STUDIES AND ANALYSES OF THE SPACE SHUTTLE MAIN ENGINE

Contract No. NASw-3737

Technical Report
Covering

SSME FAILURE DATA REVIEW, DIAGNOSTIC SURVEY AND SSME DIAGNOSTIC EVALUATION

BCD-SSME-TR-86-1

December 15, 1986

R. C. Glover, B. A. Kelley and A. E. Tischer

Prepared For

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
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ABSTRACT

The results of a review of the SSME failure data for the period 1980 through 1983 are presented. The data was collected, evaluated and ranked according to procedures established during the study. A number of conclusions and recommendations are made based upon this failure data review. The results of a state-of-the-art diagnostic survey also are presented. This survey covered a broad range of diagnostic sensors and techniques and the findings have been evaluated for application to the SSME. Finally, a discussion of the initial activities for the on-going SSME diagnostic evaluation is included.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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SSME Failure Review, Diagnostics Survey, and SSME Diagnostic Evaluation

SUMMARY

Introduction

The National Aeronautics and Space Administration (NASA) recently has shown increased interest in condition monitoring and failure diagnostics for the Space Shuttle program. This interest has been prompted primarily by the need to reuse various Space Shuttle elements. NASA is emphasizing the Space Shuttle Main Engine (SSME) as a key candidate for condition monitoring and diagnostics.

This study was initiated by NASA to (1) review the SSME failure data base and identify major failure types, (2) survey a broad spectrum of diagnostics and identify promising candidates for use on the SSME, (3) conduct a systems-level analysis of the SSME diagnostic system using the outputs of Items 1 and 2 and (4) make recommendations concerning improvements in the SSME diagnostic system.

This technical report covers the following tasks of this study:

- SSME Failure Data Review
- Diagnostics Survey
- SSME Diagnostic Evaluation (on-going).

SSME Failure Data Review

The first task of the SSME study was to develop an understanding of the engine operating characteristics and failure modes. The task included collection and reduction of data on SSME failure modes, categorization of the failure modes, ranking of the failure modes, identification and evaluation of measurable parameters for each failure mode and identification of parameters for possible trending information.

The initial activity on this task was a review of the available SSME failure data. The information used in this study included all of the 3-line UCRs written from January 1980 through November 1983, selected full-page UCRs, the Rocketdyne Failure Modes and Effects Analysis (FMEA) Report and the SSME Accident/Incident Reports for 1980 through 1983.

Approximately 3000 abbreviated UCRs were reviewed in this task. This number was reduced to about 2900 by an initial screening process. The next step in the data reduction was to chart the failure modes over time to see the effects of the recurrence control procedures, to combine like failure modes and to eliminate minor problems which did not reappear in the data. The final step in the UCR data reduction was to collect the significant full-page UCRs and to review the detailed information. At the conclusion of these three screening processes, 1440 of the original UCRs were remaining. These UCRs represented approximately 190 engine failure modes. The reduced UCRs were plotted versus failure type. The UCRs were also plotted as a function of the individual SSME components.

The eight SSME Accident/Incident Reports written between January 1980 and December 1983 were reviewed along with the FMEA Report. The review of the FMEA Report led to the development of fault tree diagrams for each of the major components to augment available data on the failure modes and their propagations. The test firing cutoff UCRs were also reviewed to determine the diagnostic role of the current SSME sensors. A procedure was developed for ranking the failure modes identified by the data collection and screening. The failure modes were ranked from 1 to 10, with 1 being the most critical.

The measurements necessary to detect each failure mode were identified and evaluated. The several hundred failure modes for the entire engine can be reduced to about fifteen types of failures. The possible measurable parameters for each failure mode are evaluated along with possible in-flight and between-flight sensors or diagnostic techniques.

The conclusions drawn from the SSME failure data review include:

- Turbopumps have the highest priority, but other components have failure modes which must be considered
- Major accidents have had random failure modes and the commonly recurring failure types generally have not been to blame
- Many failure modes presently are detected too late to implement engine shutdown without sustaining further damage

- UCR data from test firings indicate that the present sensors can be useful in reliably diagnosing many failure modes
- Several recently developed and novel sensors could be useful for detection of critical failure modes, especially in the high-pressure turbopumps
- Many fatigue or wear-related failures can be trended by information from conventional sensors.

The recommendations resulting from the SSME failure data review include:

- The design and development of an integrated diagnostic system should be pursued (including in-flight and ground-based elements)
- SSME failure diagnosis could be improved by analysis of the data being collected by the current conventional sensors coupled with signal processing and enhancement
- Promising sensing techniques which target major engine failure modes should undergo further development and testing.

Diagnostic Survey

A survey of the state of the art of machine diagnostics was performed as the second task in the SSME study. The primary goal was to identify new diagnostic sensors, processing techniques, and/or diagnostic approaches which might be applicable to the SSME. A secondary goal of this task was to identify the overall status of machine diagnostics and the relative position of the SSME diagnostic system within this framework.

The diagnostic survey section of this report begins with a number of definitions and other general information regarding the nature of machine diagnostics. This terminology and discussion is necessary to provide a foundation for organizing the survey data.

A high-level overview of the SSME diagnostic and maintenance system was also prepared to identify the major elements of the current diagnostic approach and the interactions between them. This information was used as the basis for evaluating items identified during the diagnostic survey.

The survey covered the three rather broadly defined applications areas of (1) diagnostics for liquid-fueled rocket engines, (2) diagnostics for aircraft engines, and (3) diagnostics for relevant non-aerospace industries.

The survey involved interviews with experts in NASA, USAF, and a broad range of industries. In addition, relevant Battelle experts were interviewed and a thorough literature search was performed.

The review of liquid rocket engines found that the SSME represented the state of the art in nearly all respects. This is not a startling conclusion in view of the fact that the SSME is the only major engine development program funded over the last 15-20 years. The SSME diagnostic system is also more sophisticated than its predecessors due to the engine's design attributes.

Aircraft engines and their associated diagnostic systems have received far more attention than the liquid rocket engines. This can be attributed to a number of factors including the military emphasis on weapon availability, the civilian air carriers' desire to reduce costs, and the FAA's mandate to assure safety and reliability. This particular portion of the survey was especially informative.

The non-aerospace industry has been somewhat slow in recognizing the potential of machine diagnostics. This position is probably influenced somewhat by the higher safety factors which can be utilized in non-aerospace machinery. This situation is changing rapidly for a number of reasons. A number of potentially relevant techniques such as expert systems and pattern recognition ultimately may be proven first in this arena.

The survey findings can be summarized as follows:

- Diagnostics on liquid-fueled rocket engines other than the SSME were found to contain no novel techniques
- Diagnostics on jet aircraft engines currently use a number of novel techniques that are not employed on the SSME
- Diagnostics in non-aerospace industries employ the entire spectrum of sensors and diagnostic techniques.

As a result of the survey findings, the following recommendations were made:

- The use of new types of sensors and an increase in coverage provided by on-board sensors
- The use of image processing techniques to assist in ground-based inspections
- The use of pattern recognition to improve on-board diagnostics

- The application of non-linear filters for ground-based analysis
- The establishment of an integrated data base system to include all engine performance/historical data.

SSME Diagnostic Evaluation

The third task of the SSME study is intended to assimilate the outputs of the SSME failure data review and the diagnostics survey and to use this information for evaluating the current SSME diagnostic system. The principal objective of this task is to identify potential means for improving the availability of high-quality, pertinent engine data. This information will be used both in-flight and on the ground to assess the condition of the SSME and its respective components.

To accomplish the objective outlined in the preceding paragraph, an analysis approach was formulated to address the key SSME diagnostic issues. These issues centered on maximizing the information yield from the current engine sensors. A secondary emphasis was placed on the efficient augmentation of this system in cases where major failure modes were not adequately covered by existing sensors.

The Failure Information Propagation Model (FIPM) was selected as the analysis tool for use in this task. The FIPM is a technique developed by the Battelle Columbus Division to qualitatively evaluate the potential test points in a system. The objective of this qualitative evaluation is to assess the information bearing value of each test point. The model assumes that the system being depicted is in a near-normal state of operation.

The high-pressure oxidizer turbopump (HPOTP) was selected as the initial SSME component for evaluation using the FIPM. An HPOTP FIPM was graphically constructed using the steps outlined in the SSME diagnostic evaluation section of this report. Subsequent to the development of the HPOTP FIPM, a preliminary analysis of the HPOTP failure information was performed using a failure information matrix. This matrix was used to develop a preliminary set of test signature equations for the HPOTP.

Subsequent efforts to specify a set of diagnostic sensors which would target all of the high-priority HPOTP failure modes encountered difficulty due to the need for additional data. A decision was reached to restructure the HPOTP FIPM to include the additional data needed, to adopt a more formal development methodology, and to implement the new procedure in a data base format.

The revised FIPM methodology has been completed and documentation will be provided in a subsequent technical report. The software associated with the FIPM data base is currently under development. The revised HPOTP FIPM presently is being formulated in parallel with the development of the FIPM data base software.

On-Going Research

A number of activities are currently in progress or planned in connection with this study. The tasks include:

- Development of FIPM data base software
- Generation and loading of FIPM data for the HPOTP
- Generation and loading of FIPM data for the following SSME components:
  - high-pressure fuel turbopump (HPFTP)
  - low-pressure oxidizer turbopump (LPOTP)
  - low-pressure fuel turbopump (LPFTP)
  - oxidizer preburner (OPB)
  - fuel preburner (FPB)
  - main combustion chamber (MCC)
  - heat exchanger (HE)
  - main injector
  - nozzle
- Assessment of candidate diagnostics
- Analysis of existing engine data
- Examination of on-board implications of SSME diagnostics
- Recommendations for diagnostic system development.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) recently has shown increased interest in condition monitoring and failure diagnostics for the Space Shuttle program. This interest has been prompted primarily by the need to reuse various Space Shuttle elements such as the Orbiter, Space Shuttle Main Engines (SSMEs) and Solid Rocket Boosters (SRBs). The reuse of these major hardware items has created additional requirements for acquisition of valid wear and failure data on key Space Shuttle subsystems and components. This information is needed to verify the proper functioning of the Space Shuttle during its mission as well as to evaluate the maintenance required between flights. The principal NASA goals for improved monitoring and diagnostic systems are increased Space Shuttle reliability and safety coupled with reduced maintenance and turnaround costs.

NASA is exploring the entire spectrum of monitoring and diagnostic techniques for potential application to the Space Shuttle program. Research is being conducted in the areas of instrumentation, data acquisition, data analysis, automated decision making, and automated record keeping. Several NASA field centers and a number of contractors are currently involved in these evaluations. Since diagnostics, as a science, is still in the early stages of development, much of this work is very fundamental and exploratory in nature. However, with recent technological gains in the field of electronics, specifically microprocessors and computers, the capability of performing comprehensive diagnostics and condition monitoring tasks is now limited primarily by the availability and reliability of the appropriate transducers, and by the ability to understand and interpret the data being collected.

NASA is emphasizing the SSME as a key candidate for condition monitoring and diagnostics. The need for additional SSME data is the direct result of the engine's vital role during Space Shuttle launch and ascent. The ability to monitor, diagnose, and control degradations or failures of an operating engine is very important to both crew safety and mission success. It is also desirable to obtain an accurate assessment of the engine's overall condition after completion of the firing cycle. Decisions concerning an engine's suitability for a subsequent mission and the extent of any post-flight maintenance or repairs require detailed data on major engine components. Information on engine condition both during and after firing is equally important for ground test operations. However, the goal of accurately monitoring and diagnosing conditions in the SSME is complicated by a number of factors including the general engine design which maximizes performance while minimizing size and weight, the severe thermal and acoustic environments during engine operation, the reactivity and other properties of the liquid oxygen and liquid hydrogen propellants, and the extremely small time constants associated with major degradations and failures.

This study was initiated by NASA to (1) review the SSME failure data base and identify major failure types requiring diagnostic monitoring, (2) survey a broad spectrum of diagnostic sensors and processing techniques and identify promising candidates for application to the SSME, (3) conduct a systems-level analysis of the current SSME diagnostic system using the outputs from Items 1 and 2, and (4) make recommendations concerning improvements in the SSME diagnostic system and approach.

The task reports presented here cover three efforts to provide NASA with information to determine the major SSME failures, means to detect indications of failures in time to take appropriate actions, and ways to evaluate the need for and usefulness of those means.

The task reports accordingly cover and are entitled:

- SSME Failure Data Review
- Diagnostics Survey
- SSME Diagnostic Evaluation.

The SSME failure data review has been completed from the standpoint that the data from January 1980 to November 1983 has been collected and analyzed for use in the diagnostic evaluation and other areas. The diagnostics survey has similarly been completed, with the information being incorporated in the diagnostic evaluation as well as providing a background for other work. The SSME diagnostic evaluation is being performed using Battelle's Failure Information Propagation Model which is described in the third section of this report. The FIPM process will rely heavily on the data collected and assessed in the first two tasks. Detailed results from the FIPM are only now being realized, and these are to be presented in a separate report.

SSME FAILURE DATA REVIEW

The first task of the SSME study was to develop an understanding of the engine operating characteristics and failure modes. The task included collection and reduction of data on SSME failure modes, categorization of the failure modes, ranking of the failure modes, identification and evaluation of measurable parameters for each failure mode, and identification of parameters for possible trending information. This information is necessary to evaluate the effectiveness of diagnostic monitoring systems.

Failure Modes Analysis

Data Collection

Most of the data necessary for the failure modes analysis was supplied by the Rocketdyne Division, Rockwell International Corporation, Canoga Park, CA. The main source of information was the Unsatisfactory Condition Reports (UCRs). Since there were many UCRs written and Rocketdyne's previous study had included UCR information through 1979, it was decided in the present study to review all UCRs in a three-line format from January 1980 through November 1983. After the preliminary data reduction had taken place, selected full-page UCRs were collected for review. Other supplemental information received from Rocketdyne included the Failure Modes and Effects Analysis (FMEA) Report and Accident/Incident Reports for 1980 through 1983.

To provide Battelle personnel with additional information, engine data from a recent test firing and a Shuttle flight were obtained from NASA Marshall Space Flight Center (MSFC) along with general information on the SSME program. A diagnostics overview presentation was given by NASA Lewis Research Center (LeRC) personnel along with other general information needed to educate the Battelle researchers about various aspects of the SSME program. Information was also obtained from Rocketdyne personnel at NASA Kennedy Space Center (KSC) with regard to maintenance procedure and history.

