ENGINEERING OPERATIONS REPORT

TURBOPUMP RELIABILITY
BLOCK DIAGRAM AND FAILURE MECHANISM DEFINITION

PROJECT 121
24 FEBRUARY 1972

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MASTER

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LIST OF REFERENCES

- (a) Letter N2200:497L, "Response to Technical Directive 72-1, Action Item 9", G. F. Mader to R. W. Schroeder, dated 11 January 1972

- (b) NERVA Engine Reliability Allocations, N8200:M3041, dated 4 August 1971

MASTER

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I. INTRODUCTION

In response to Item 5 of Reference (a), a reliability block diagram for the turbopump was developed which relates the engine failure modes to failure mechanisms; which are subsequently broken down to a part/mechanism relationship that is amenable to probabilistic analysis.

This report contains the results of this work.

II. DISCUSSION

The NERVA Engine Reliability allocations, Reference (b), identify six failure modes which are applicable to the turbopump.

1. Failure to Start
2. Low Performance
3. Premature Stop
4. Loss of Containment
5. Excessive Vibration
6. External Leakage

In accordance with Item 5 of Reference (a), these failure modes were used to generate a turbopump (TPA) reliability block diagram as shown in Appendix A. The block diagram was then broken down, in steps, until part/mechanism relationships were established which are amenable to probabilistic analysis.

Upon completion of the probabilistic analysis, for each part/mechanism relationship, the reliability values may be examined (probably a product relationship) to determine if the overall turbopump and the failure mode reliability allocations are satisfied.

II. (Continued)

Prior to completion of all of the models, the block diagram may be used as a device for allocating reliability requirements down to the part/mechanism relationship. This is simply done by first defining the failure mode reliability value, then summing the total number (n) of part/mechanism relationship for that mode and then taking the failure mode reliability allocation to the nth root. In other words:

$$\text{Part/Mechanism Allocation} = (\text{Failure Mode Allocation})^{1/n}$$

Appendix A contains the complete listing of part/mechanism relationships, including any applicable intermediate considerations.

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APPENDIX A

TPA RELIABILITY MODEL SUMMARY

FAILURE MODES	FAILURE MECHANISMS					
	HYDRODYNAMIC/AERODYNAMIC	MECHANICAL				
		HOUSING ASSEMBLY	ROTOR ASSEMBLY			BEARINGS, SEALS, CLEARANCE INTERFERENCE JOINTS INSTRUM.
FAILURE TO START $R_1 =$				EXCESSIVE BREAK AWAY TORQUE $R_{1.1} =$		
LOW PERFORMANCE $R_2 =$	SLOW TRANSIENT RESPONSE $R_{2.1} =$ LOW STEADY STATE EFFICIENCY $R_{2.2} =$					
PREMATURE STOP $R_3 =$		TRUNNION ASSEMBLY FRACTURE $R_{3.1} =$	INSUFF. AXIAL CLAMPING $R_{3.2} =$ BLADE FRACTURE $R_{3.3} =$ SHROUD FRACTURE $R_{3.4} =$ SPLINE FRACTURE $R_{3.5} =$ DRIVE BOLT FRACTURE $R_{3.6} =$			EXCESSIVE SHAFT MOVEMENT $R_{3.7} =$ LOSS OF CRITICAL CLEARANCE $R_{3.8} =$ IMPROPER OUTPUT $R_{3.9} =$
LOSS OF CONTAINMENT $R_4 =$		MEMBRANE RUPTURE $R_{4.1} =$ JOINT RUPTURE $R_{4.2} =$	BURST OF INDUCER $R_{4.3} =$ BURST OF SPINNER $R_{4.4} =$ BURST OF PUMP IMPELLERS $R_{4.5} =$ BURST OF TURBINE ROTORS $R_{4.6} =$			RUPTURE OF INTERFERENCE JOINTS $R_{4.7} =$
EXCESSIVE VIBRATION $R_5 =$	HYDRAULIC OSCILLATIONS $R_{5.1} =$		ROTOR INDUCED VIBRATIONS $R_{5.2} =$			
EXTERNAL LEAKAGE $R_6 =$		MEMBRANE CRACKS $R_{6.1} =$ SEALS LEAK $R_{6.2} =$		SEALS LEAK $R_{6.3} =$		

