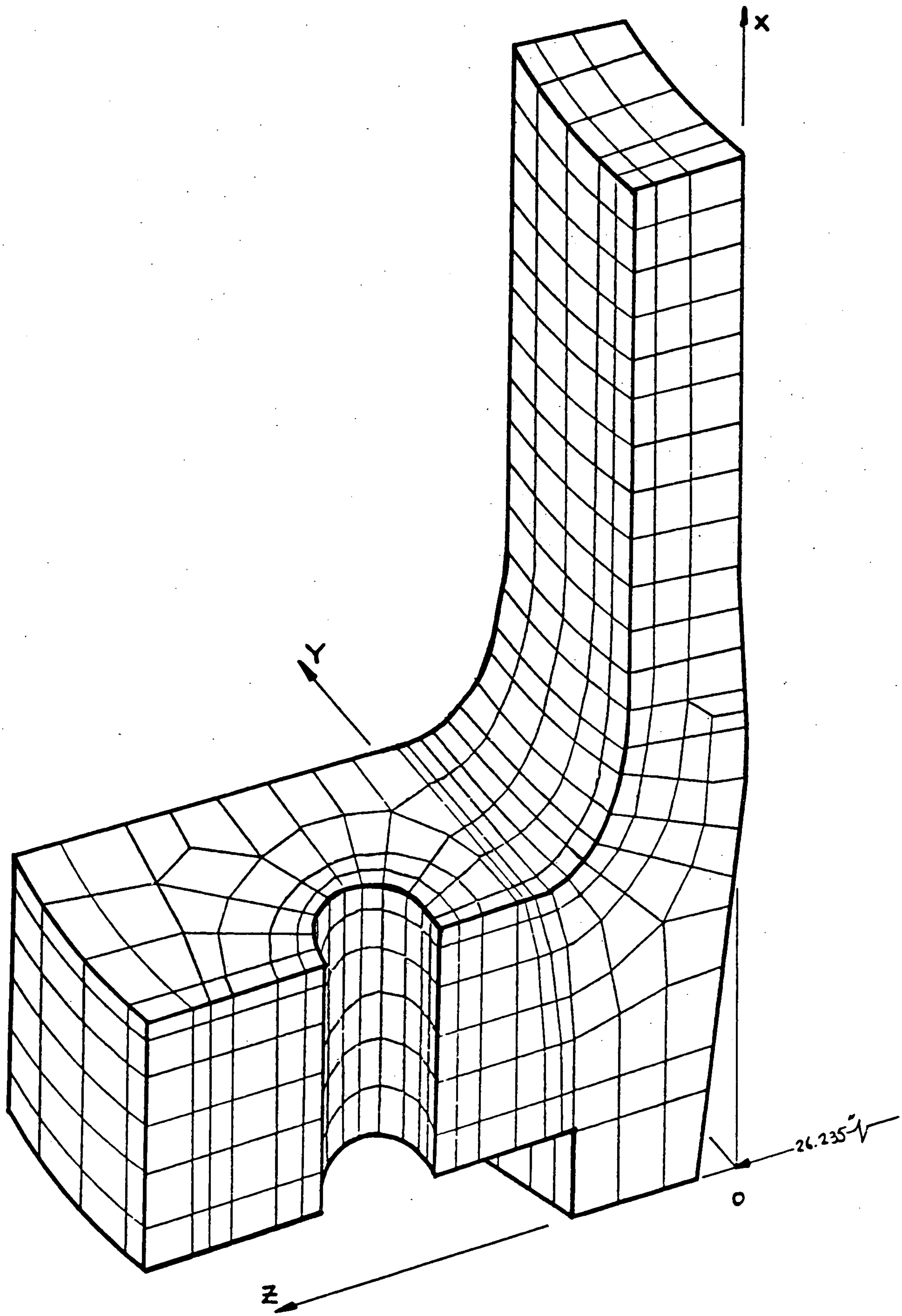


Figure I-2. Model Geometry and Coordinate System

I-3 BLADE TEST PROGRAM

Three areas of testing have been planned for the Mod-1 blade. To verify design assumptions or to demonstrate specification compliance:

1) ENGINEERING DEVELOPMENT TESTS

   Tests performed on sub-element structures to obtain early indication of design adequacy.