UCR Review

To identify the SSME failure modes and their relative importance, all three-line UCRs written from January 1980 through November 1983 were reviewed and categorized. Approximately 3000 UCRs were used in the review process. Each UCR had a criticality factor associated with it which ranged from one to three, one being the most dangerous. The only UCRs that were eliminated on the basis of their low criticality factor were those that had criticality N, or no criticality factor. These were very minor problems for which a UCR should not necessarily have been written. Some UCRs of criticality three were eliminated because the problem described could not possibly cause any failures. Examples of this type include UCRs written on normal discolorations of the main combustion chamber or small contaminants on the nozzle that could not affect engine performance. Approximately 2900 UCRs were included in the first-cut review.

Appendix A contains the listing of the UCRs and their criticalities by component and a sample of the listing is shown in Figure 1. The high-pressure fuel turbopump had the most UCRs followed by the high-pressure oxidizer turbopump and the nozzle, respectively. The high-pressure oxidizer turbopump had the most criticality one UCRs, followed by the main injector, heat exchanger, and high-pressure fuel turbopump, in that order.

Component	Description	Total No. of UCR'S	CRITICALITY 1	2	3	N*
A100	Hot Gas Manifold	80	2		77	1
A150	Heat Exchanger	18	4		12	2
A200	Main Injector	175	5	3	162	5
A330	Main Combustion Chamber	105	1	3	98	3
A340	Nozzle	296		2	285	9
A600	Fuel Preburner	171		2	165	4
A700	Oxidizer Preburner	13			13	
B200	High Pressure Fuel Turbopump	457	3	11	429	14
B400	High Pressure Oxidizer Turbopump	331	7	11	302	11

FIGURE 1. SAMPLE OF FIRST UCR REVIEW LISTING BY COMPONENT

Appendix B contains a breakdown of the failure modes, cause, and recurrence control for each component. A sample of these tables is given in Figure 2. There were literally hundreds of failure modes identified, many having several causes. A large percentage of the problems were assembly or manufacturing problems. Most listed design, assembly, or manufacturing changes to correct the problems.

The next step in data reduction was to chart the failure modes over time to see whether the recurrence control procedures had remedied the problems. Also, the failure mode listings were revised to combine like failure modes and to eliminate those that were minor, had occurred only once or twice, and where the corrective action showed that there were no recurrences. Appendix C contains the results of this review and a sample is shown in Figure 3. After this step, the number of UCRs remaining was approximately 1900 from the original 3000 reviewed including 260 failure modes.

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
1	Leak					
	(a) Pin Plug Leak--Inadequate Seal--Add Leak Test	1			1	
	(b) Wireway Leak--Epoxy Did Not Adhere--Process Change	3			3	
	(c) Internal Leak--Tolerance Stackup--Detectable in Test	2			2	
	(d) Hyd Oil Leak--Excessive Proof Test Cycling--None	2			2	
	(e) Static Seal Leak--Burr Induced Scratch--New Inspection	1			1	
	(f) Vent Port Leak--Defective O-Ring--Open	2			2	
	(g) Wireway Leak--Inadequate Epoxy Coverage--Spec. Change	2			2	
2	Hydraulic Lockup Drift--Mfg. Error--Detectable--None	5			5	
3	Slew Rate Error--Contamination--None	2			2	

FIGURE 2. SAMPLES OF FIRST UCR REVIEW FAILURE MODE TABLES

Comp. J-600 Failure	Time Period (Months) 1980		1981		1982		1983		Criticality			Description - Cause Resolution
	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12	1	2	3	
1							2		--	--	2	Low insulation resistance-damage @ fabrication-none
3					1				--	--	1	Broken wire-suspect thermal induced-thermal test revised
4a	1	2			1				--	--	4	Output failure-unknown-none
4c				1					--	--	1	Erratic output-suspect sensor nut variations-evaluation
5		2							--	2	--	Open circuit, encapsulement cracks-assembly-assy. change

FIGURE 3. SAMPLE OF SECOND-CUT UCR TABLES

The final step in the UCR data reduction was to collect the significant full-page UCRs and review the detailed information. At least one full-page UCR was requested from Rocketdyne for each failure mode identified. As a result of this step, several more failure modes were eliminated because they were minor problems of an aesthetic nature or were items which quality control and/or engine pretesting would eliminate. Some failure mode descriptions were modified using the more detailed information in the full-page UCRs. The full-page UCRs also provided more information as to the severity of the failure mode for use in the ranking of the failure modes. At the conclusion of the full-page UCR review, some failure modes were found to be similar enough to be grouped together. With some of the failure modes being eliminated, there were 1440 of the original 3000 UCRs and approximately 190 failure modes.

Many of the failure modes in the UCR review were of an infrequent nature and were the result of assembly, procedure, or repair mistakes. Only a few of the failures were recurrent in nature and posed an important safety risk. (Among these were turbopump bearing wear, turbine blade cracking, nozzle leaks, injector erosion, and sensor system failures.)

The failure modes were then placed into fifteen categories and tabulated for each component. This categorization resulted in a matrix which forms Appendix D. Figure 4 gives one dimension of the matrix, the number of UCRs versus failure type after the completed screening process. Cracking, usually caused by vibration or thermally induced fatigue, was shown to be the dominant failure type followed by various leakage problems. Most of the leakage UCRs were written on the nozzle coolant tubes which are mainly a time consuming maintenance item. The electrical problems mostly related to the sensors and their associated wiring. Contamination was a significant problem and was found on many of the components; it was usually caused by assembly errors and some contamination could precipitate many other failures depending upon the type of contaminant and location involved. Erosion was mainly a problem in the high temperature areas such as the injectors, turbines, and igniters. Wear was typically a problem for the high-pressure oxidizer turbopump bearings and this has been a continuing problem on the SSME. Torque, vibration, and excess travel problems are measurements made on the turbopumps to check for problems before they lead to catastrophic failure. The rest of the categories are not indicative of any particular component of the SSME.

Figure 5 shows the number of UCRs versus individual SSME components. The dominance of the two high-pressure turbopumps along with the disparity between the preburners are the most striking features in the graph. A detailed listing of the failure types and causes for each component is located in Appendix E.

A brief description of the failure modes and general problems for most of the major components follows:

High-Pressure Fuel Turbopump (HPFTP) - The turbine area of the HPFTP is subjected to higher temperature and pressure than the other turbopumps in the SSME and consequently has more problems. Erosion and fatigue cracking were the subject of many UCRs for the turbine blades, turbine sheetmetal, and preburner to turbine joint area.

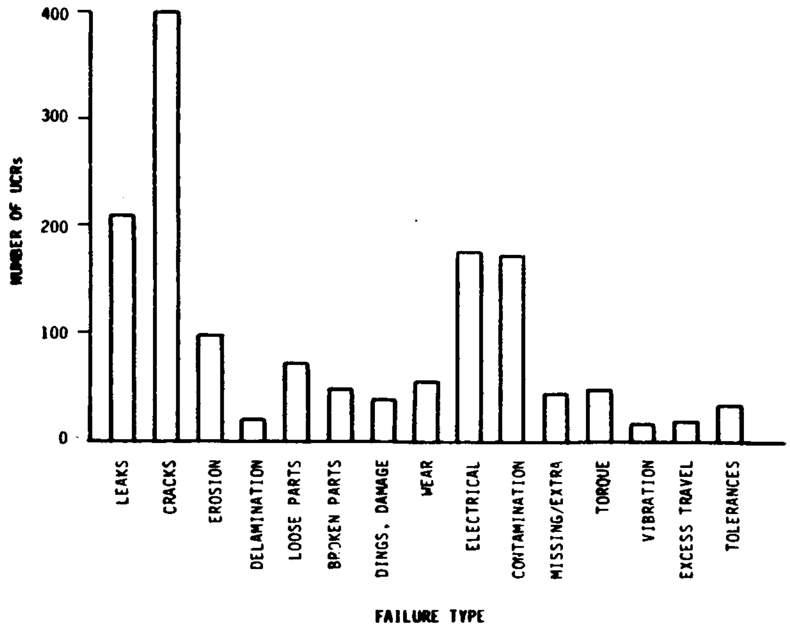

FIGURE 4. NUMBER OF UCRS BY FAILURE TYPE

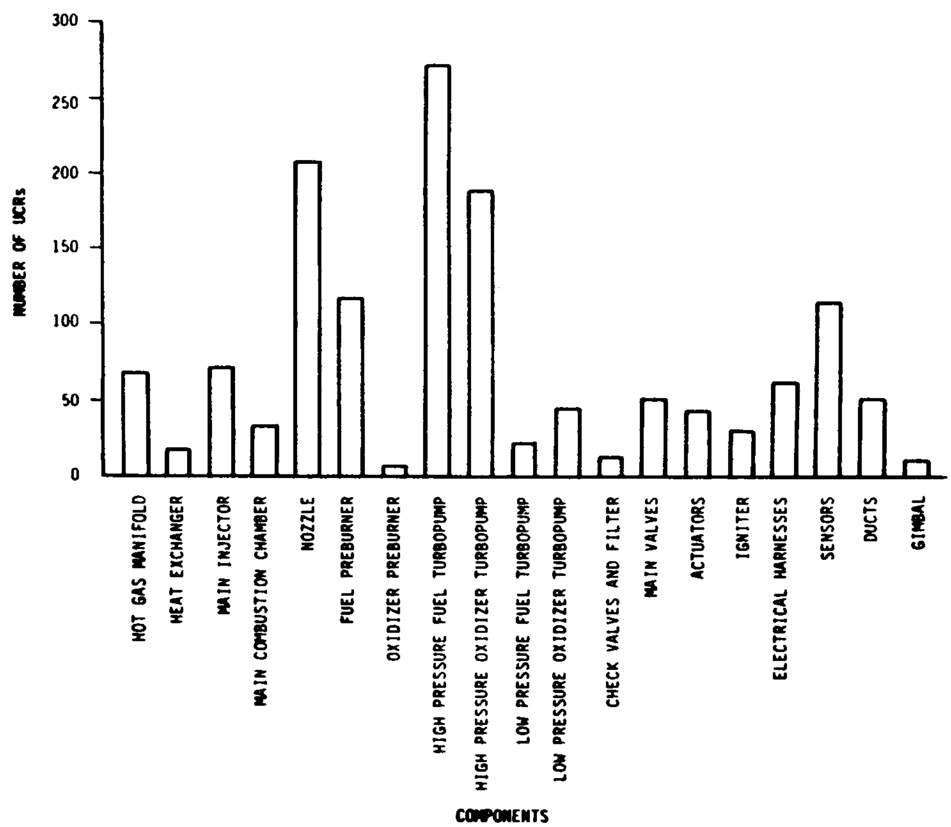

FIGURE 5. NUMBER OF UCRS BY COMPONENT

The pump inlet and diffuser had a few failures along with some minor bearing problems. Seal leakage and rubbing has been more of a problem than in the high-pressure oxidizer turbopump. Vibration due to cavitation and possible near resonance vibration conditions have been the subject of several UCRs.

High-Pressure Oxidizer Turbopump (HPOTP) - Bearing problems have been a major source of UCRs for the HPOTP including severe vibration levels during testing as well as bearing ball and race wear. Bearing cage delamination has also occurred several times. Turbine blade cracking and erosion has been a lesser problem on this turbopump than for the fuel turbopump. Contamination and erosion of the turbine area is also a concern. Turbine area rubbing and minor sheetmetal cracking have also been reported.

Nozzle - Unlike the rotating machinery, the nozzle has only a few problems. Cracking and leakage in the small nozzle coolant tubes that line the inside of the nozzle are the most common source of UCRs. Nozzle coolant tube leakage is caused by vibration fatigue, thermal fatigue, and brazing anomalies in assembly or repair. While these leaks are usually a nuisance item, the nozzle has been the source of at least one catastrophic failure. A steerhorn rupture caused by the use of incorrect weld wire during fabrication destroyed an engine on the National Space Technology Laboratories (NSTL) test stand.

Sensors and Electrical Harnesses - Sensor or sensor output failures were a frequent problem and are to be expected in view of the environmental extremes associated with the SSME. Typically, temperature and pressure sensors had the highest failure rate. Sensor reliability is an extremely important factor in designing an on-board diagnostic system. To date, the only specific action taken with respect to a postflight data review is to replace faulty sensors or sensor cabling.

Fuel Preburner (FPB), Oxidizer Preburner (OPB), and Main Injector - All three of these components have similar problems even though the fuel preburner dominates the number of UCRs. This is probably due to the higher temperature and pressure in the FPB. Erosion and cracking of the LOX posts and injector faceplates are the most frequent subject of the UCRs on the injectors. Vibration, temperature, and nonconcentricity of the LOX posts are the primary causes of injector failures.

Hot-Gas Manifold (HGM) - Cracking and rupture of ducting was the primary failure mode and this is caused by vibration loading or assembly error. Leakage at the joints along with loose fasteners which could cause leakage was also a problem.

Main Combustion Chamber (MCC) - Most of the UCRs were written for erosion or cracking on the hot-gas wall of the MCC. Low-pressure fuel turbine drive manifold leaks were the only major failure occurrences for this component.

Heat Exchanger (HE) - There were few UCRs written for the heat exchanger, probably because of the extreme precautions taken during assembly. Small leaks of oxygen from the HE would be catastrophic, so even minor tolerance and clearance discrepanices were reported in UCRs.

Low-Pressure Turbopumps (LPFTP) and (LPOTP) - These had problems similar to those for the high-pressure turbopumps, but they were minor in nature and much less frequent.

Valves and Actuators - Leaks were the common thread throughout the UCRs on these components. Internal leakage and ball seal leakage occurred in various valves and actuators. Also, valves did not function properly due to contaminants or a noisy or erratic position transducer signal.

Igniter - The igniter UCRs usually dealt with either the electrical connection or tip erosion failures.

Fuel Line, Oxidizer Line, and Drain Line Ducts - Joint problems and joint leakage were the focus of most of these UCRs. Weld and seal cracks also occurred.

Gimbal - Wear of the gimbal and cracks in the bushing were the two failure modes which caused UCRs to be written for the gimbal.

SSME Accident/Incident Reports Review

Major failures of the SSME or its components are subjected to a rigorous review with the results summarized in Accident/Incident Reports. The eight reports written between January 1980 and December 1983 were reviewed for failure mode information and the value of present instrumentation for failure detection. Summaries of the individual reports are contained in Appendix F.

During this four-year period, there were no duplications of any of these major failures. This indicates the complexity of the SSME and the degree of randomness involved in the failures. The nonrepetitiveness of the failures is also influenced by the detailed analysis of the incidents and the corrective actions taken to prevent recurrence.

Certain reports showed that human error in the SSME fabrication and assembly cannot totally be eliminated. The use of the wrong weld wire on the steerhorn portion of the nozzle caused a catastrophic failure and a welding mistake on the heat exchanger coil could have destroyed an engine or worse had it gone undetected. The UCR data reviewed has shown that human error in fabrication, assembly, and repair has been a constant source of problems.