EXCESSIVE BREAKAWAY TORQUE

R1.1

- R1.1.1   Loss of Clearance
- R1.1.2   High Bearing Friction
- R1.1.3   Low Turbine Torque

EXCESSIVE BREAKAWAY TORQUE

LOSS OF CLEARANCE

R1.1.1

R1.1.1.1	Inducer Blade Tip Clearance
R1.1.1.2	First Impeller Shroud Labyrinth Clearance
R1.1.1.3	First Impeller Backface Labyrinth Clearance
R1.1.1.4	Pump End Bearing Aft Labyrinth Clearance
R1.1.1.5	Second Impeller Shroud Labyrinth Clearance
R1.1.1.6	Turbine End Bearing Forward Labyrinth Clearance
R1.1.1.7	Turbine End Bearing Aft Labyrinth Clearance
R1.1.1.8	First Stator Labyrinth Clearance
R1.1.1.9	First Rotor Labyrinth Clearance
R1.1.1.10	Second Stator Labyrinth Clearance
R1.1.1.11	Second Rotor Labyrinth Clearance
R1.1.1.12	Thrust Balancer Tip Land Clearance
R1.1.1.13	Thrust Balancer Hub Land Clearance
R1.1.1.14	Pump End Distance Detector Clearance
R1.1.1.15	Thrust Balancer Distance Detector Clearance
R1.1.1.16	Speed Pickup Clearance
R1.1.1.17	Radial Rotor Distance Detector Clearance
R1.1.1.18	Axial Rotor Distance Detector Clearance

EXCESSIVE BREAKAWAY TORQUE
HIGH BEARING FRICTION
R1.1.2

R1.1.2.1	Contamination
R1.1.2.2	Excessive Preload
R1.1.2.3	Excessive Loads Due to Cooldown
R1.1.2.4	Cage Binding Rolling Elements
R1.1.2.5	Space Welding
R1.1.2.6	High Coefficient of Friction
R1.1.2.7	Bearing Clearance

EXCESSIVE BREAKAWAY TORQUE
LOW TURBINE TORQUE
R1.1.3

- R1.1.3.1   Efficiency Effects
- R1.1.3.2   Flowrate Effects
- R1.1.3.3   Pump Windmilling Effects

SLOW TRANSIENT RESPONSE
R2.1

R2.1.1 By Pass Weight Flow Requirements

R2.1.2 Rotor Inertia Effects

SLOW TRANSIENT RESPONSE
R2.1
BYPASS WEIGHT FLOW REQUIREMENTS
R2.1.1

R2.1.1.1	Pump Efficiency
R2.1.1.2	Pump Head/Flow Characteristic
R2.1.1.3	Turbine Efficiency
R2.1.1.4	Turbine Weight Flow Characteristic

NOTE: ASSESSMENT OF CHARACTERISTICS FOR FULL OPERATING RANGE REQUIRED.

SLOW TRANSIENT RESPONSE

R2.1

ROTOR INERTIA EFFECTS

R2.1.2

R2.1.2.1	Rotor Inertia Value
R2.1.2.2	Thermal Transient Effects
R2.1.2.3	Clearance (Thrust Stability)

LOW STEADY STATE EFFICIENCY
R2.2

R2.2.1 By Pass Weight Flow Requirements at Steady State Point

LOW STEADY STATE EFFICIENCY
R2.2
BY PASS WEIGHT FLOW REQUIREMENTS AT STEADY STATE POINT
R2.2.1

R2.2.1.1	Pump Efficiency
R2.2.1.2	Pump Head/Flow Characteristic
R2.2.1.3	Turbine Efficiency
R2.2.1.4	Turbine Weight Flow Characteristic

TRUNNION ASSEMBLY FRACTURE

R3.1

- R.3.1.1 Line Rupture
- R3.1.2 Diagnostic Instrumentation
- R3.1.3 Flange (Seal) Leakage
- R3.1.4 Deflection Induced Rotor Rub