2) BLADE DEVELOPMENT TESTS

   Tests performed on full-scale portions of the blade to ascertain structural adequacy. In most cases, the test data from these tests will be available after the final design is complete.

3) BLADE TESTS

   Tests which will be performed on the completed blade to determine dynamic characteristics or basic property data such as elastic axis location, static moment, chordwise c.g. locations, and stress and deflection data vs. load.

A summary of the tests in each of the above categories follows in Table I-3, I-4 and I-5.

TABLE I-3 ENGINEERING DEVELOPMENT TESTS

TESTS	CONFIGURATION	NO.	TYPE TEST	CONDITIONS	DURATION	COMMENTS
T.E./SPAR ATTACH. INBD SPECIMEN	STA. 212 (2' long 1' wide 3" thick)	1	STATIC	AMBIENT	1 TEST CYCLE	STATIC TEST OF ATTACH. DESIGN
OUTBD SPECIMEN	STA. 844 (10" long 6" wide 1" thick)	1	DYNAMIC	TEMP: $-31^{o}F$ to $140^{o}F$ HUM: 10% to 100%	5×10^7	FATIGUE TEST OF ATTACH. DESIGN.
SUB-ELEMENT T.E. JOINT SPECIMENS	LAP SHEAR	20	STATIC	10 AMBIENT 10 R.T. & $140^{o}F$		TO OBTAIN DATA ON ADHESIVE STRENGTH OF BONDED JOINT DESIGN
		3	DYNAMIC	TEMP. & HUM. CYCLED	5×10^7	

TABLE I-4 BLADE DEVELOPMENT TESTS

TEST	CONFIGURATION	NO.	TYPE TEST	CONDITIONS	EXPECTED DURATION	COMMENTS
STATIC TEST [1.7.3]	16' SECTION OF SPAR BETWEEN STA. 388 & STA. 580	1	STATIC	EMERGENCY FEATHER LOAD COND. AMB. ENVIRONMENT	100% D.L.L (INCL. 1.15 COMPRESSIVE BUCKLING FACTOR)	TO ESTABLISH VALIDITY OF COMP. BUCK-LING ANAL. OF LOWER CAMBER.
FATIGUE STRENGTH OF WELDS [1.7.4]	6 COUPONS CUT FROM A SECTION OF BLADE THRU WELDS FABRICATED BY APPROVED PROCEDURES	6	FATIGUE	AMBIENT (R.T.)	VARIABLE DEPENDING UPON IMPOSED STRESS LEVEL 1×10^8 CYCLES MAX	TO ESTABLISH VALIDITY OF WELD JOINT FATIGUE ALLOWABLES
FATIGUE STRENGTH OF BONDED T.E./SPAR JOINT [1.7.5]	6 FT. SPANWISE LENGTH OF TRAILING EDGE. CONFIG. PER BLADE STA. 1000.	1	FATIGUE	35 MPH FATIGUE LOADING COND. ENVIRONMENTAL CONDITIONS	50×10^6 CYCLES	WILL BE LOADED TO SIMULATE MAX. BLADE BOND STRESS