Most of the catastrophic failures occurred on test stands after the instrumentation had indicated an unsafe condition and shutdown procedures had been started. In these cases, the time between detection of the measured failure condition and the consequent engine destruction was much shorter than the time to safely shut down the engine. To correctly and safely shut down the SSME, deteriorating conditions must be detected earlier than is presently being done. Because of the random causes of these major failures, the diagnostic system design should include as many of the engine parameters as is economically and technically possible.

Failure Modes and Effects Analysis Report Review

The Failure Modes and Effects Analysis (FMEA) Report prepared by Rocketdyne was reviewed to evaluate failure modes to help in ranking them. Although it was some help for major failure types and valve procedure problems, the FMEA Report did not contain a sufficiently thorough analysis of the failure modes and their propagation paths.

Fault tree diagrams are very helpful in charting failure modes and their effects on the engine. Figure 6 shows an example of such a diagram for the hot-gas manifold. Appendix G contains fault tree diagrams for each of the major components. The diagrams provided in this report are not at a detailed piece-part level, but at the level shown, they can help with two major tasks. They show the cause and effect of particular failure modes in a simple graphical fashion which determines their relevant importance and provides a means for diagnosis. Another important aspect of the fault tree diagram is that they allow the representation of failure propagation times for each step in the failure process, and this is important in structuring a diagnostic system, as indicated below.

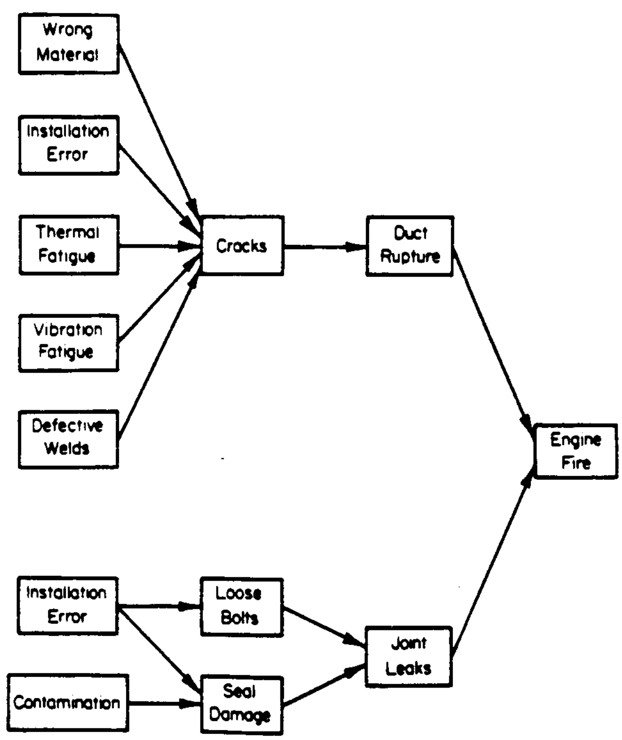

FIGURE 6. FAULT TREE DIAGRAM FOR HOT-GAS MANIFOLD

Because the time between the duct rupturing and engine fire (Figure 6) could be practially instantaneous, detection of such ruptures is too late for shutdown and would not be an effective diagnostic measurement. The diagram shows that cracking preceeds rupturing of the duct and may be detectable for many seconds before rupture occurs. If the failure could be detected at this level, the engine could be safely shut down and repaired. To detect all the causes of cracking, however, might take a prohibitive amount of time and be very costly.

In many cases, the most desired failure mode to detect may be realistically undetectable because of the advanced level of technology needed or because the environment within the engine would preclude measurement. In these cases, ground inspection techniques for the failure modes may be necessary. The fault tree diagram can be used to check the completeness of the diagnostic system. If the system checks for cracking of the ducts, but fails to detect loose bolts, the diagram in Figure 6 indicates that an engine fire would still be a possibility. Thus, if a particular failure mode propagates very quickly and there is presently no method for detection, then it may be cost effective to develop an appropriate sensor.

To conclude, the FMEA report should be greatly expanded with inputs from the Rocketdyne design groups for each particular component by assessing the thermal and vibration environment in conjunction with the design parameters.

Test Firing Cutoff UCRs Review

The UCRs that resulted from test firing cutoffs (shutdowns) from early 1975 through late 1983 were reviewed to assist in determining the usefulness of the present sensors on the SSME for the design of a diagnostic system. Even though the sensors produced a significant number of improper cutoffs, as shown in the tables in Appendix H, there were also many shutdowns that were due to valid measurements. These shutdowns were usually due to simple signal-level-activated commands. However, several catastrophic failures occurred after some safety limits ("red lines") had been exceeded but before shutdown could be completed.

Figure 7 is an example of the tables of the reduced UCR data. The data are organized by the measurement that caused shutdown. The year of occurrence, the number of improper cutoffs, the criticality of the UCR, the place they occurred, and the determined cause and action taken are included in the table. If there was a valid reason for the measurement to have exceeded the appropriate "red line" level, it was not an improper cutoff. Of over 255 test firing cutoffs, 41 (16 percent) were the fault of the test facility or the controller; 130 (51 percent) of the UCRs involved cutoffs for valid reasons.

This does not, however, mean that a similar event would result in an engine shutdown during flight. The importance of engine power output to the safety of a flight is such that many undesirable conditions would be accepted, but the basis for an overall diagnostic system may well reside with these previously used basic sensors. Other activities, moreover, will be required to adapt these sensors. For example, signal processing techniques, such as frequency domain and trend analysis, may be utilized to locate specific failures. Outputs from several sensors may indicate a unique failure mode (pattern recognition). Downstream and upstream sensors can be used to validate sensor output to improve the reliability of any diagnosis. Some of these techniques can be used for prognostic monitoring, and with the inclusion of a ground-based data acquisition and maintenance computer system, the results can be in the maintenance personnel's hands before the Shuttle returns. Such an "expert system" would be too slow for on-board diagnosis using today's computer technology, but may become a viable on-board tool in the future.

For the most part, fast-propagating and high-criticality failure modes are key targets for any on-board diagnostic or shutdown decisions. The present sensors should be helpful, but optimized placement of these sensors may be necessary. Also, knowledge of the background signal levels and expected signal levels of the failure modes is important.

Failure Mode Ranking

To assess the importance of each failure mode to the design of a diagnostic monitoring system, a procedure for ranking the failure modes was developed. Three factors were given equal weighting for the ranking:

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPFT Axial Accelerometer R/L	2	5										7		NSTL	Dynamic instability (whirl) - redesign
	1	1								2		2		NSTL	Facility device design limit - modify device
		1								1		1		NSTL	Axial thrust bearing welded - design changes
Totals	3	7								3		10			
HPFT Thrust Bearing Speed		2								2		2		NSTL	Erratic transducer output - add filter
Totals		2								2		2			
Fuel Preburner Temperature		1								1		1		NSTL	Facility malfunction - correct problem
		1										1		NSTL	Degraded performance of HPFT from tip seal erosion - redesign
Totals		2								1		2			
Oxidizer Preburner	1	6										7		NSTL	Valve Sequencing - change sequence
Temperature		1								1		1		NSTL	Erroneous reading - change to HPOT turbine discharge temperature
		1										1		NSTL	CCV Position error - change schedule
		2										2		NSTL	Degraded performance of HPFT from tip seal erosion - redesign
Totals	1	10								1		11			
HE Coil Delta Pressure		1										1		NSTL	Increased pressure buildup delay due to facility orifice - change
HE Discharge Pressure				1								1		NSTL	High HPOT break torque, unknown cause - none
				1							1			NSTL	Rework weld damage - change weld procedures
HE Purge Pressure			1							1		1		NSTL	Facility solenoid failure - repair
Totals		1	1	2						1	1	3			
LPOT Discharge Pressure				1						1		1		NSTL	Sensor short circuit - metal contamination
Totals				1						1		1			

FIGURE 7. EXAMPLE OF TEST FIRING CUTOFF UCR's REVIEW TABLES

Cost Factor - estimated cost per year of the failure after subtracting the cost that diagnostics could not eliminate

Risk Factor - based on the criticality factor

Time Factor - estimated time for failure mode to propagate to a catastrophic failure

A detailed explanation of the ranking procedure is in Appendix I along with the tabulated results. The failure modes are ranked in categories of importance from 1 to 10, with 1 being the most critical and 10 the least.

Failure modes in Categories 1 through 5, listed in Table 1, are most important and must be considered in the design of an on-board diagnostic system. In Categories 6 through 10, some failure modes may still be economically included in an on-board system although they are not ranked very high. Their inclusion should depend on the additional cost involved to detect each failure mode. Due to economic and technical considerations, some highly-rated failure modes may be impossible to include in an on-board system in the near future, but they are important areas for research and development of either in-flight or ground-based detection methods.

Measurement Parameter Analysis

Once the importance of the failure modes to the design of a diagnostic system has been evaluated, the measurements that can detect each failure mode must be identified and evaluated. To evaluate the measurement parameters, certain factors must be assessed such as signal level, background noise, existence of commercially available transducers, feasibility of developing special transducers, and the information necessary to uniquely identify the failure modes.

Signal level and background noise can only be roughly evaluated by experience and engineering judgment. An important step in evaluating signal levels quantitatively is to review the real-time data recordings of test stand and flight engine firings. Analyzing the real-time analog data should provide enough information to assess signal and noise levels, and may also indicate signal processing enhancements that would discriminate particular failure occurrences.

TABLE 1. FAILURE MODE RANKING RESULTS FOR RANK 5 OR ABOVE

RANK	COMPONENT	FAILURE MODE
1	HPOTP	Vibration - bearing loading
	Heat Exchanger	Cracks, leak in coil
2	Hot-Gas Manifold	Cracks, rupture in duct
	Hot-Gas Manifold	Leak in MCC ignition joint
	Main Injector	ASI supply line cracks
	HPOTP	Bearing ball and race wear
3	MCC	Turbine drive manifold leak
	HPFTP	G-5 joint erosion
4	Sensors	Temp. and press. output failures
	Nozzle	Steerhorn rupture
	Fuel Preburner	Faceplate erosion
	HPFTP	Diffuser failure
	HPFTP	Inlet failure
	HPFTP	Missing shield nuts
	Ball Valves	Ball seal leak and ball melting
	Poppet Valves	Cracked poppet
	Sensors	Temperature sensor debonding
5	Main Injector	Heat shield retainer cracks
	Fuel Preburner	Baffle and LOX post erosion
	Fuel Preburner	Baffle, molyshield, and liner cracks
	Fuel Preburner	Missing/extra support pins
	HPFTP	Turbine blade and platform erosion
	HPFTP	Seal cracking
	HPFTP	Coolie cap nut cracking
	HPFTP	Broken turbine blades
	HPOTP	Turbine blade cracks
	HPOTP	Bearing cage delamination
	Check Valves	Check valve leaks
	Igniter	Igniter tip erosion
	Electrical Harnesses	Birdcaged harness
	Electrical Harnesses	Loose, defective connector
	Electrical Harnesses	Debonded torque lock
	Duct Seals	Seal damage
	HPOTP	Vibration level - cavitation

With reference to Figure 4, the several hundred failure modes for the entire engine can be reduced to about fifteen failure types. In particular leaks and cracks are by far the most common failure type among all the failure modes. Each failure type has a unique signature, but since many failure modes have the same failure type, it may be difficult to identify a particular failure mode. A brief description of each failure type, the nature of the signal produced, and the possibility of identifying individual failure modes follows:

Leaks - Leakage of a liquid or gas from the system, or from one component to another within the system, can occur in several ways. It may be due to a crack in a structure, a bad seal, or possibly a malfunctioning valve. Presently, leaks are detected between flights by pressurizing the system with helium. The signals produced by leakage for possible in-flight detection are sound, vibration, optical, and possibly, in some cases, temperature or engine performance. In most cases, the sound and vibration signals will be low when compared to the background noise, probably even at ultrasonic frequencies (acoustic emission frequencies). An acoustic emission method for leak detection would moreover require many transducers to detect all the possible places that leaks can occur even if selected as a between-flight method of leak detection. Optical methods such as holographic leak detection are still in the developmental stages and also have resolution problems in detecting small leaks and are moreover only applicable where easy access is possible (e.g., for external leakage). In many cases, indirect measurements such as temperature, flow, or pressure may infer leakage. For example, leakage of hot gas into coolant passages could be detected by temperature measurements. Also if the leakage is severe enough, it will affect the downstream pressure and flow.

Cracks - Cracking of a structure is usually caused by mechanical or thermal loading which can eventually lead to failure of the structure with possible secondary effects such as fluid leakage. One present method of detecting cracking is by measuring the acoustic signal in the structure's material caused by the energy released through the cracking phenomena. These signals are detected by acoustic emission transducers at a frequency dependent upon material properties. High background noise, however, may be a problem in the application of this technique to many parts of the SSME. Other detection methods include magnetic, electric potential, and mechanical impedance methods. When the cracking leads to other problems, detection of these failure modes may be easier. But, since these are secondary effects, catastrophic failure of a component may be imminent, and the ability to shut down the SSME with minimal damage at this point may be impossible. Nevertheless, predicting cracking by trending vibration and temperature data should be useful in monitoring structural fatigue life.

Erosion - Erosion of surfaces usually occurs in the hot-gas turbine sections of turbopumps and in injectors. In the case of injectors, local hot spots may indicate erosion. In the case of both turbine and injector erosion, the performance of the turbopump and downstream components will directly be affected and should give rise to indicative measurements. Temperature trending of these components may be the most useful measurement possible in flight. Detection of ablated particles or, more likely, surface wear is possible in the case of erosion. Isotope wear detection, presently being developed by Rocketdyne, is considered to have the best chance of success for erosion detection.

Wear - Wear is caused by surface friction on a component due to mechanical contact or flow impingement. Erosion is a special case of wear, but it has been considered in a separate category of its own. Wear was considered, in this study, to result from mechanical contact between components with relative motion. Wear in the SSME generally occurs in the rotating machinery, e.g. the turbopumps. Bearings are the most critical parts affected by wear, followed by seals. Rubbing usually causes vibration, and in many cases the nature of the vibration signal can be used to identify which parts are involved. For example, seal rubbing may involve some RPM related vibration as well as indirect measurements such as reduced shaft RPM and torque. Wear is usually detected at high frequencies where the ambient noise is relatively low. More accurate measurements may be made by isotope wear detection (but not for pitting), magnetic wear detection, or ultrasonic doppler transducer. Magnetic wear detection measures the ball passage frequency. Ultrasonic doppler transducers can detect the shaft vibration, and should be more sensitive to bearing wear than vibration of the housing. Detection of worn particles or surface wear is also possible, as in the case of erosion. Isotope wear shows the most promise in this category. All these wear detection methods, moreover, are nonintrusive. Another possible wear measurement device, the fiberoptic deflectometer, however, would be intrusive.