LINE RUPTURE

R3.1.1

- R3.1.1.1 Lug Failure
- R3.1.1.2 Bolt Failure
- R3.1.1.3 Weld Failure
- R3.1.1.4 Fastener Loosens

DIAGNOSTIC INSTRUMENTATION

R3.1.2

- R3.1.2.1 Excessive Lead Load
- R3.1.2.2 Excessive Housing Distortion, i.e. Loss of Proper Clearance
- R3.1.2.3 Excessive Connector Load

FLANGE SEAL

R3.1.3

- R3.1.3.1 Excessive Deflection
- R3.1.3.2 Fracture of Support

DEFLECTION INDUCED ROTOR HUB

R3.1.4

- R3.1.4.1 Excessive Deflection
- R3.1.4.2 Fracture of Support

INSUFFICIENT AXIAL CLAMPING

R3.2

- R.3.2.1 Spinner Tie Bolt Preload
- R3.2.2 Pump Impeller Tie Bolt Preload
- R3.2.3 Inducer to Impeller Tie Bolt Preload
- R.3.2.4 Turbine to 2nd Impeller Tie Bolt Preload
- R3.2.5 1st to 2nd Stage Turbine Rotor Tie Bolt Preload
- R3.2.6 Aft Bearing Cartridge Axial Clamping Assembly
- R3.2.7 Axial Distance Detector Clamping Assemblies

BLADE FRACTURE

R3.3

- R3.3.1 Inducer Blade Failure
- R3.3.2 First Impeller Blade Failure
- R3.3.3 Second Impeller Blade Failure
- R3.3.4 Crossover Vane Failure
- R3.3.5 Diffuser Vane Failure
- R3.3.6 First Stator Failure
- R3.3.7 First Rotor Blade Failure
- R3.3.8 Second Stator Failure
- R3.3.9 Second Rotor Blade Failure

BLADE FRACTURE
INDUCER BLADE FAILURE
R3.3.1

- R3.3.1.1 Excessive Blade Loading
- R3.3.1.2 Fatigue Failure of Blade

FIRST IMPELLER BLADE FAILURE
R.3.3.2

- R3.3.2.1 Excessive Blade Loading

SECOND IMPELLER BLADE FAILURE
R.3.3.3

- R.3.3.3.1 Excessive Blade Loading

CROSSOVER VANE FAILURE
R3.3.4

- R3.3.4.1 Excessive Blade Loading

DIFFUSER VANE FAILURE
R3.3.5

- R3.3.5.1 Excessive Blade Loading
- R3.3.5.2 Blade Fatigue Failure

FIRST STATOR FAILURE
R3.3.6

- R3.3.6.1 Excessive Blade Loading
- R3.3.6.2 Blade Fatigue Failure

BLADE FRACTURE

FIRST ROTOR BLADE FAILURE

R3.3.7

- R3.3.7.1 Excessive Blade Loading
- R3.3.7.2 Blade Fatigue Failure

SECOND STATOR BLADE FAILURE

R3.3.8

- R3.3.8.1 Excessive Blade Loading
- R3.3.8.2 Blade Fatigue Failure

SECOND ROTOR BLADE FAILURE

R3.3.9

- R3.3.9.1 Excessive Blade Loading
- R3.3.9.2 Blade Fatigue Failure

SHROUD FRACTURE

R3.4

- R3.4.1 First Impeller Shroud Fracture
- R3.4.2 Second Impeller Shroud Fracture
- R3.4.3 First Turbine Rotor Shroud Fracture
- R3.4.4 Second Turbine Rotor Shroud Fracture

FIRST IMPELLER

R3.4.1

- R3.4.1.1 Excessive Pressure Differential
- R3.4.1.2 Excessive Centrifugal Loading
- R3.4.1.3 Excessive Load Imposed by Blading

SECOND IMPELLER

R3.4.2

- R3.4.2.1 Excessive Pressure Differential
- R3.4.2.2 Excessive Centrifugal Loading
- R3.4.2.3 Excessive Load Imposed by Blading