TABLE I-5 BLADE TESTS

TEST	OBJECTIVE	BLADE SPEC 273A6684 REQUIREMENT	COMMENTS
• WT. & BALANCE INCLUDING SPANWISE STATIC MOMENT	DETERMINE EA. BLADE TOT. WT. & C.G. LOC.	3.14.1	THIS TEST WILL DETERMINE TIP WT. BALANCE REQUIREMENTS
• CHORDWISE C.G. LOCATION	DETERMINE OVERALL BLADE CHORDWISE C.G. LOCATION	3.14.1	THIS TEST WILL LOCATE THE CHORDWISE C.G. LOCATION. IF IT IS WITHIN SPEC., IT WILL PRECLUDE CERTAIN DYNAMIC INSTABILITY
• ELASTIC AXIS DETERMINATION	DETERMINE BLADE ELASTIC AXIS	3.14.3	ALSO REQUIRED TO JUSTIFY DYNAMIC STABILITY
• STATIC LOAD TESTS	TO LOAD A CANTILEVERED BLADE WITH A REPRESENTATIVE AIR LOAD, RUN AN ATLAS ANALYSIS OF THIS CONDITION AND COMPARE ANAL. RESULTS WITH MEASURED DATA.	3.14.3 & 3.14.4	THIS TEST WILL VERIFY THE OVERALL BLADE ATLAS ANALYSIS AND MODELLING TECHNIQUE. THIS TEST CAN ALSO BE USED TO CALIBRATE THE STRAIN GAGES
• DYNAMIC TESTS MODE SHAPES FUNDAMENTAL FREQUENCIES STRUCTURAL DAMPING	DETERMINE BLADE DYNAMIC CHARACTERISTICS	3.14.2	VERIFY ADEQUACY OF DYNAMIC ANAL. OF THE BLADE AND THE OVERALL WTG EFFECTS

I-4 QUALITY PROGRAM

The blade Quality Program is summarized on Table I-6. The trailing edge portion of the blade is, at this writing, just completing the development phase. Consequently, the Quality Control plans for it are preliminary and subject to change.

TABLE I-6 BLADE QUALITY PROGRAM

BLADE ITEM	CRITICAL PARAMETERS	ACCEPTANCE CRITERIA	INSPECTIONS PERFORMED & SPECIFIC CONTROLS
LOWER CHORD WELDS, LEADING EDGE WELD, TRAILING EDGE OUTBOARD OF ST. 301 BULKHEAD WELD TRANSITION CHORD WELD TRANSITION SPAN WELD TRANSITION LEADING EDGE WELD TIP SECTION WELD	DIMENSIONAL, ALIGNMENT PROCESS, OPERATOR, MATERIAL, INSPECTION CAPABILITY, REPAIR PROCEDURE	DIMENSIONAL ALIGNMENT TO DWG. REQ'TS FLAW CRITERIA-UNACCEPTABLE: 1. Any crack or zone of incomplete fusion or penetration 2. Any indication, elongated or rounded with a length > .125 in. 3. Any group of indications in line that have an aggregate length > 3/8 in. in a length of 4-1/2" except where distance between the successive indications exceeds 6L, where L = longest indication in the group 4. Rounded indications whose total area exceeds .03 $\overline{IN}^2$ in 6 linear inches of weld.	SPAR WELD JIG CONTROLS CONTOUR & ALIGNMENT, GO-NO-GO GAGES FOR DIMENSIONAL INSPECTION, WELDING BY CERTIFIED OPERATORS & PROCESSES, WELDS INSPECTED VISUALLY - D276-10503-1 DYE PENETRANT - D276-10504-1 ULTRASONIC - D276-10502-1 RADIOGRAPHIC - D276-10505-1 WELD STRAIGHTENING & REPAIR TO PROVEN PROCEDURES FLAME STRAIGHTENING D277-10086-1 WELD REPAIR D277-10087-1 POST WELD HEAT TREATMENT D277-10086-1
TRAILING EDGE ASSEMBLY UPPER AND LOWER SKINS FOAM SECTIONS	BONDING QUALITY - FOAM TO FOAM, FOAM TO STEEL AND STEEL TO STEEL	TOTAL BONDED AREA $\geqq$ 80% LOCAL VOIDS $\leqq$ TBD	PRELIMINARY PLAN IS TO USE ULTRASONIC INSPECTION TECHNIQUE FOR VOID DETECTION. PROCESS CONTROLS INCLUDE CONTROL OF: POT LIFE SHELF LIFE DIMENSIONAL STABILIZATION (200°F FOR 24 HRS.) DIMENSIONAL CONFIGURATION CONTROL (FIXTURES)
BLADE ASSEMBLY SPLICE PLATES	DIMENSIONAL BONDING QUALITY-STEEL TO STEEL	DWG. 132D6479 SPECIFICATION 273A6684 BLADE ACCEPTANCE TESTS	VISUAL, DIMENSIONAL INSPECTION USING GAGES, ULTRASONIC INSPECTION FOR SPLICE PLATE BOND INTEGRITY. QUALITY VERIFICATION OF ACCEPTANCE TEST RESULTS & LOGBOOK