Dings, Dents, and Damage - This is a general category that usually relates to debris impacting a part of the SSME. This can usually be detected by vibration sensors as a high-energy impulse signal.

Electrical - Electrical problems is this study relate to sensors, sensor cabling, and electrical connections. Many systems presently can self-check for continuity and other transducers can be used to verify the validity of a sensor's output (analytic redundancy), rather than using multiple sensor redundancy to increase sensor reliability.

Contamination - Contamination is a broad category of foreign deposits or objects present in a component. In most cases there is little or no effect, but problems such as reduced coolant flow through passages and impaired valve operation can occur. The effects of contamination can manifest themselves in different ways, but temperature, flow, and pressure measurements generally provide a good indication of a serious contamination problem.

Delamination and Broken Parts - These failure types are further extensions of cracking and several other failure types previously discussed. When a part fails structurally, the vibration signal will increase dramatically in most cases, but catastrophic failure of the engine may also be imminent.

Loose Parts - This cateogry usually refers to connections involving bolts or other fasteners. The possibilities for detection include increased vibration levels, an optical method, and measurement of torque on the bolt.

Missing/Extra Parts - This failure type is usually a problem with stud keys or other small parts that are installed in large quantities. Inspection and verification during assembly or between firings is the only way to directly detect missing or extra parts. One verification method might involve accurately weighing subcomponents before final assembly. Missing/extra parts may also result in another failure type that may be detected in flight, e.g. loose bolts.

Torque, Vibration, and Excess Travel - These measurements have all been used as criteria for assessing turbopump condition. All three have the potential for being performed in flight and could be used in combination to adequately evaluate turbopump condition.

Tolerance - Tolerance problems can possibly be detected in flight by optical methods, but ground inspection is usually required. Optical methods for enhancing ground-based inspection of injector parts could possibly save time, but these techniques will need extensive development.

Information on potentially useful transducers for detecting particular failure modes came from several sources including the diagnostic survey conducted as part of this study, the Rocketdyne Reusable Rocket Engine Maintenance Study, Final Report, and Battelle's past experience. Detailed descriptions of several promising sensors and diagnostic techniques are included in this section's recommendations or in the section covering the diagnostic survey.

To evaluate diagnostics for detection of particular failure modes, a Battelle developed tool, the Failure Information Propagation Model (FIPM), has been used and is described in detail in a subsequent section of this report. This tool can be used to evaluate the information at a transducer location and to assess the ability of the entire transducer set to identify engine failure modes.

The results of the measurement parameter analysis for each compoent are described in tabular form in Appendix J. A sample table of results is shown in Figure 8. The failure modes, their causes, rankings, and effects are listed in the tables. The possible measurable parameters for each failure

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Cracks, Ruptured Duct -vibration- -thermal- -no heat treatment- -defective welds-	3	Engine Fire	Vibration (F)(T) Temperature (F)(T)(D) Acoustic (B)(D) Loads (F)(T) Optical (B)(D) Performance (F)(D) Leak Detection (G)(D) Pressure (F)(D)	Accelerometer Thermocouple, RTD Acoustic Emission Strain Gages Holography (leak) Various (MCC) Pressure Sensor	Ultrasonic (leak) NDT, Visual Various	AE is a possibility for crack detection, but may be difficult to implement. Present instrument information may be helpful in detecting leakage, but may not be sensitive enough to stop the engine before catastrophic failure. Trending with vibration and temperature sensors could be helpful in tracking life limits.
Loose Stud Fasteners -wrong torque- -stretching- -soft keys-	7	Hot-gas Leak Engine Fire	Vibration (F)(D) Torque (G)(D) Optical (B)(D) Load (F)(T)	Accelerometer ? Strain Gages	Torquemeter Visual	Using some sort of alignment marks with an optical system for detection may be possible on flight or at least as ground check. Vibration data may indicate a loose fastener also.
G-5 Seal and MCC Ignition Joint Leaks -installation problems-	7,1	Engine Fire	Optical (B)(D) Leak Detection (G)(D) Temperature (F)(D) Acoustic (B)(D) Performance (F)(D)	Holography (leak) Thermocouple, RTD Acoustic Emission Various	Various Ultrasonic (leak)	Same as duct leaks.
Contamination -unknown-	8	Performance Degradation	Performance (F)(D) Optical (G)(D)	Various	Borescope, Visual	Not much can be done except some sort of monitoring of performance degradation.

FIGURE 8. EXAMPLE OF MEASUREMENT PARAMETER TABLES

mode are listed along with possible in-flight and between-flight sensors or techniques. Additional comments are also supplied to indicate relative strengths and weaknesses of the measurement techniques.

For most failures, the possibility exists to trend or detect their occurrence with conventional transducers that are already being used on the SSME. The problem is that current engine transducers may not be strategically located for detection of many of these failures. Knowledge of the signal content is also insufficient to differentiate between the many possible failure modes detectable by a given transducer. There are also some transducing methods that need development, but which have excellent promise for detecting failure modes which are undetectable by conventional methods.

The use of sensor data for failure trending could reduce the amount of between-flight inspections. Any failure mode that involves a slow degradation or fatigue type of failure could be trended. Detailed descriptions of measurements that can be used for trending particular failure modes are included in the measurement parameter tables in Appendix J. Many fatigue failures in the turbopumps and other components can be trended with mechanical and thermal load history information obtained by accelerometers, other vibration transducers, and temperature sensors. Injector and hot-gas component erosion can be trended with temperature measurements and, in some cases, pressure measurements.

Conclusions

The conclusions drawn from the failure modes and measurement parameter analyses are:

- Turbopumps have the highest priority for in-flight monitoring, but many other components also have high-ranking failure modes which must be considered.
- Major accident failure modes have been random in nature and the commonly recurring failure modes generally have not been to blame. Many of the major accidents were due to either assembly, manufacturing, or design problems which must be considered in the development of a diagnostic system.

- Presently, many failure modes are detected too late to safely shut down the SSME with minimal damage. The propagation rate of many failure modes provides an extreme challenge in designing an effective diagnostic system.

- Test firing cutoff UCR data reveal that the present sensors can be valuable for reliably diagnosing many failure modes. This could and should be achieved with proper signal processing, pattern recognition (unique combination of sensor outputs), analytical redundancy (correlate outputs from upstream and downstream sensors), and development of more rugged sensors and cabling.

- Some recently developed and novel sensors could be useful for detection of critical failure modes, especially in the high-speed turbopumps. Some of these can target key failure modes that may be masked from conventional sensors. They are described in the diagnostic survey discussion or in this section's recommendations. In many cases, there will be a great deal of development required before these new sensors are flight ready. The most immediate gains may be made by improving the use of the present sensors.

- Many slow-developing fatigue or wear related failures can be trended by information from conventional sensors, both to predict eventual failure and to reduce the amount of between-flight inspections. Such applications are possible for many turbopump and injector failure modes.

Recommendations

Diagnostic monitoring of the SSME can be improved by better use of present instrumentation, installation of more conventional sensors, and use of some recently developed sensing techniques which target specific failure modes. Three important steps for improving flight safety and maintenance costs are:

- Design of an integrated diagnostic system including both in-flight monitoring and ground inspection and maintenance.

- Improving failure diagnosis with conventional sensors by analysis of present flight and test firing data as well as assessment of signal processing and enhancement techniques to identify failure modes.
- Further development and testing of promising sensing techniques which target costly and hazardous failure modes that are difficult to detect with conventional sensors.

To design an effective diagnostic system for reduction of maintenance costs, turnaround time, and catastrophic failure risk; failure information in the entire SSME must be evaluated. The Failure Information Propagation Model (FIPM) is being used to evaluate failure information for all possible failure modes on the high-pressure oxidizer turbopump and assess sensing opportunities at various locations in the turbopump. Once the FIPM is completed for all components, a qualitative evaluation of a complete SSME diagnostic system can be made. The FIPM will help determine how better to use conventional and advanced technology sensors for in-flight monitoring and trending of information in conjunction with necessary ground inspections. An important aspect in the design of the complete diagnostic system is to incorporate an effective computerized information system for data processing and retrieval. Such a system would give maintenance personnel the relevant information to quickly assess and complete between-flight inspection and maintenance and would also be adaptable to incorporate new diagnostic developments.

There are many opportunities to improve the capabilities of the present sensor set as well as possible additional conventional sensors. The key to developing the use of these sensors is analyze the recorded analog flight and test firing data. By looking at the full bandwidth of the sensors, combining various sensor outputs, and correlating the signals with the known failure occurrences, diagnosis of many failure modes may be improved. Also, the FIPM can be useful in identifying possible applications for the present sensors and situations where additional conventional sensors would be helpful. The reliability problems of the present conventional sensors can be attacked by technological gains in hardening the sensors and through analytical redundancy in checking the validity of the sensor outputs. Analytical redundancy could reduce the number of sensors needed and thus reduce the amount of sensor repair and replacement. Specific applications are detailed in the measurement parameter tables in Appendix K.

Some new sensors may see applications on the SSME in the next couple years and others could be developed for use on the engine within five years. Most of these new or additional sensors target specific failure modes that are both costly and not presently detectable by conventional sensors. A list of the most promising sensors or sensing techniques follows:

Partially Developed and Tested

- Isotope Wear Detection - Between-flight noninstrusive detection of slowly developing wear-related failure modes. Potential uses, mainly in the turbopumps, include bearings, seals, and turbine blades. Cannot detect cracking or pitting. Presently being tested by Rocketdyne with funding from NASA LeRC.
- Ultrasonic Doppler Transducer - Nonintrusive means of detecting shaft vibration through solid and liquid interfaces. Extremely sensitive to imbalance and other RPM related vibration and may be useful for detecting other failure modes on the information rich shaft assemblies of the turbopump. It can detect cavitation, bearing wear, and seal rubbing. Developed by Battelle and tested at NASA MSFC in the mid-70's.
- Fiberoptic Deflectometer - Possibly more durable than conventional accelerometers and can potentially target specific vibration problems that need intrusive measurement capabilities such as bearing wear. Presently being tested at NASA LeRC by Rocketdyne.
- Ultrasonic Flowmeter - Has been tested as a means of nonintrusively measuring flow through ducts. The mounting conditions, however, have caused a duct to rupture. With proper design of the duct and transducer mounting, this sensor is believed to be a reliable method of detecting flow rate.

- Optical Pyrometer - For possible trending of turbine blade cracking. May have resolution and calibration problems, but there is no other acceptable method of detecting this failure mode at present. Under test by Rocketdyne with funding by NASA LeRC.
- Borescope Image Processor - Off-the-shelf packages are available to enhance the visual inspection of internal parts. New generation borescopes may be much better for low-light situations.

Devices with Major Development Efforts Needed

- Magnetic Wear Detector - A small experiment at Battelle showed that the ball passage rate can be monitored by a Hall-effect sensor. Bearing ball wear will change the contact angle and thus the ball speed. If the signal can be cleaned up enough, higher order effects may also be detected. Could be used as either a flight sensor or ground inspection method.
- Acoustic Emission Detectors - Possible in-flight applications for detecting cracks and leaks of quickly propagating failure modes. May have resolution problems in high background noise environment. Cracks and leaks are by far the most predominate types of failures.
- Laser Doppler Velocimeter - Can measure flow speed and direction, but needs access via an optic fiber through a hole or "window".
- Tracers Added to Helium Leak Detection - A radioactive tracer (Krypton, Tritium, etc.) could improve leak detection for ground-based applications.
- Holographic Leak Detection - Has the possibility of detecting and locating leaks faster and more effectively than the present helium method. Being investigated in a detailed Rocketdyne study.
- Exo-Electron Emission - May be useful in ground inspection for cracked parts. Also detailed in Rocketdyne study.

All of the above measurement applications should be evaluated for cost effective means of improving the present diagnostic system, but the most immediate improvements should come through studying the on-board sensors.

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DIAGNOSTICS SURVEY

A survey of the state of the art of machine diagnostics was performed as the second task in the SSME study. In this survey, a general look was taken at the area of machine diagnostics across three rather broadly defined application areas:

1. Diagnostics for liquid-fueled rocket engines,
2. Diagnostics for aircraft engines,
3. Diagnostics in relevant non-aerospace industries.

The survey involved interviews with experts in a broad range of industries, NASA, and the military. In addition, relevant Battelle experts were interviewed and the literature was reviewed. The current diagnostic methods for the Space Shuttle Main Engine (SSME) were also examined and the relevant survey findings were identified for potential use on the SSME.

Survey Approach and Methodology

Approach

This diagnostic survey has two objectives: (1) the determination of the state-of-the-art of machine diagnostics, and (2) the identification of new, candidate diagnostic techniques and/or approaches for potential application to the SSME. Throughout this effort, the focus is on those techniques that are considered to be off-the-shelf, or mature areas of research and development.

The intent of the diagnostic survey is to be broad, spanning as wide a spectrum of industries as possible. Within the general area of machine diagnostics, three topics are considered:

1. Maintenance logistics and strategies,
2. Diagnostic techniques,
3. Design approaches for diagnostic systems.

Because of its breadth, this study does not attempt to focus on any specific technique or approach in great detail. Throughout the survey, only enough detail was sought to permit an assessment of the usefulness of the techniques under study.

Methodology

There are two phases in diagnostics survey, a state-of-the-art survey and the subsequent assessment of the survey findings. For the survey phase, we selected three application categories:

1. Diagnostic systems for liquid rocket engines,
2. Diagnostic systems on civil and military aircraft,
3. Diagnostic systems in non-aerospace industries.

Information was gathered using literature reviews and interviews with a number of industry, government, and military experts. Figure 9 depicts the overall survey strategy.