FIRST TURBINE ROTOR

R3.4.3

- R3.4.3.1 Excessive Pressure Differential
- R3.4.3.2 Excessive Centrifugal Loading
- R3.4.3.3 Excessive Load Imposed by Blading

SECOND TURBINE ROTOR

R3.4.4

- R3.4.4.1 Excessive Pressure Differential
- R3.4.4.2 Excessive Centrifugal Loading
- R3.4.3.3 Excessive Load imposed by Blading

SPLINE FRACTURE

R3.5

- R3.5.1 First to Second Stage Impeller Spline Fracture
- R3.5.2 First Turbine Rotor to Second Impeller Spline Fracture

FIRST TO SECOND STAGE IMPELLER

R3.5.1

- R3.5.1.1 Shaft Failure
- R3.5.1.2 Tooth Shear
- R3.5.1.3 Compressive Failure of Spline Teeth
- R3.5.1.4 Tensile Failure of Internally Splined Part

FIRST TURBINE ROTOR TO SECOND IMPELLER

R3.5.2

- R3.5.2.1 Shaft Failure
- R3.5.2.2 Tooth Shear
- R3.5.2.3 Compressive Failure of Spline Teeth
- R3.5.2.4 Tensile Failure of Internally Splined Part

DRIVE BOLT FRACTURE

R3.6

- R3.6.1 Failure of Inducer Drive Bolts
- R3.6.2 Failure of Rotor Coupling Bolts

FAILURE OF INDUCER DRIVE BOLTS

R3.6.1

- R3.6.1.1 Bolt Shear Failure
- R3.6.1.2 Bolt Bearing Load Failure
- R3.6.1.3 Loss of Bolt Preload
- R3.6.1.4 Inadequate Bolt Strength

FAILURE OF ROTOR COUPLING BOLTS

R3.6.2

- R3.6.2.1 Bolt Shear Failure
- R3.6.2.2 Bolt Bearing Load Failure
- R3.6.2.3 Loss of Bolt Preload
- R3.6.2.4 Bolt Centrifugal Bending Effect
- R3.6.2.5 Bolt Unbalance Effect

EXCESSIVE SHAFT MOVEMENTS

R3.7

- R3.7.1 Excessive Unbalance
- R3.7.2 Critical Speed Effects
- R3.7.3 Excessive Bearing Clearance
- R3.7.4 Bearing Misalignment

EXCESSIVE UNBALANCE

R3.7.1

- R3.7.1.1 Misalignment of Rotating Elements
- R3.7.1.2 Loss of Pilot Fits
- R3.7.1.3 Loss of Tie Bolt Preload, Pump End
- R3.7.1.4 Loss of Tie Bolt Preload, Turbine End
- R3.7.1.5 Improper Final Assembly

CRITICAL SPEED EFFECTS

R3.7.2

- R3.7.2.1 Relationship of Critical Speed to Operating Speed
- R3.7.2.2 Rotor Assembly Response Characteristic

EXCESSIVE BEARING CLEARANCE

R3.7.3

- R3.7.3.1 Cartridge and Shaft Fit Effect
- R3.7.3.2 Bearing Wear Effect
- R3.7.3.3 Thermal Effects

BEARING MISALIGNMENT

R3.7.4

- R3.7.4.1 Pilot Eccentricity Effects
- R3.7.4.2 Improper Assembly Effects

LOSS OF CRITICAL CLEARANCE

R3.8

- R3.8.1 Inducer Blade Tip Clearance
- R3.8.2 First Impeller Shroud Labyrinth Clearance
- R3.8.3 First Impeller Backface Labyrinth Clearance
- R3.8.4 Pump End Bearing Aft Labyrinth Clearance
- R3.8.5 Second Impeller Shroud Labyrinth Clearance
- R3.8.6 Turbine End Bearing Forward Labyrinth Clearance
- R3.8.7 Turbine End Bearing Aft Labyrinth Clearance
- R3.8.8 First Stator Labyrinth Clearance
- R3.8.9 First Rotor Labyrinth Clearance
- R3.8.10 Second Stator Labyrinth Clearance
- R3.8.11 Second Rotor Labyrinth Clearance
- R3.8.12 Thrust Balancer Tip Land Clearance
- R3.8.13 Thrust Balancer Hub Land Clearance
- R3.8.14 Pump End Distance Detector Clearance
- R3.8.15 Thrust Balancer Distance Detector Clearance
- R3.8.16 Speed Pickup Clearance
- R3.8.17 Radial Rotor Distance Detector Clearance
- R3.8.18 Axial Rotor Distance Detector Clearance