TABLE I-6 BLADE QUALITY PROGRAM

BLADE ITEM	CRITICAL PARAMETERS	ACCEPTANCE CRITERIA	INSPECTIONS PERFORMED & SPECIFIC CONTROLS
SPAR			
A533 STEEL (LUKENS FINELINE)	CHEMICAL & MECHANICAL CHARACTERISTICS	PER ASTM A533, GR. B CLASS 2 SUPPLEMENTAL REQUIREMENTS PER ASTM-A20 S-14 BEND TESTS S-5 CHARPY V NOTCH, 20 FT-LBS AT -10°F S-12 ULTRASONIC INSPECTION (STRAIGHT BEAM) PER ASTM A578	
RING FORGING TO ASTM-A508, CL. 4B		CHEMICAL ANALYSIS, GRAIN SIZE PER ASTM A508, MAGNETIC PARTICLE PER ASTM-A275, ULTRASONIC INSP. PER BAC5439, Cl.A & ASTM A388, CHARPY V-NOTCH (20 FT-LBS @ -10°F) ULTIMATE & YIELD STRENGTH	
WELD MATERIAL	CHEMICAL & MECHANICAL PROPERTIES		CHEMICAL & PHYSICAL TESTS ON EACH LOT ORDERED. WELDING MATERIAL STORAGE & HANDLING TO D277-10089-1
SPAR FORMING & TRANSITION FORMING	DIMENSIONAL, INDUCED FLAWS & CRACKS		FORMING USING BOEING SUPPLIED TEMPLATES DIMENSIONAL USING TEMPLATES VISUAL INSPECTION & DYE PENETRANT INSPECTION PER D276-10504-1
UPPER CHORD WELDS, TRAILING EDGE WELD INBOARD ST. 301, TRANSITION TRAILING EDGE WELD, RING ADAPTER/TRANSITION WELD, SPAR TO TRANSITION WELD	DIMENSIONAL, ALIGNMENT, PROCESS, OPERATOR, MATERIAL, INSPECTION CAPABILITY, REPAIR PROCEDURE	DIMENSIONAL & ALIGNMENT TO DRAWING REQUIREMENTS FLAW CRITERIA-UNACCEPTABLE: 1. Any crack or zone of incomplete fusion or penetration; 2. Any indication, elongated or rounded with a length .125 in.; 3. Any group of indications in line that have an aggregate length > 3/8 in. in a length of 4-1/2 except where distance between the successive indications exceeds 6L, where L = longest indication in the group; 4. Rounded indications whose total area exceeds .03IN² in 6 linear inches of weld.	SPAR WELD JIG CONTROLS CONTOUR & ALIGNMENT, GO-NO-GO GAGES FOR DIMENSIONAL INSPECTION, WELDING BY CERTIFIED OPERATORS & PROCESSES, WELDS INSPECTED VISUALLY - D276-10503-1 DYE PENETRANT - D276-10504-1 ULTRASONIC - D276-10502-1 RADIOGRAPHIC - D276-10505-1 WELD STRAIGHTENING & REPAIR TO PROVEN PROCEDURES FLAME STRAIGHTENING D277-10086-1 WELD REPAIR D277-10087-1 POST WELD HEAT TREATMENT D277-10086-1 WELD MATERIAL CONTROL D277-10086-1 D277-10089-1

APPENDIX B

ROTOR OVERSPEED

ROTOR OVERSPEED

One of the more serious failure scenarios on a wind turbine is rotor overspeed. If permitted to "run-away", blade separation due to large rotor centrifugal stress is a probable final result. The MOD-1 pitch control system is the mechanism whereby overspeed is controlled, with redundant stored energy and redundant deadman control valve elements built into the system.