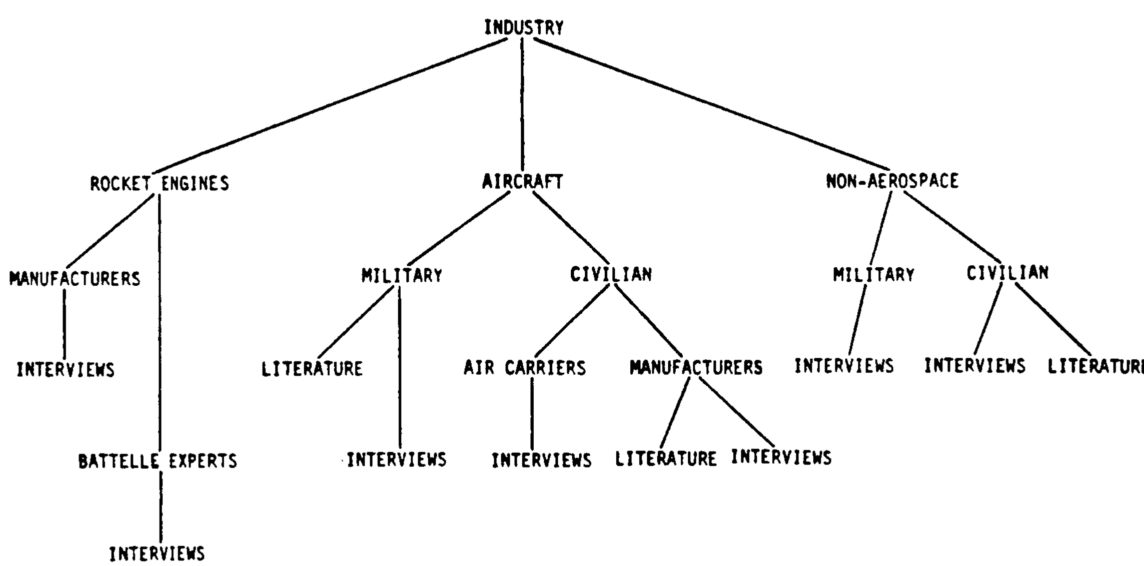

FIGURE 9. STRATEGY FOR STATE-OF-THE-ART SURVEY OF MACHINE DIAGNOSTICS

The second phase of the Diagnostics Survey was a preliminary assessment of the survey findings to screen out those that were not considered relevant to the SSME. This was done in two steps:

1. The diagnostic systems and maintenance strategy currently employed for the SSME were reviewed.
2. The survey findings were reexamined in light of the current SSME environment, and those that were not considered useful were dropped.

Information sources for the review of current SSME diagnostic systems and maintenance practices were NASA and Rocketdyne experts, and selected published reports.

Diagnostics Background

By its very nature, machine diagnostics encompasses a broad set of disciplines. Much of the scientific knowledge necessary to design and fabricate machines, as well as to understand the physics of their failures, falls under the technological umbrella of machine diagnostics. Because of this breadth, it is necessary to provide an organization through a hierarchy of related functions. This organization results in a logical, manageable set of elements.

Definitions

We begin our discussion with a set of definitions to remove ambiguity in terminology. The following are taken from Reference 3-8:

- FAULT DETECTION - the act of identifying the presence of an unspecified failure mode in a system resulting in an unspecified malfunction.
- MALFUNCTION - an inability to operate in the normal manner or at the expected level of performance.
- FAULT ISOLATION - the designation of the materials, structures, components, or subsystems that have malfunctioned. Fault isolation extends fault detection to the detection/identification of the specific part that must be repaired or replaced in order to restore the system to normal operation.

- FAILURE DIAGNOSIS - the process of identifying a failure mode or condition from an evaluation of its signs and symptoms. The diagnostic process extends fault isolation to the detection/ identification of the specific mode by which a part or component has failed.
- FAILURE MODE - a particular manner in which the omission of an expected occurrence (or performance of a task) happens.

By examination, the universe of states for any given system may be partitioned into two overlapping regions, operational states and faulty states (see Figure 10). This partitioning does not, however, produce a dichotomy, and there is overlap between the two regions.

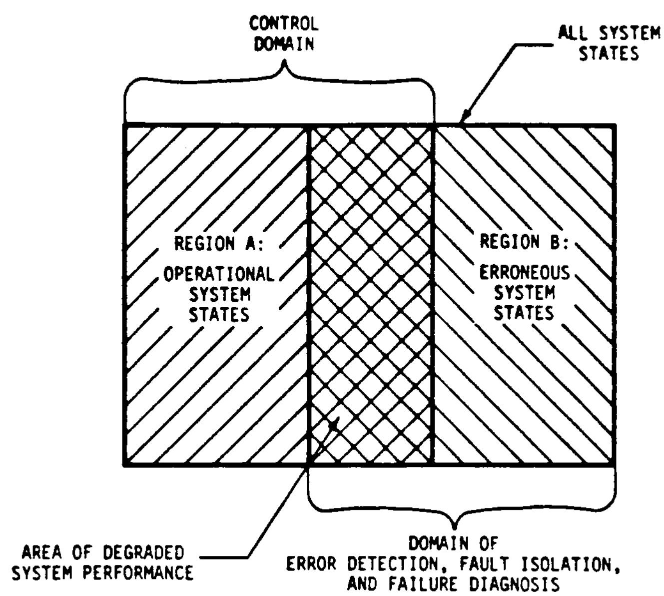

FIGURE 10. PARTITIONING OF SYSTEM STATES INTO OPERATIONAL AND ERRONEOUS STATES. Notice the Overlap.

This area of overlap represents states of degraded system performance. In general, the region of operational states represents the control domain, whereas the faulty states, constitutes the domain of fault detection, fault isolation, and failure diagnosis. The above definitions can now be rewritten so that they are in terms of these states.

- FAULT DETECTION - the identification of a system state lying within the region of faulty states.
- FAULT ISOLATION - identification of a class of system states within the region of faulty states which classify the malfunction of a specific module or component.
- FAILURE DIAGNOSIS - identification of a system state within the region of faulty states which classifies a specific failure mode of the malfunctioning module or component.
- STATE IDENTIFICATION - the determination of the condition or mode of a system with respect to a set of circumstances at a particular time.

In addition to redefining some of the diagnostic-related elements, one can also express the concept of control in terms of system states.

- CONTROL - the identification of a current system operational state and the subsequent adjustment of the system so as to maneuver it to another desired operational state.

From the above discussion the following, self-evident conclusion results:

> All types of detection associated with error perception, fault isolation, failure diagnosis, and system control are classes of state identification.

This conclusion is quite important in that it allows the grouping of the various facets of machine diagnostics, fault detection, fault isolation, and failure diagnosis under the more general topic of state identification. Additionally, since detection for control purposes is also a class of state identification, the importance of considering both the machine diagnostics and control in an integrated fashion is emphasized. Therefore, there exists a common denominator, state identification, around which this study is logically focused.

State Identification Process Hierarchy

One can specify a hierarchy of elements that are necessary for the state identification process. First, at the lowest level, information about the system or machine in question must be gathered. Second, once this information has been gathered, it must somehow be reduced to a manageable set of relevant features. Finally, at the highest level, that set of features can be used to perform the state identification. This hierarchy of functions is shown in Figure 11.

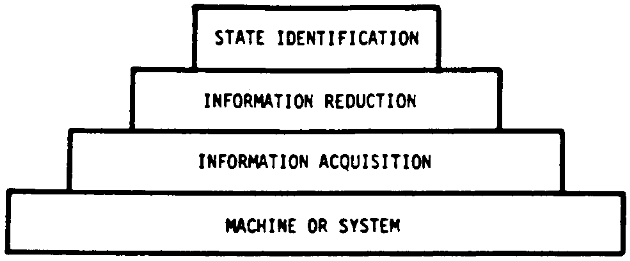

FIGURE 11. THE HIERARCHY OF PROCESS REQUIRED FOR STATE IDENTIFICATION

Information Acquisition

The potential sources of information about a given system or machine necessary for state identification are: specifications, history, sensors, and inspection. Optimally, all of these are utilized in the state identification process for machine diagnostics.

Specifications. Specifications are those documents which define the normal operating characteristics of the system or machine. Deviations from this norm may be caused by component failures, design errors, or both.

If a given system is operating according to specifications, it is in that sector within the region of operational states which does not overlap with the region of faulty states (see Figure 10), otherwise it is in the region of faulty states. The specifications define the performance explicitly for the system controller, and implicitly for the system fault detection mechanism.

History. History about a system or machine's performance can be of a short-term or long-term nature. Short-term history represents those events which are related to one another and take place within the physical or characteristic time cycles of the machine. For example, all events occurring within the decay time for a pendulum might be considered short-term history. Long-term history consists of those events which occur in a time frame greater than that considered to be short-term (as previously defined). Observation of all events, whether they are of short-term or long-term historical nature are made using sensors or by inspection (see below).

Sensors. The transducers that measure the various physical parameters. Sensors may either be permanently installed on-board a machine or used as part of test instrumentation. The sensor output information is often called raw data. This raw data must be reduced to a set of features in order to perform state identification for diagnostic or control purposes.

Inspection. Inspection techniques are often used in lieu of sensors. In effect, a human serves the function of a wide-band sensor. Some tools are available to assist the human during the inspection process. The physician's stethoscope is an example of such a tool.

Information Reduction

Having acquired information about the performance of a machine or system, it must be subsequently processed and reduced to produce a set of features from which to perform the state identification. Usually, this part of the process involves the reduction of the information by removing that which is redundant or irrelevant. Sometimes data from several sources are combined to generate features which cannot be or which have not been physically measured at a single place or time. A commonplace example of this is the combination of sensory data about a machine, along with its long-term history, in order to derive a feature which describes a machine's failure trends.

There are two principal means by which this reduction of information takes place, signal processing and/or human expert analysis. The difference between these two approaches may be seen simply as the difference between machines and humans. Signal processing can be accomplished in a number of machine domains:

- Analog electronics (continuous or discrete),
- Other analog domains,

- Digital electronics (hardware only),
- Hardware and software.

Human expert analysis may be accomplished with or without the assistance of mechanized tools. A mechanic listening to the noise of an automobile engine to discern the tapping of a valve exemplifies the later case. An automotive engineer observing the output of an acoustic spectrum analyzer to make the same determination represents the former case.

State Identification

Having acquired information about a system or machine, and subsequently generating a set of relevant features, the state identification must be performed. As is the case with information reduction, the same identification can be carried out either by humans or automated devices.

In general, there are three approaches for automated state identification:

1. Pattern recognition (with the most trivial case being a table lookup).
2. Nonlinear filters (with the simple algorithm representing the most trivial case).
3. Expert systems.

In the specific cases where state identification is used for error detection or fault isolation, a fourth technique is at our disposal, i.e., voting. In the voting process, a society of identical hardware modules operate in parallel to highlight any nonconformists (malfunctioning modules).

Human-based decisions (state identifications) are the most common in the diagnostic/maintenance areas. In the vast majority of these cases, the expert has no assistance (other than perhaps another human expert). Recently however, the use of computer expert systems as decision aids is gaining acceptance. Witness, for example, the increasing commercialization of computer-based expert systems to assist in medical diagnosis.

Summary and Conclusions

In an effort to find a common denominator for the various aspects of machine diagnostics (namely fault detection, fault isolation, and failure diagnosis), it was determined that all were classes of the more general process of state identification. In addition, it was concluded that detection for control purposes was also a class of state identification.

The process of state identification can be thought of as a hierarchy. First information must be gathered about the system in question. Then, the information must be reduced to a set of features. Finally, based upon those features, an identification of the system state may be accomplished.

Viewing this hierarchy from the perspective of machine diagnostics versus machine control, we can gain insight into the interaction between those two functions. Revising the pyramid of Figure 11 we obtain that of Figure 12. It is evident from the above discussion that machine control requires many of the same elements as do machine diagnostics. As shown in Figure 12, there is every reason to expect that a sharing of hardware between the control and diagnostic functions is both possible and desirable. Reliability theory tells us that the addition of any component into a system will always increase the likelihood of failure--even though the component may serve a diagnostic purpose (it is possible that system reliability could be increased if the addition of the component in question added redundancy of some type). By allowing control and diagnostic functions to share resources, system reliability is kept to a maximum. Because diagnostics help to reduce system downtime, once a failure has occurred, system availability is improved.

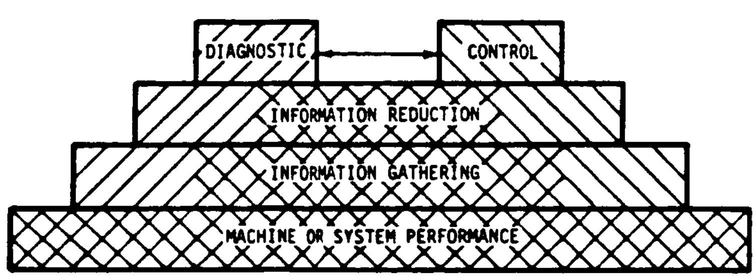

FIGURE 12. MACHINE CONTROL VERSUS MACHINE DIAGNOSTICS. NOTE THE OPPORTUNITY FOR SHARING RESOURCES

Taking the elements from the above hierarchy and using the classifications discussed earlier in this section, Table 2 is formulated. We are now in a position to use this classification as a tool for organizing the results of our diagnostic survey.

TABLE 2. BREAK-DOWN OF THE DIAGNOSTIC HIERARCHY

DIAGNOSTIC	AUTOMATED DECISION	PATTERN RECOGNITION
		NONLEAR FILTERS
		EXPERT SYSTEMS
		VOTING SYSTEMS
	HUMAN EXPERT OPINION	HUMAN ONLY
		MACHINE ASSISTED
INFORMATION REDUCTION	SIGNAL PROCESSING	ANALOG ELECTRONICS
		OTHER ANALOG DOMAINS
		DIGITAL ELECTRONICS
	HUMAN EXPERT ANALYSIS	HUMAN ONLY
		MACHINE ASSISTED
INFORMATION SOURCES	SPECIFICATIONS	
	HISTORY	SHORT TERM
		LONG TERM
	SENSORS	ON-BOARD
		TEST INSTRUMENTATION
	INSPECTION	HUMAN ONLY
		MACHINE ASSISTED

SSME Diagnostic and Maintenance System Overview

This section presents a brief description of the SSME diagnostic and maintenance system. It should be noted that the current maintenance/diagnostic structure is highly complex. In the interest of brevity, the elements chosen represent rather coarse groupings of the numerous related components. Nevertheless, it is felt that the categorizations are accurate and that the description is therefore a good representation of the diagnostic system.

The diagnostic system elements for the SSME may be broadly categorized as either "on-board" or "ground-based". For the sake of this discussion, by the term "on-board" we mean those diagnostic elements that are physically close to the engine, whether it is flying on a Space Shuttle or operating on a test stand. "Ground-based" elements of the diagnostic and maintenance system are those that are not considered to be on-board ("everything else").

In addition to the "ground-based" versus "on-board" categorization of the SSME diagnostic elements, they may also be classified according to the diagnostic hierarchy discussed in the previous section. There are a number of levels in the hierarchy, the lowest of which is the plant level (the level containing the engine itself). The next-to-the-bottom level can be thought of as the information gathering level. All elements which have a role in the acquisition of information about the plant's (engine's) performance belong to this level. Control actuators also reside at the information gathering level. The next-to-the-highest level is termed the information reduction level. It is here that any signal processing or conditioning occurs. Finally, the highest level is termed the decision level. At this level, diagnostic and control decisions are made.