IMPROPER INSTRUMENTATION OUTPUT

R3.9

- R3.9.1 Temperature Detector Failure
- R3.9.2 Speed Pickup Failure
- R3.9.3 Distance Detector Failure

TEMPERATURE DETECTOR FAILURE

R3.9.1

- R3.9.1.1 Loss of Required Clearance
- R3.9.1.2 Transducer Failure
- R3.9.1.3 Connector Failure
- R3.9.1.4 Lead Failure

LOSS OF REQUIRED CLEARANCE

R3.9.1.1

- R3.9.1.1.1 Probe Retainer Failure
- R3.9.1.1.2 Incorrect Assembly

TRANSDUCER FAILURE

R3.9.1.2

- R3.9.1.2.1 Casing Failure
- R3.9.1.2.2 Thermal Incompatibility
- R3.9.1.2.3 Element (Electronic) Failure
- R3.9.1.2.4 Mechanical Failure

CONNECTOR FAILURE

R3.9.1.3

- R3.9.1.3.1 Pin Failure
- R3.9.1.3.2 Solder Joint Failure
- R3.9.1.3.3 Retainer Feature Failure

LEAD FAILURE

R3.9.1.4

- R3.9.1.4.1 Wire Fatigue
- R3.9.1.4.2 Insulation Failure
- R3.9.1.4.3 Loss of Proper Slack
- R3.9.1.4.4 Wire Structural Failure

IMPROPER INSTRUMENTATION OUTPUT

R3.9

SPEED PICKUP FAILURE

R3.9.2

- R3.9.2.1 Loss of Required Clearance
- R3.9.2.2 Transducer Failure
- R3.9.2.3 Connector Failure
- R3.9.2.4 Lead Failure

LOSS OF REQUIRED CLEARANCE

R3.9.2.1

- R3.9.2.1.1 Probe Retainer Failure
- R3.9.2.1.2 Incorrect Assembly

TRANSDUCER FAILURE

R.3.9.2.2

- R3.9.2.2.1 Casing Failure
- R3.9.2.2.2 Thermal Incompatibility
- R3.9.2.2.3 Element (Electronic) Failure
- R3.9.2.2.4 Mechanical Failure

CONNECTOR FAILURE

R3.9.2.3

- R3.9.2.3.1 Pin Failure
- R3.9.2.3.2 Solder Joint Failure
- R3.9.2.3.3 Retainer Feature Failure

LEAD FAILURE

R3.9.2.4

- R3.9.2.4.1 Wire Fatigue
- R3.9.2.4.2 Insulation Failure
- R3.9.2.4.3 Loss of Proper Slack
- R3.9.2.4.4 Wire Structural Failure

IMPROPER INSTRUMENTATION OUTPUT

R3.9

DISTANCE DETECTOR FAILURE

R3.9.3

- R3.9.3.1 Loss of Required Clearance
- R3.9.3.2 Transducer Failure
- R3.9.3.3 Connector Failure
- R3.9.3.4 Lead Failure

LOSS OF REQUIRED CLEARANCE

R3.9.3.1

- R3.9.3.1.1 Probe Retainer Failure
- R3.9.3.1.2 Incorrect Assembly

TRANSDUCER FAILURE

R3.9.3.2

- R3.9.3.2.1 Casing Failure
- R3.9.3.2.2 Thermal Incompatibility
- R3.9.3.2.3 Element (Electronic) Failure
- R3.9.3.2.4 Mechanical Failure

CONNECTOR FAILURE

R3.9.3.3

- R3.9.3.3.1 Pin Failure
- R3.9.3.3.2 Solder Joint Failure
- R3.9.3.3.3 Retainer Feature Failure