The maximum rotational speed of the rotor is a function of rotor inertia, accelerating torque due to loss of load and wind increases, a time delay from the start of acceleration to initiation of blade pitch motion towards feather, and the torque rate of change with time, which is a function of pitch rate. In order to simplify the following analysis, step changes in wind velocity over the entire rotor disc were assumed, a condition not reasonably occurring in nature. Acceptable response to these step inputs will indicate better than acceptable response to realistic wind perturbations.

Values utilized in the analysis are:

Inertia of rotating system	2.1×10^6 lb-ft-sec^2
Rated torque (2160 KW, 34.7 RPM)	4.4×10^5 ft-lb (100%)
Nominal control delay	0.2 sec
Maximum blade rate	14 deg/sec
Maximum torque rate	150% /sec at 14 deg/sec

Wind steps considered and their torque effects are:

1.0 to 1.4 normalized velocity = 100% to 235% normalized torque
1.0 to 1.8 normalized velocity = 100% to 376% normalized torque

The torque increase does not follow a wind velocity cubic due to assuming initial conditions just at rated wind velocity near the peak power coefficient value. Any wind increase thus is effective at a reduced power or torque coefficient value. A linear torque-pitch relationship, no compensation for torque change with rotor speed, and no losses are assumed. The combined effect of these assumptions is believed to balance out as the second and third assumptions are conservative, while the first is not conservative.

Four scenarios, as follows, describe a range of increasingly severe accelerating torque conditions. Loss of load is considered to be a "normal" design event as the main circuit breaker can be tripped open due to a variety of electrical anomolies.

Case 1	loss of 40% load	No Gust
Case 2	loss of 100% load	No Gust
Case 3	loss of 100% load	1.4 Gust
Case 4	loss of 100% load	1.8 Gust

Response was computed on the basis of a normal control system de-energization of the feather solenoid valves, permitting the fluid in the feather accumulators to discharge into the blade actuators towards feather through a programmed flow valve. This valve has the characteristics and adjustability shown in Figure 1.

A nominal program for the flow valve has been selected with the dual goals of limiting peak speed in a significant upgust wind and also limiting blade loading in decelerating torque conditions. The initial rate is at a blade equivalent of 14 deg/sec for 0.8 seconds, followed by a linear decrease to 4.4 deg/sec over the next 1.6 seconds, then maintained at 4.4 deg/sec. Starting from 0.0 degrees, this schedule reaches 90.0 degrees feather in 17 seconds, with 25 degrees change in the first 2.5 seconds. The flow program is field modifiable for rate change, final rate, and time at maximum rate.

Results, with 0.2 second nominal control delay and activation of the feather system due to either high wind, breaker opening, large yaw error, or vibration are as follows:

Case	1	2	3	4
Max. spd % over 100%	.77	3.08	10.71	22.7
Time at max sec	.47	.87	1.25	1.72

Hybrid runs of cases analogous to the above cases 2 and 4 were made during the course of system design simulation. The control algorithm was to shift to speed control at rated speed reference with no delay. On 100% load loss, 2.2% overspeed occurred and with a 1.8 gust, 11% overspeed occurred. Pitch angle response started at the maximum rate near 14 deg/sec and maintained a higher rate than the programmed valve, due to the speed control loop gain. These two cases are shown in Figures 2 and 3.

If a control system failure prevents initiation of the feather system at rated rotor speed, software and hardware switch actuation of the feather valves are provided as backup. Present settings for the software and hardware overspeed switches are 5% and 10% respectively. These speeds are additive to the response values and in the case of the realistic 1.4 wind gust, result in 15.7 to 20.7% overspeed. Resetting of these switches to 3 and 6% respectively is recommended to reduce maximum speed, providing adequate separation from startup variation, overshoot and switch tolerance bands can be maintained. The lower settings would result in 13.7 or 16.7% overspeed for software and hardware initiated feather with the nominal valve program and a Case 3 scenario.