Based upon the previously described hierarchical organization we can identify (albeit somewhat broadly) the various elements that comprise the diagnostic system for the SSME. Such an overview is given schematically in Figure 13. It must be noted that those elements which are classified as on-board (including crew) are meant to apply to test stand firings as well as in-flight service.

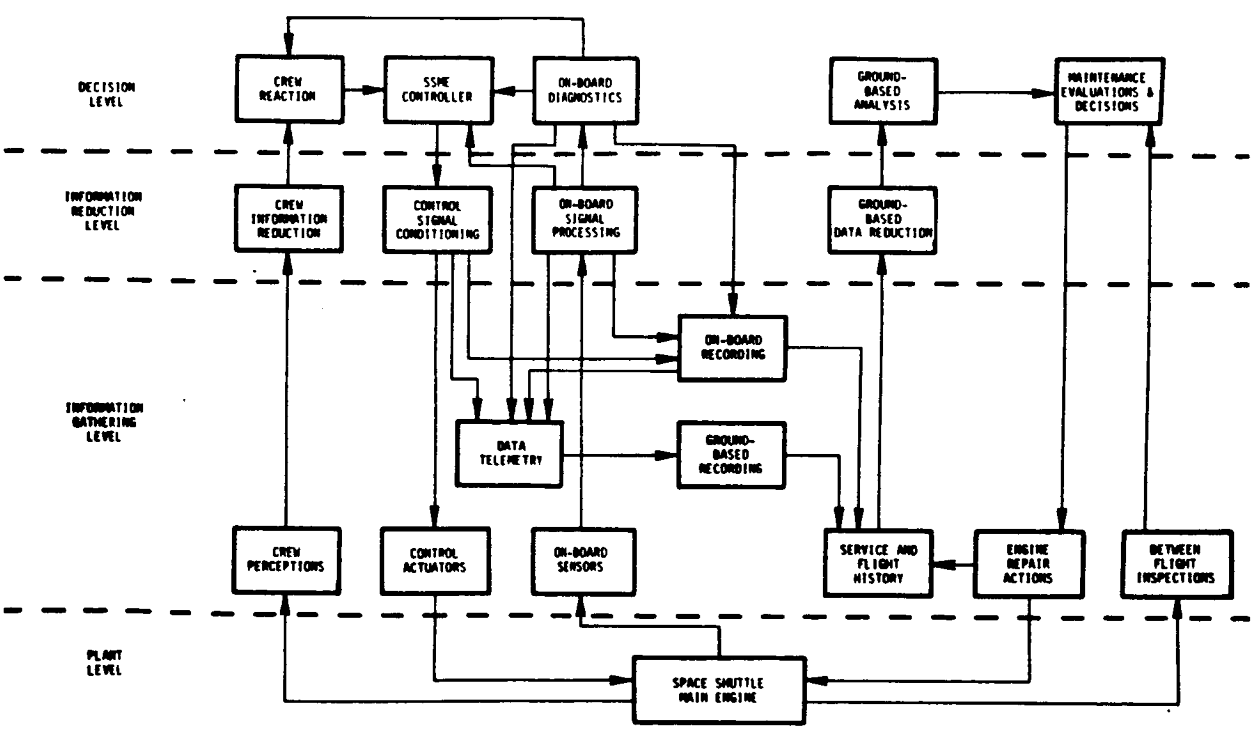

FIGURE 13. OVERALL SSME DIAGNOSTICS AND MAINTENANCE PICTURE

Information Gathering

There are two on-board elements which provide the function of data acquisition: crew perceptions and on-board sensors. The crew perceptions are those observations of the flight crew on the Orbiter, and the support staff during test stand engine firings. These observations are results of the physical senses and should not be confused with information presented to the crew by the diagnostic subsystems.

A number of on-board sensors are used primarily for control purposes. The remaining sensors are dedicated to diagnostic functions. Some of the control related sensor outputs are also used for diagnostic purposes.

Aside from the data acquisition function, there are on-board elements for data telemetry and data recording. Nearly all sensor outputs are ultimately telemetered for ground-based analysis. A number of these data are also recorded on-board the Orbiter.

On the ground-based side, a large amount of diagnostic data comes from between-flight inspections. Data acquired by on-board subsystems are ultimately integrated with the results of ground-based inspections and engine repair actions to establish the engine flight and service history. This historical data represents a valuable information pool for detailed analysis.

Information Reduction

All of the data, whether acquired by sensor, observation, or between flight inspection must be reduced to a manageable set of features so that the appropriate diagnostic or control decision may be quickly and accurately made. Sensor data is characteristically reduced using signal processing techniques such as time integration or low-pass filtering. Observations and inspection results are typically reduced by the inspection specialists through the use of heuristics.

Diagnostic Decisions

The on-board diagnostic subsystem uses a basic form of pattern recognition. A table of "red lines", dynamically adjusted for changes in the engine's operational modes, is employed to flag potentially dangerous conditions and dictate responses. Similarly, the crew reactions represent a human pattern recognition resulting in well practiced responses.

Currently, the ground-based analysis employs an analytical model of the engine combined with heuristic-based decisions to identify potential trouble spots. This information is used to some degree to direct the between-flight inspections, and aids in the maintenance evaluations and repair decisions.

Summary

This section has presented a high level overview of the SSME diagnostic and maintenance system. The various diagnostic and maintenance elements as well as their interactions (or possible interactions) have been described and are depicted in Figure 13. The intent of the state-of-the-art diagnostic survey is to identify possible techniques to improve the performance of those elements and/or to improve the quality of their interconnections.

Survey Findings

This section presents the significant findings and highlights of the state-of-the-art diagnostic survey. These findings are broken down into three major application areas:

1. Liquid-fueled rocket engines,
2. Aircraft,
3. Non-aerospace industries.

Within each application area, the findings are further organized according to the hierarchical classification discussed in the previous sections.

Liquid-Fueled Rocket Engines

The principal sources of information for this part of the survey were rocket engine manufacturers, instrumentation vendors, Battelle experts, and NASA reports.

The SSME is unique in that is the first truly reusable rocket engine not on an experimental vehicle. This fact, combined with a design which allows for smaller error margins than previous rocket engines, has dictated a much more comprehensive diagnostic and maintenance philosophy than any of its predecessors.

Data Acquisition. The vast majority of the sensing and instrumentation techniques are based upon well-seasoned approaches. In the case of on-board devices, such well-established transducers as thermocouples, pressure sensors, accelerometers, etc. are typically used. The data from these transducers are usually telemetered for ground-based analysis. Historically, manufacturers have not had a great deal of confidence in on-board instrumentation. Rocketdyne is currently under contract with NASA to develop new instrumentation as a part of an advanced condition monitoring system.

Ground-based inspections are characteristically manual in nature. Some instruments such as mass spectrometers have found application in the isolation of gas leaks. Some new techniques for data acquisition have been proposed and/or are under development, but none of those are yet considered to be mature products.

Signal Processing. Because of the basic nature of the diagnostic systems employed on prior rocket engines, minimal on-board signal processing techniques were used. The techniques used are basic in nature and have as their objective the enhancement of the signal-to-noise ratio or sensor signals. Ground-based analyses of telemetered data characteristically employ more sophisticated approaches.

Diagnostic Techniques. The sophistication of the diagnostic techniques used on-board previous rocket engines has been minimal. The most common real-time monitoring technique was based upon the violation of limits or "red lines". Post-flight analyses, were usually more thorough, relying on tools such as computer simulations.

Highlights. Items of particular interest which were obtained during the liquid rocket engine portion of the survey include:

Awareness of Need for Diagnostics. All of the manufacturers of rocket engines that were interviewed (Rocketdyne, Pratt and Whitney, and Aerojet) indicated an awareness of the need for comprehensive diagnostics on reusable engines. Rocketdyne, due to its involvement with the SSME, has already embarked on the development of a comprehensive condition monitoring system. Both Aerojet and Pratt and Whitney intend to develop such systems on future engine programs.

Current SSME Diagnostics. The engine monitoring system currently employed on the SSME has been successful from the standpoint of crew/vehicle safety. However, it is labor intensive and does not lend itself well to the quick turnaround objectives of the STS program. The on-board diagnostics are based upon violations of a series of safety limits ("red lines") some of which are dynamically allocated. The on-board sensor set includes the following:

- temperature - resistive temperature detectors, thermocouples
- pressure - strain gauge, piezoelectric
- tachometer - magnetic pickup
- position - potentiometers, RVDT, LVDT
- vibration - piezoelectric accelerometer
- flowmeter - turbine
- calorimeter - thermopile
- radiometer - foil.

These sensors are considered by Rocketdyne to be adequately reliable. Data from some of these sensors are telemetered for ground-based recording at 20 millisecond intervals during engine firings. The ground-based portion of the diagnostic system is centered around a series of routine and periodic inspections. The routine inspections include the following:

- external inspection
- internal inspections - HPFTP, HPOTP, MCC
- leak tests
- automatic/electrical checkouts.

Borescopes are used for some of the internal inspections. Instrumentation required for leak tests includes flowmeters and mass spectrometers. The periodic inspections involve the removal of either the HPOTP, HPFTP, or both. During this activity turbine blades are inspected using optical microscopy, and the respective preburner sections are inspected visually and with concentricity gauges. In addition to the physical inspections of the various engine components, the recorded flight sensor data is reviewed to identify anomalies. The results of this review are communicated to the inspection team when any action is deemed necessary.

Future SSME Condition Monitoring System. Rocketdyne is currently under contract with NASA LeRC to develop an advanced engine condition monitoring system. The first phase of this study involved an analysis of failure reports for a number of liquid-fueled rocket engines, including the SSME, J-2, H-1, F-1, RS-27, Thor, and Atlas. The failure reports were reduced by successive screening and the resulting reports categorized into sixteen general failure types.

- bolt torque relaxation
- coolant passage splits
- joint leakage
- hot-gas manifold transfer tube cracks
- high torque
- cracked turbine blades
- failure of bellows
- loose electrical connectors
- bearing damage
- tube fracture
- turbopump face seal leakage
- lube pressure anomalies
- valve fails to perform
- valve internal leakage
- regulator discrepancies
- contaminated hydraulic control assembly.

Sensors were subsequently evaluated based upon their ability to aid in the detection of the sixteen failure groups. An implicit philosophy during this selection process was that one sensor (or group of sensors) would be dedicated to each failure mode. A number of state-of-the-art and novel concepts were identified. The sensors selected from those concepts were:

- fiberoptic deflectometer
- optical pyrometer
- isotope wear detector
- tunable diode-laser spectrometer
- ultrasonic thermometer
- optical tachometer
- ultrasonic flowmeter
- digital quartz pressure sensor
- holographic leak detector
- thermal conductivity leak detector
- exo-electron fatigue detector
- connector continuity checking
- particle analysis.

Ultimately, the first three of these concepts were identified for development and testing. This program is currently in progress. Another of the sensors mentioned above, an ultrasonic flow meter, was tested during an NSTL test firing. Because of problems arising from the sensor mounting, a duct rupture occurred precipitating a catastrophic engine failure.

In addition to the identification of applicable sensors, the study identified and evaluated the required signal processing techniques for use with sensors to isolate the various failure modes. These techniques are:

- amplitude histogram
- RMS histogram
- filtered histogram
- cross correlation
- transfer function
- product histogram
- ratio histogram
- differentiated histogram
- phase diagram histogram
- time profile
- power spectrum density
- integral over threshold
- RPM profiles
- Cambell diagram

The various instrumentation vendors interviewed provided information regarding many of the currently implemented SSME and aircraft test programs. However, little information was obtained regarding new or novel instrumentation concepts.

Ultrasonic Doppler Vibration Sensor. Under contract with NASA MSFC, Battelle's Columbus Division developed a shaft vibration sensor and successfully tested it on a J-2 rocket engine. The sensor was of a non-invasive nature and determined the velocity of shaft vibrations by measuring doppler shifting from reflected ultrasonic waves. Although a success, this sensor was never developed further or utilized.

Aircraft

Sources for this part of the survey included interviews with experts from the military, commercial air carriers, airframe manufacturers, engine manufacturers, and instrumentation vendors. Information was also gathered from literature and interviews with Battelle experts.

Aircraft engines and their diagnostics have received considerable attention over the years. This attention is due to a number of factors, including the military's emphasis on weapon system availability, the civilian air carriers' push to minimize maintenance costs, and the FAA's desire to assure safety and reliability. Consequently, this part of the survey yielded a good deal of relevant information.

The current diagnostic/maintenance philosophies in the Air Force and the civilian air carriers are similar. The Air Force is attempting to establish a policy termed "retirement for cause". This concept is most easily described as an interactive preventative maintenance program. Component failures are carefully analyzed and accurate life indicators are derived for the engine components. The components will then be replaced only when a component is deemed to have degraded sufficiently that it will not last until the next periodic maintenance cycle.

The air carriers have a slightly different approach to maintenance. Given the need to reduce ground time and keep the aircraft flying as much as possible, a modified life limit approach to maintenance seems to prevail. An engine is used until a component failure occurs, albeit in some cases an incipient failure, or until life limits dictate a scheduled repair cycle. If the engine is being repaired after a component failure, additional components which would exceed their life limit prior to the next scheduled repair cycle may be replaced.

Both the military and the commercial carriers employ a multi-tiered maintenance structure. The first level is that of the flight line at which major modules are replaced. A second level is responsible for troubleshooting the modules that have been replaced so that they may be quickly placed back in inventory. The third (ultimate) repair level is that of the specialized shops. This level may also include the equipment vendors. Here the damaged components are repaired and returned to the inventory of good parts.

Data Acquisition. Commercial aircraft engines all come equipped with an array of accelerometers, temperature sensors, flow meters, pressure transducers, and tachometers. The presence of some of those transducers is due to FAA requirements placed on the manufacturers. While all of the airlines use the majority of the installed sensors, there has been some mistrust of the accelerometers. Historically, they have experienced high false alarm rates. As such, at least one airline removes them upon receipt of new engines. The sensor manufacturers insist that the current generation of sensors exhibit high reliability. Their claims seem to be substantiated by the number of airlines that do use the entire sensor package for sophisticated analyses such as trending.

Military aircraft engines usually carry many of the same transducers as commercial engines. They serve both control and diagnostic purposes.

In the area of ground-based test, visual inspections, borescope inspections, x-ray checks, eddy current checks, and oil analyses all find application. Some sophisticated instrumentation systems are employed to acquire data from engines in test cells. Temperatures, hot-gas flows and pressures, and other similar data are gathered for off-line analysis.