LEAD FAILURE

R3.9.3.4

- R3.9.3.4.1 Wire Fatigue
- R3.9.3.4.2 Insulation Failure
- R3.9.3.4.3 Loss of Proper Slack
- R3.9.3.4.4 Wire Structural Failure

MEMBRANE RUPTURE

R4.1

- R4.1.1 Pump Housing Failure
- R4.1.2 Turbine Inlet Manifold Failure
- R4.1.3 Turbine Exhaust Manifold Failure

PUMP HOUSING FAILURE

R4.1.1

- R4.1.1.1 Failure Due to Excessive Pressure
- R4.1.1.2 Membrane Weld Joint Failure
- R4.1.1.3 Failure Due to Inadequate Strength

TURBINE INLET MANIFOLD FAILURE

R4.1.2

- R4.1.2.1 Failure Due to Excessive Pressure
- R4.1.2.2 Membrane Weld Joint Failure
- R4.1.2.3 Failure Due to Inadequate Strength

TURBINE EXHAUST MANIFOLD FAILURE

R4.1.3

- R4.1.3.1 Failure Due to Excessive Pressure
- R4.1.3.2 Membrane Weld Joint Failure
- R4.1.3.3 Failure Due to Inadequate Strength

JOINT RUPTURE

R4.2

- R4.2.1 Failure of Pump Inlet Flange Joint
- R4.2.2 Failure of Inducer Housing to Pump Housing Joint
- R4.2.3 Failure of Pump Volute Discharge Flange Joint
- R4.2.4 Failure of Pump Housing to Bearing Housing Flange Joint
- R4.2.5 Failure of Bearing Housing to Turbine Inlet Manifold Flange Joint
- R4.2.6 Failure of Turbine Manifold Inlet Flange Joint
- R4.2.7 Failure of Turbine Manifold to Exhaust Manifold Flange Joint
- R4.2.8 Failure of Turbine Exhaust Manifold Flange Joint

FAILURE OF PUMP INLET FLANGE JOINT

R4.2.1

- R4.2.1.1 Flange Structural Failure
- R4.2.1.2 Bolt Failure
- R4.2.1.3 Failure Due to Excessive Pressure
- R4.2.1.4 Failure Due to Excessive External Loads

FAILURE OF INDUCER HOUSING TO PUMP HOUSING JOINT

R4.2.2

- R4.2.2.1 Flange Structural Failure
- R4.2.2.2 Bolt Failure
- R4.2.2.3 Failure due to Excessive Pressure
- R4.2.2.4 Failure due to Excessive External Loads

FAILURE OF PUMP VOLUTE DISCHARGE FLANGE JOINT

R4.2.3

- R4.2.3.1 Flange Structural Failure
- R4.2.3.2 Bolt Failure
- R4.2.3.3 Failure due to Excessive Pressure
- R4.2.3.4 Failure due to Excessive External Loads

JOINT RUPTURE

R4.2

FAILURE OF PUMP HOUSING TO BEARING HOUSING FLANGE JOINT

R4.2.4

- R4.2.4.1 Flange Structural Failure
- R4.2.4.2 Bolt Failure
- R4.2.4.3 Failure due to Excessive Pressure
- R4.2.4.4 Failure due to Excessive External Loads

FAILURE OF BEARING HOUSING TO TURBINE INLET MANIFOLD FLANGE JOINT

R4.2.5

- R4.2.5.1 Flange Structural Failure
- R4.2.5.2 Bolt Failure
- R4.2.5.3 Failure due to Excessive Pressure
- R4.2.5.4 Failure due to Excessive External Loads

FAILURE OF TURBINE MANIFOLD INLET FLANGE JOINT

R4.2.6

- R4.2.6.1 Flange Structural Failure
- R4.2.6.2 Bolt Failure
- R4.2.6.3 Failure due to Excessive Pressure
- R4.2.6.4 Failure due to Excessive External Loads