To summarize, maximum rotor overspeed is expected to be less than 5% (3.08 % calculated) on loss of load and less than 20% on loss of load plus a sustained 1.4 upgust plus a primary control input or output failure requiring use of the hardware backup overspeed circuit. These values are acceptable for a rotor and blade system with positive stress margin at a rotor speed above 20% overspeed. The MOD-1 blade has positive margin near 20% overspeed.

Figure B-1

Programmed Flow Valve Characteristics

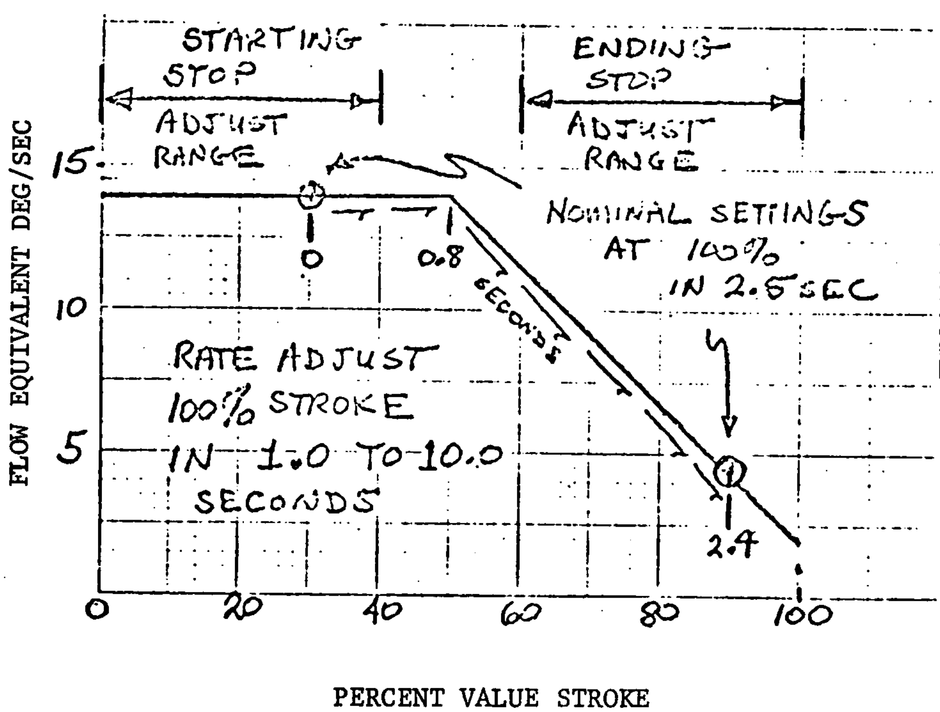
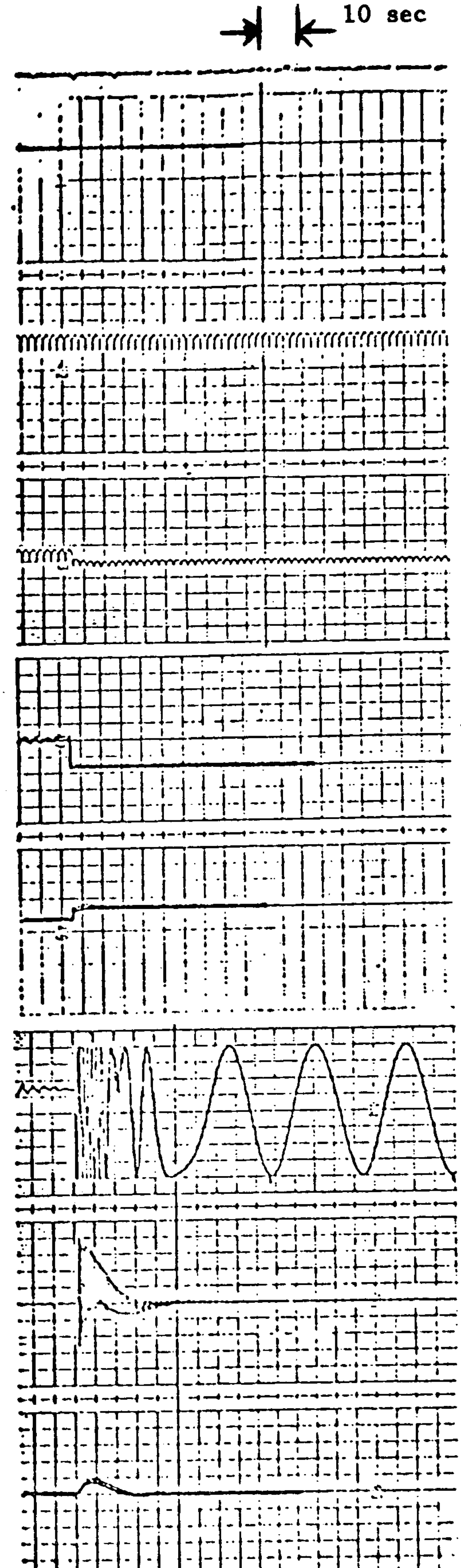