Signal Processing. The signal processing employed for data from on-board sensors is centered around the enhancement of signal-to-noise ratios. Techniques such as low-pass, high-pass, and band-pass filtering are common place. Features are sometimes generated using straight-forward approaches such as integrating acceleration signals to derive velocity information. Ground-based instrumentation employs similar signal processing approaches.

Diagnostic Techniques. The most common approach employed for on-board jet engine diagnostics relies on a table of limits. When a limit has been exceeded, the appropriate alarm is signaled and the response, if any, initiated. Recently, this approach has been extended or supplemented by some carriers who perform limited on-board trend analysis. Data gathered by on-board sensors are recorded at regular intervals (ranging from several seconds to several minutes). Trends are calculated in order to estimate when the measured parameters will exceed their "red lines". This estimate may be modified to allow for changes in the rate of degradation. Some air carriers are now relying on information from ground-based trend analyses to conveniently schedule engine repair.

One diagnostic technique used by both the military and the civilian air carriers merits discussion. This technique is referred to as "gas path analysis". Developed and popularized by Hamilton Standard, the approach involves the optimal estimation of the state, and subsequently the health, of jet engines. In practice, a mathematical model is developed which represents a simulation of a particular engine. Sensor data are then used as a gauge for the optimal adjustment of the model parameters. When those parameters exceed acceptable limits, a failure is declared.

At Kelly Air Force Base, the Air Force uses such a system for test cell analysis of engines. TWA has also recently purchased such a system from Hamilton Standard. In addition, TWA has initiated a program whereby sensor data is telemetered from their latest generation of aircraft, and a quasi-real-time analysis is performed to assess engine performance. The air carriers rely heavily on an integrated system where in-flight data is analyzed and used in conjunction with ground-based test results to plan maintenance actions.

An on-going research and development effort is focused on the concept of an expert system (artificial intelligence based computer program) for jet engine diagnostics. This concept is based on the transfer of human expertise to the expert system computer program. Although these systems are maturing very rapidly, they are not yet considered to be off-the-shelf.

Highlights. Items of particular interest which were obtained during the aircraft portion of the survey include:

USAF Retirement for Cause. The USAF is in the process of implementing a maintenance policy referred to as "retirement for cause". In short, this policy requires that an experimental analysis be performed on each batch of engine components in order to accurately understand and predict the life limits in the presence of the potential failures. For example, the level of propagation that a crack in a turbine vane must attain before failing will be empirically determined. Once these life limits are known (or at least estimated), the engine monitoring systems and periodic inspections are used to track engine component failures. Only when the life limits are approached are the faulty components replaced.

USAF On-Board Diagnostic System. An on-board engine monitoring system similar to the AIDS (see below) was experimentally implemented on five tactical F-15A aircraft (F100 Engines). The parameters monitored were:

- augmentor fuel pump discharge pressure
- augmentor permission fuel pressure
- burner pressure
- fan/core mixing pressure
- fan exit duct pressure
- fuel pump boost pressure
- fuel pump inlet pressure
- fuel pump discharge pressure
- main breather pressure
- number four bearing scavenge pressure
- rear compressor variable vane pressure
- fuel pump inlet temperature
- main oil temperature
- compressor exit static temperature
- fan exit duct temperature
- diffuser case vibration
- inlet case vibration
- power level angle position.

The on-board data acquisition system monitored these parameters and subsequently transferred the data for ground-based analysis. Such analyses, in conjunction with ground-based tests were used as the basis for a maintenance program. On the whole, the experiment was considered to be successful.

Experience with Commercial Carriers. Three domestic air carriers were interviewed in addition to making a review of literature describing some of the maintenance policies of European airlines.

Nearly all carriers utilize a variation of the aircraft integrated data system (AIDS). This data system was specified by ARINC and has the following attributes:

- diagnostic information is centralized
- some data is available for in-flight analysis
- data is recorded on a cassette tape for later ground-based analysis.

A number of carriers have implemented engine monitoring systems which are also integrated with the AIDS. In these systems, important engine parameters are monitored in-flight such as gas pressures and temperatures, fuel flows, rotor velocities, lubricant temperatures, and vibrations. Engine condition reports are available during flight to the flight engineer for short-term trending analyses. Long-term trending is performed using the AIDS data tapes during ground-based analyses.

In addition to the engine monitoring systems, ground tests and inspections are used to identify failures and trends. Ground-based inspections may include:

- visual inspection
- borescope inspections
- x-ray checks
- eddy current checks
- spectrographic oil analysis
- ferrographic oil analysis

The general consensus in the European air carrier community is that such sophisticated diagnostic and maintenance programs are cost justified. The domestic air carriers are not quite so aggressive. TWA, however, has a maintenance and diagnostic program which is very much along the lines of the European carriers. United Air Lines on the other hand, seems to employ a more conservative, people intensive approach to maintenance and diagnostics.

Gas Path Analysis. Hamilton Standard Division of United Technologies has been marketing a computer software package called Gas Path Analysis. This software relies upon a linearized mathematical model of a specific jet engine to estimate the performance characteristics of the engine's constituent modules using measured input parameters such as temperatures, pressures, spool speeds, and fuel consumption. The program also estimates the performance of the various sensors that are used to acquire the data used in the analysis.

The mathematics of gas path analysis is based on the premise that it is possible to linearize any thermodynamic cycle model by deriving matrices of influence coefficients which relate deviations in measured parameters and component performances to coefficients describing component faults for each of the engine's operating points. The equations solved are:

$$A = H\ X + \theta$$

$$Y = Ge\ Xe$$

where $X = \left(\frac{Xe}{Xs}\right)$ and $H = (He \mid Hs)$

The significance of the various variables is as follows:

- Z is a column vector of measurement deviations or deltas
- Y is a column vector of performance deltas for the engines' constituent modules

- Xe is a column vector of engine fault deltas
- Xs is a column vector of apparent sensor errors
- He and Ge are the matrices of coefficients derived from the engines' mathematical model
- Hs is a matrix of sensor fault coefficients
- θ is a random vector denoting sensor non-repeatability.

The dimensions are such that there is an over-specified set of equations which are a result of analytical redundancy in the measured parameters. It is also this fact which allows the determination of sensor errors as well as engine component malfunctions.

A number of air carriers use this technique for ground-based analysis. Some European carriers and TWA use the gas path analysis program for analysis of flight data. Other carriers and the USAF use it only for test cell analysis of engine performance.

Sensors and Instrumentation Development. The area of sensor development receiving the greatest amount of attention for flight applications is that of fiber optic sensors. These sensors are especially desirable from the standpoint of weight and noise immunity. At this stage of development, however, the fiber optic connector technology is not sufficiently robust to allow widespread use on flight engines. A recent NASA study has examined applications for fiber optic sensors such as:

- rotary encoders
- optical tachometers
- rotor blade tip clearance
- optical temperature sensors (pyrometers).

Optical pyrometers have also been used in experiments to accurately determine turbine blade life. Solar Turbines Incorporated has provided such instrumentation for a number of these experiments. Optical clouding due to the presence of combustion products has been the principal operational drawback of this type of instrumentation.

In the more general area of data acquisition, a number of instrumented engine core test programs have been carried out. An off-the-shelf system for telemetering data from an engine rotor is available from Acurex Corporation. These systems are not considered to be sufficiently robust for flight applications.

Expert Systems. There are at least two programs underway for the development of rule-based expert systems for jet engine diagnosis. On the military side, the Air Force has been funding such a development at General Electric. In the commercial sector, Boeing has also been developing an expert system for jet engine diagnosis.

Non-Aerospace Industries

Information sources for this part of the survey included interviews with experts in fields ranging from medical electronics to transportation systems. In addition, interviews were conducted with Battelle experts and relevant publications were reviewed.

In general, the industrial sector has been somewhat slow in recognizing the potential of machine diagnostics, but recently, there has been an increasing emphasis in this area. The motives for this interest are varied. For example, NRC regulations have had a strong influence on the nuclear power industry while customer support issues have had an impact on the use of diagnostics in the automobile industry. Whatever the motives, some interesting techniques have resulted which may ultimately be of value to the SSME program.

Data Acquisition. In the area of transducers, most industries have embraced the proven sensors, e.g., accelerometers, thermocouples, etc. The manufacturers of those devices have been developing more reliable and "ruggedized" transducers and recognize that their sensors will be located in progressively more hostile environments.

In terms of sensing concepts, a number of techniques in development or use merit discussion. These concepts are described in the following paragraphs.

In the nuclear power industry, a device known as a miniature accelerator or MINAC has been developed for radiographing pump housings. The device is placed inside the housing and photographic film is placed around the outside of the housing. Once activated, the MINAC generates radiation that penetrates the pump and exposes the film--from the inside-out. This device has simplified a difficult imaging problem.

For the conventional power industry, Solar Turbines Incorporated is under contract with the Electric Power Research Institute to instrument a gas power turbine with an optical pyrometer. The pyrometer is positioned to scan the passing turbine blades and provide measurements leading to accurate predictions of the blades' life.

A number of novel fiberoptic-based sensors have been under development. An example of this is the laser-doppler-velocimeter (LDV) which measures the velocity, not speed, of moving material. The material being measured can be a solid or a fluid. Because of its optical nature, the information can be communicated from the moving medium to the sensor by optical fibers. This sensor is already finding application in the manufacture of synthetic fibers.

A new class of semiconductor devices for measuring the presence of various elements has been under development. This device is called an ion selective field effect transistor (ISFET). These devices have been proposed for measuring such parameters as hydrogen concentrations in gases, and glucose levels in human blood. ISFETs have certain stability problems that have not as yet been resolved.

Cooperative sensing schemes are finding increased usage. The principal behind this concept is not new: the design of the system or component to be examined is altered so as to provide a clear, unmistakable signature which is easily monitored. Putting a tracer in a gas to measure concentrations and flows represents a well developed application of this technique. In a more recent example, bearing balls where magnetized to allow the monitoring of their behavior by simple magnetic field sensors.

For the storage of performance data, the memory card, an extremely portable device, is gaining popularity. This device is comprised of a microcomputer and nonvolatile data memory in a very small package (typically the size of a credit card). Memory cards, because they are inexpensive and portable, can permit the highly accurate tracking and monitoring of modules and components as they progress through the repair cycles. Unfortunately, the storage capacities of the data memory are still limited.

Vibration monitoring is common in numerous industries ranging from petrochemical plants to paper mills. For example, at Exxon's petrochemical plant in Baytown, Texas much of the machinery is continuously monitored using a minicomputer and on-board accelerometers. The signal levels of the accelerometers are analyzed to determine trends. Based upon such trends, maintenance can be optimally scheduled. In this same plant, such phenomena as pump cavitation were also detected by more careful analysis of the accelerometer signals. However, the ability to gather this additional information has not been integrated into the monitoring system.

Signal Processing. In the realm of signal processing, the most impressive developments have been in the area of hardware. Integrated circuits are now available which perform such functions as real-time digital filtering or real-time Fast Fourier Transforms. A manufacturer of charge-coupled-device (CCD) arrays, EG&G Reticon, also manufacturers semiconductor devices which perform many of the filtering and analysis functions in the discrete time analog domain. Prior to the availability of those devices, these filtering techniques were only possible using digital electronics.

In the continuous time domain, a number of sensors have been developed for specific applications to perform filtering functions in a non-electronic fashion. One well developed example of this approach is the use of a tuned acoustic transducer for the monitoring of predetonation in GM automobile engines. This approach was used by GM in a effort to minimize production costs.

In the field of automated inspection systems a good deal of progress has been made in image processing and image interpretation. Commercial systems are now available for the automated inspection of pieces on an assembly line for manufacturing defects. Similar techniques have been developed for the autonomous inspection of printed circuit boards. This area will likely continue to evolve due to the recent successes.

Recent research in the human factors associated with display technology is directed toward the presentation of high level information, rather than machine parameters, in a graphical format. In industries such as nuclear power, the operators of the systems need diagnostic information in a high-level and unambiguous format, thus, permitting the decisions to be made quickly and accurately via human pattern recognition.

Diagnostic Techniques. The approaches used in the industrial sector for making diagnostic decisions span the entire spectrum, from the simple table lookup technique employed on most automobiles, to expert system computer programs for the diagnosis of failures in train locomotives. Of the information gathered during this part of the survey, there are several concepts worth mentioning. These make up the remainder of this section.

General Electric Corporation has developed an expert system (computer program) for the diagnosis of failures on railroad locomotives. In this approach, the computer program was written to reason and draw conclusions based upon a set of rules. The set of rules is derived from interviews with human experts in the area (that of repairing GE's locomotives). In operation, the expert system guides the actions of a repair technician. This is only one of several diagnostic "experts" that have been developed: Westinghouse's Steam Turbines Division has developed a diagnostic expert system for steam turbines. The Westinghouse program, moreover, identifies sensor malfunctions as well as turbine component failures.

On-going research in the area of non-linear diagnostic filters promises to improve their performance by increasing sensitivity and reducing false alarm rates. In one particular effort involving Case Western Reserve University and Bailey Controls Division of Babcock and Wilcox, an industrial heat exchanger will be the test bed for an improved non-linear diagnostic filter. The benefits of such research efforts are likely to be incremental in nature, but available in the relatively short term.

The commercial application of pattern recognition based upon statistically derived and/or empirically determined features has been a reality for a number of years. The benefits of this approach is that the computation times for making decisions about a machine's performance can be very brief. Other computationally oriented techniques, non-linear diagnostic filters and expert systems, typically require substantially more time than pattern recognition. Historically, most pattern recognition systems have been custom tailored to the signatures of single specific machines, rather than, for example, other identical machines. This shortcoming has been addressed through the use of adaptive pattern recognition systems.

Vibration trend analysis is becoming a commonly used technique, especially in industries such as petrochemicals and paper manufacturing. This technique usually involves the monitoring of vibration sensors (most often the integrated outputs of accelerometers) to watch for change. The rate of increase is estimated, and repairs scheduled according to the estimated time until a failure occurs.

Predictive diagnostics based upon ferrographic analysis of lubricant has been a reality for a number of years. This technique is based upon the gathering and analysis of wear particles to determine the mechanisms and severity of wear. While there are machine mounted sensors available for automated ferrographic analysis, the most thorough analyses are performed off-line using bichromatic microscopy.

Voting systems have been used to address anticipated failures (i.e., those failures that result from known component failure modes). However, unanticipated faults due to such causes as design errors cannot be addressed by voting systems. The more complex a machine, the greater is the likelihood of latent design errors.

Recommendations

Given the nature of the SSME environment and maintenance structure, several of the approaches and techniques identified in the previous section are recommended. We will hold to the same organization that has been used throughout this report. These recommendations are further summarized in Table 3.