FAILURE OF TURBINE MANIFOLD TO EXHAUST MANIFOLD FLANGE JOINT

R4.2.7

- R4.2.7.1 Flange Structural Failure
- R4.2.7.2 Bolt Failure
- R4.2.7.3 Failure due to Excessive Pressure
- R4.2.7.4 Failure due to Excessive External Loads

FAILURE OF TURBINE EXHAUST MANIFOLD FLANGE JOINT

R4.2.8

- R4.2.8.1 Flange Structural Failure
- R4.2.8.2 Bolt Failure
- R4.2.8.3 Failure due to Excessive Pressure
- R4.2.8.4 Failure due to Excessive External Loads

BURST OF INDUCER

R4.3

R4.3.1   Blade Failure

R4.3.2   Hub Failure

BLADE FAILURE

R4.3.1

R4.3.1.1   Blade Failure Due to Pressure and Centrifugal Loading

R4.3.1.2   Blade Fatigue Failure

BURST OF SPINNER

R4.4

R4.4.1   Burst Due to Centrifugal Loading

R4.4.2   Burst due to Pressure Loading

BURST OF PUMP IMPELLERS

R4.5

- R4.5.1 Burst of First Stage Pump Impeller
- R4.5.2 Burst of Second Stage Pump Impeller

BURST OF FIRST STAGE PUMP IMPELLER

R4.5.1

- R4.5.1.1 Failure of First Impeller Shroud
- R4.5.1.2 Failure of First Impeller Blade
- R4.5.1.3 Failure of First Impeller Hub

FAILURE OF FIRST IMPELLER SHROUD

R4.5.1.1

- R4.5.1.1.1 Failure due to Excessive Pressure Loading
- R4.5.1.1.2 Failure due to Centrifugal Loading
- R4.5.1.1.3 Excessive Stress Concentration
- R4.5.1.1.4 Low Cycle Fatigue Failure

FAILURE OF FIRST IMPELLER BLADE

R.4.5.1.2

- R4.5.1.2.1 Failure due to Pressure Loading
- R4.5.1.2.2 Failure due to Centrifugal Loading
- R4.5.1.2.3 Excessive Stress Concentration
- R4.5.1.2.4 Low Cycle Fatigue Failure
- R4.5.1.2.5 High Cycle Fatigue Failure

FAILURE OF FIRST IMPELLER HUB

R4.5.1.3

- R4.5.1.3.1 Failure due to Centrifugal Loading
- R4.5.1.3.2 Failure due to Low Cycle Fatigue

BURST OF PUMP IMPELLERS

R4.5

BURST OF SECOND STAGE PUMP IMPELLER

R4.5.2

- R4.5.2.1 Failure of Second Impeller Shroud
- R4.5.2.2 Failure of Second Impeller Blade
- R4.5.2.3 Failure of Second Impeller Hub

FAILURE OF SECOND IMPELLER SHROUD

R4.5.2.1

- R4.5.2.1.1 Failure due to Excessive Pressure Loading
- R4.5.2.1.2 Failure due to Centrifugal Loading
- R4.5.2.1.3 Excessive Stress Concentration
- R4.5.2.1.4 Low Cycle Fatigue Failure

FAILURE OF SECOND IMPELLER BLADE

R4.5.2.2

- R4.5.2.2.1 Failure due to Pressure Loading
- R4.5.2.2.2 Failure due to Centrifugal Loading
- R4.5.2.2.3 Excessive Stress Concentration
- R4.5.2.2.4 Low Cycle Fatigue Failure
- R4.5.2.2.5 High Cycle Fatigue Failure

FAILURE OF FIRST IMPELLER HUB

R4.5.2.3

- R4.5.2.3.1 Failure due to Centrifugal Loading
- R4.5.2.3.2 Failure due to Low Cycle Fatigue

BURST OF TURBINE ROTORS

R4.6

- R4.6.1 Burst of First Turbine Rotor
- R4.6.2 Burst of Second Turbine Rotor

BURST OF FIRST TURBINE ROTOR

R4.6.1

- R4.6.1.1 Rotor Failure due to Centrifugal Loading
- R4.6.1.2 Failure due to Low Cycle Fatigue