Figure B-2

VARIABLE	FULL SCALE UNITS
WIND AT 1.2 sec AHEAD	0 ± 125 FPS
BLADE #1 WIND	0 ± 125 FPS
BLADE #1 TORQUE	0 ± 1,250,000 ft-lb
GENERATOR POWER	.8 ± 2.5 pu
PITCH ANGLE	0 ± 50 deg.
COS POWER ANGLE	0 ± 1.25
GENERATOR SPEED	1800 ± 119 rpm
ROTOR SPEED	34.7 ± 4.8 rpm

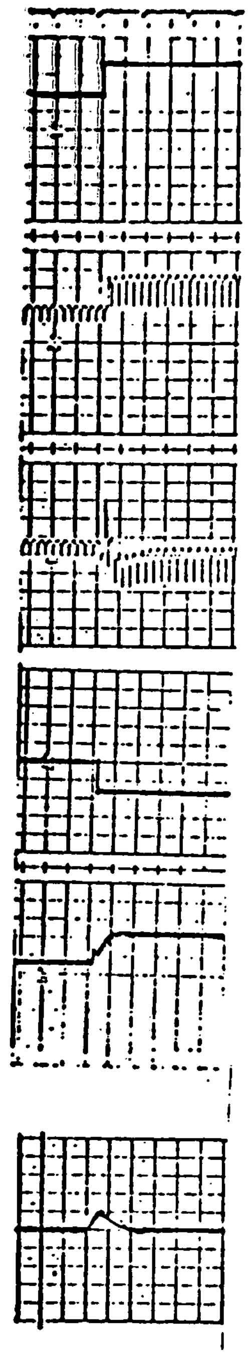


.77 rpm

= 2.2% overshoot

Figure B-3

VARIABLE	FULL SCALE UNITS	
WIND AT 1.2 sec AHEAD	0 ± 125 FPS	1.5 GUST
BLADE #1 WIND	0 ± 125 FPS	
BLADE #1 TORQUE	0 ± 1,250,000 ft-lb	
GENERATOR POWER	.8 ± 2.5 pu	
PITCH ANGLE	0 ± 50 deg.	6^o to 22^o
ROTOR SPEED	34.7 ± 24 rpm	3.84 rpm = 11% overshoot



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15. Supplementary Notes

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Project Manager, R. Puthoff
NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

A Failure Modes and Effects Analysis (FMEA) was performed for the Mod 1 Wind Turbine Generator. The analysis was directed primarily at identifying those critical failure modes that would be hazardous to life or would result in major damage to the system. Each subsystem was approached from the top down, and broken down to successive Lower Levels where it appeared that the criticality of the failure mode warranted more detail analysis. The results were reviewed by knowlegeable specialists from outside the Mod 1 program, and corrective action taken wherever recommended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind turbine generator; failure modes, Mod 1 WTG	Unclassified - unlimited STAR Category 44 DOE Category UC-60

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