BURST OF SECOND TURBINE ROTOR

R4.6.2

- R4.6.2.1 Rotor Failure due to Centrifugal Loading
- R4.6.2.2 Failure due to Low Cycle Fatigue

RUPTURE OF INTERFERENCE JOINTS

R4.7

- R4.7.1   Loss of Tie Bolt Pilot Fit
- R4.7.2   Loss of Inducer Pilot Fit
- R4.7.3   Loss of First Impeller to Second Impeller Pilot Fit
- R4.7.4   Loss of Second Impeller to First Turbine Rotor Pilot Fit
- R4.7.5   Loss of First Turbine Rotor to Second Turbine Rotor Pilot Fit

HYDRAULIC OSCILLATIONS

R5.1

R5.1.1   Cavitation Effects

R5.1.2   Stall Margin Effects

R5.1.3   Improper Chillover

ROTOR INDUCED VIBRATIONS

R5.2

- R5.2.1 Loss of Rotor Pilot Fits
- R5.2.2 Improper Assembly
- R5.2.3 Improper Balancing
- R5.2.4 Operation Near Critical Speed
- R5.2.5 Thrust Balancer Instability
- R5.2.6 Loss of Bearing Preload
- R5.2.7 Bearing Failure

LOSS OF ROTOR PILOT FITS

R5.2.1

- R5.2.1.1 Loss of Tie Bolt Pilot Fit
- R5.2.1.2 Loss of Inducer Pilot Fit
- R5.2.1.3 Loss of First Impeller to Second Impeller Pilot Fit
- R5.2.1.4 Loss of Second Impeller to First Turbine Rotor Pilot Fit
- R5.2.1.5 Loss of First Turbine Rotor to Second Turbine Rotor Pilot Fit

IMPROPER ASSEMBLY

R5.2.2

- R5.2.2.1 Inducer to Impeller Mismatch
- R5.2.2.2 First to Second Impeller Mismatch
- R5.2.2.3 Second Impeller to First Turbine Rotor Mismatch
- R5.2.2.4 First to Second Stage Rotor Mismatch

IMPROPER BALANCING

R5.2.3

- R5.2.3.1 Improper Part Balance
- R5.2.3.2 Improper Assembly Balance

OPERATION NEAR CRITICAL SPEED

R5.2.4

- R5.2.4.1 Rotor Critical Speed to Operating Speed Relationship
- R5.2.4.2 Rotor Response Characteristics

ROTOR INDUCED VIBRATIONS

R5.2

THRUST BALANCER INSTABILITY

R5.2.5

R5.2.5.1 Internal Hydraulic Stability

R5.2.5.2 External (Pump and Turbine) Forcing Frequencies

LOSS OF BEARING PRELOAD

R5.2.6

R5.2.6.1 Cartridge Retainer Failure

R5.2.6.2 Preload Spring Failure

R5.2.6.3 Excessive Bearing Wear

MEMBRANE CRACKS

R6.1

- R6.1.1 Pump Housing Failure
- R6.1.2 Turbine Inlet Housing Failure
- R6.1.3 Turbine Exhaust Housing Failure
- R6.1.4 Bearing Coolant Line Failure
- R6.1.5 Thrust Balancer Return Line Failure

HOUSING SEAL FAILURE

R6.2

- R6.2.1 Inducer Housing to Pump Housing Seal Failure
- R6.2.2 Pump Housing to Bearing Housing Seal Failure
- R6.2.3 Bearing Housing to Turbine Inlet Manifold Seal Failure
- R6.2.4 Turbine Inlet Manifold to Turbine Exhaust Manifold Seal Failure
- R6.2.5 Bearing Coolant Line Seal Failure
- R6.2.6 Thrust Balancer Return Line Seal Failure
- R6.2.7 Instrumentation Connector Seal Failure
- R6.2.8 Seal Failure of Access Cap for Torque Check Device

INTERFERENCE JOINT SEAL LEAKS

R6.3

- R6.3.1 Tie Bolt Pilot Leaks
- R6.3.2 First to Second Impeller Joint Leak
- R6.3.3 First Turbine Rotor to Second Impeller Joint Leak