Data Acquisition

To the extent possible, those existing on-board sensors which have experienced reliability problems, should be considered for replacement. As existing sensors are continually improved for sensitivity and durability, they should be examined and, as warranted, tested and considered for use on the SSME. A sensor data base would be beneficial for both the SSME, and for future rocket engine development programs.

The on-board sensors should be more effectively used. For example, the accelerometers currently on the SSME are only used for the RMS values of their outputs. There is undoubtedly a great deal of information available in the higher frequency harmonics that is not being used. The full bandwidth of all existing sensors should be recorded onboard and the data later used for detailed ground-based analysis. It also may be possible to telemeter this recorded data while the STS is on orbit.

TABLE 3. SUMMARY OF DIAGNOSTICS RECOMMENDATIONS

Diagnostics Category	Recommendations On-Board	Recommendations Ground-Based
Data Acquistion	More Reliable Sensors Increased Bandwidth for Existing Accelerometers and Transducers (pressure, temperature, flow, and speed) Additional Conventional Sensors Extensive Data Recording Continued Development of: Optical Pyrometer Fiber Optic Deflectometer Ultrasonic Doppler Transducer Ultrasonic Flow Meter	Continued Development of Isotope Wear Detector Extension of Isotope Wear Detector Concept to Include Ferrographic Analysis Use of Tracer Elements (Tritium or Sulfur Hexafluoride) for Leak Detection
Signal Processing	Improve S/N Ratios by Spectral Filtering and Noise Cancellation	Image Processing to Enhance Borescope Inspections
Diagnostic Techniques	Analysis and Development of Pattern Recognition Diagnostic System	Develop Gas Path Analysis Model of SSME Evolve Gas Path Analysis Model to Include Non-Linear Diagnostic Filter Establish and Maintain Integrated SSME Data Base (diagnostic and maintenance)

It is estimated that upwards of 85 percent of all failures are intermittent in nature. Over the course of our survey, two approaches to the isolation of intermittent failures were identified: marginal testing and extensive logging. The use of marginal testing techniques on the SSME is not feasible. Therefore, we recommend that extensive on-board recording of the engine be performed. By analyzing this extensive amount of data, either on the ground or on-board, intermittent problems may be identified and isolated. In addition, the extra sensors required for such monitoring will augment the analytical redundancy of the diagnostic system.

The sensors proposed by Rocketdyne for the monitoring of turbomachinery should be carried through to application. Specifically, the optical pyrometer, fiberoptic deflectometer, and isotope wear detectors, will significantly improve the information available on the health of the turbopumps. In addition, the isotope wear detector program should be extended to encompass ferrographic analysis. Numerous precedents suggest that this type of analysis would be valuable for predictive diagnosis.

For ground-based inspections, we recommend that tracing elements should be considered to aid in the detection of hydrogen and other fluid leaks. It is felt that this would result in the simplified sensing apparatus.

Signal Processing

For ground-based tests, image processing should be used to augment certain inspection processes, especially the borescope inspections. It is believed that such techniques could both improve the accuracy, and reduce the time required for inspections.

For on-board instrumentation, more elaborate signal processing will be required. Given the noise environment of the SSME, both spectral filtering and statistical noise cancellation techniques could be used to provide improved signal-to-noise ratios. High signal-to-noise ratios are essential if the existing sensors are to be more fully utilized.

Diagnostic Techniques

In the arena of diagnostic techniques there are three recommendations, one for on-board diagnosis and two for ground-based analysis. The principal purpose of the on-board diagnostics is to avert rapidly developing, catastrophic failures. Because of the speed of diagnosis and level of accuracy required, pattern recognition is the only realistic technique. To increase the coverage and accuracy of the on-board diagnostic system, a pattern recognition-based diagnostics should be considered.

For ground-based analyses, an effort to improve the analytical model for the SSME should be undertaken. In conjunction with such a model, a non-linear diagnostic filter should be developed. This effort might begin by initiating a gas path analysis program, and improving the analysis on an incremental basis. It may even be possible to run such a program in real-time based upon telemetered data (given adequate computing resources). If the system is sufficiently accurate, detailed trend analysis capabilities could result.

Finally, a thorough and highly integrated data base should be established to track and correlate information about engines and components. Information from on-board sensors, ground-based inspections, repair actions, and component histories should be included. Analysis of this data base must be made highly interactive to be most effective. Ultimately, such a data base could benefit the SSME maintenance staff, the operations staff, and the engine component manufacturers.

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SSME DIAGNOSTIC EVALUATION

The third task of the SSME study is intended to assimilate the outputs of the SSME failure data review and the diagnostics survey and to use this information for evaluating the current SSME diagnostic system. The principal objective of this task is to identify potential means for improving the availability of high-quality, pertinent engine data. This information will be used both in-flight and on the ground to assess the condition of the SSME and its respective components. To accomplish this objective, an analysis tool has been selected to perform a systematic examination of the diagnostic information in the SSME. This tool (Failure Information Propagation Model) and its initial application to an SSME component is described in this section.

Issues and Approach

To evaluate the overall SSME diagnostic system, the information gathered during the failure data review and diagnostic survey must be integrated and analyzed. At the outset of this evaluation task, the following data were available:

- Results of the SSME failure data review
- Knowledge of the existing SSME inspection and maintenance process
- Knowledge of the current SSME sensors
- Information on sensor research and development underway for the SSME
- Results of the diagnostic survey.

This information was believed to provide a solid foundation for performing the required evaluation.

The first step in the analysis was to select the actual tool or technique to be used. To facilitate selection of a suitable analysis method, an overall approach was defined for the task. The approach adopted centered on addressing several key diagnostic issues. These issues included the following:

- What additional diagnostic information is available to the existing SSME sensors?

- Are there any information rich test points on the SSME that should be instrumented? If so, which sensors should be considered?
- How can we optimize the placement of additional sensors so as to minimize their total number and cost while maximizing their information gathering potential and reliability?
- Which instrumentation research and development areas represent the best investment relative to the diagnostic needs of the SSME?

The common denominator for all of the issues mentioned above is an understanding and characterization of the engine failure information and its flow paths.

The major focus of the initial effort on this task was directed, therefore, at finding a suitable means to represent the SSME failure information and at developing a data format which could be easily manipulated to address each of the above issues. The tool which appeared to satisfy all of the proposed requirements was the Failure Information Propagation Model (FIPM). The FIPM concept is discussed in the following subsection.

Failure Information Propagation Model

The Failure Information Propagation Model (FIPM) is a technique developed by the Battelle Columbus Division to qualitatively evaluate the potential test points in a system. The objective of this qualitative evaluation is to assess the information bearing value of each test point. The FIPM basically divides the system under analysis into its principal components or functions, describes the failure modes for these components, catalogs the physical connections between the components, details the flow of failure information through the various connections and groups the failure information according to signalproperties. It must be emphasized at this point that the FIPM models the propagation of failure information and not the failure itself. The model assumes that the system being depicted is in a near-normal state of operation. The failure information flow is described for the instant of time immediately following a given failure.

The FIPM was initially developed to evaluate the factors affecting copy quality in a photographic copy machine. This proprietary study was performed for an industrial client. Due to the nature of the system involved, this analysis was primarily concerned with the electronic functions of the device. Subsequent to this study, the FIPM was applied to an ion chamber and a home furnace. All of this work preceded the FIPM's consideration for this task. As a result of this early work, the FIPM has demonstrated the capability to adapt to a broad range of mechanical and electronic systems.

Three principal applications exist for the output of this model. These applications are:

- Design of sensor systems for new devices or components
- Evaluation of existing sensor systems to maximize the information yield
- Identification of sensor research and development needs to target key diagnostic data.

These important features of the FIPM made it especially attractive for use in the SSME diagnostic evaluation.

FIPM Example

The formulation of an FIPM must begin with the identification of the modules (components or functions) that comprise the system being evaluated. These modules may be piece parts, subassemblies, or subsystems depending on the level of detail sought. In the case of a typical exhaust fan, which is used here solely as an example, the constituent modules are subassemblies which have been selected to illustrate a top-level FIPM. In the case of the high-pressure oxidizer turbopump (HPOTP) FIPM which will be discussed later in this section, the constituent modules generally are piece parts.

The modules selected to illustrate the FIPM concept for the exhaust fan are the AC motor, the fan belt, the fan, the fan bearing, and the frame which supports these components. These elements are shown in Figure 14. The resulting model is very simple in that the AC motor actually has both electrical and mechanical parts, the fan has both blades and a pulley for the drive belt, etc. It is recognized that this model ignores many factors which would be considered in a thorough engineering analysis.

The network of connections between the exhaust fan modules is depicted in Figure 15. As indicated in this figure, the motor is mechanically mounted to the frame and transforms electrical power into mechanical power

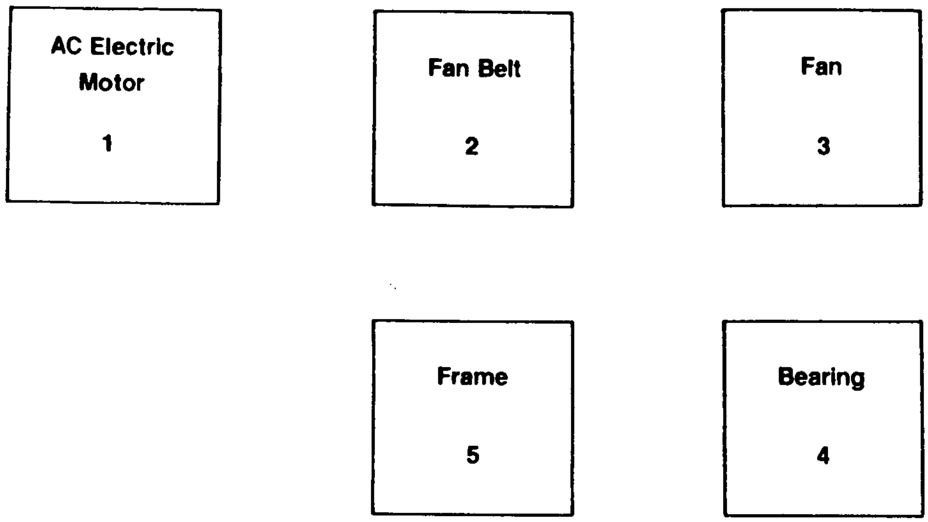

FIGURE 14. MODULES COMPRISING EXHAUST FAN FIPM

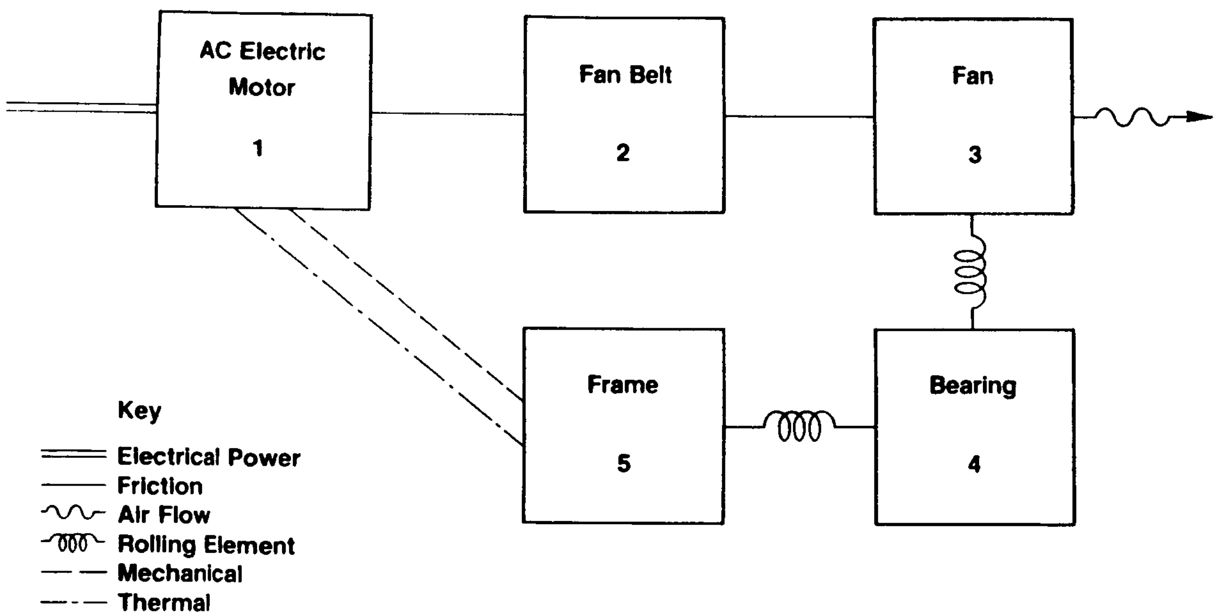

FIGURE 15. CONNECTIONS BETWEEN EXHAUST FAN MODULES

through friction with the fan belt. The fan belt also is connected by friction to the fan. The fan and frame are joined through the bearing by means of rolling elements. A thermal connection also exists, in normal operation, between the AC motor and the frame. The final element in the network is an air flow path out of the fan.

The failure modes of each of the exhaust fan modules is shown in Figure 16. It should be noted that these failure modes do not include mechanisms which are external to the module. Failures due to such outside causes as fire, explosion, or mechanical damage are not considered. Events such as fire in the fan motor also are not considered since these are actually effects of more fundamental failure modes. It should be reiterated that the FIPM is modeling the situation immediately following a failure and not the longer-term effects and consequences of that failure.

The occurrence of any exhaust fan failure mode produces failure information which can be detected externally to the component and which will, in general, be transmitted to adjacent components. An assessment of the failure information propagations for the exhaust fan example is shown in Figure 17. It is interesting to note that, in this example, all of the failure modes transmit failure information to all of the other modules. The large amount of failure data which is available at any given connection in the system is evident in this figure.

The failure information in the current example can be further categorized at each connection according to the type of measurement or sensor required for detection. An open winding [1C] or breakage of the fan belt [2B] could be detected by an ammeter on the electrical line. Similarly, binding of the motor [1A], a shorted winding [1D], or dirt on the fan [3B] can be detected by a voltmeter across the motor terminals. In Figure 18, the failure information for each connection has been grouped according to the type of measurement involved. This clustering of the failure information is the final step in the development of the FIPM. Analysis of the data in the model can now be initiated.

A sensor of the appropriate type would detect any or all of the failure modes within a particular group. It would be necessary, therefore, to provide additional information or to further process the signal to uniquely identify any single failure mode. The process of determining the failure signatures and respective sensor sets is highly detailed and has not been undertaken for the exhaust fan example.

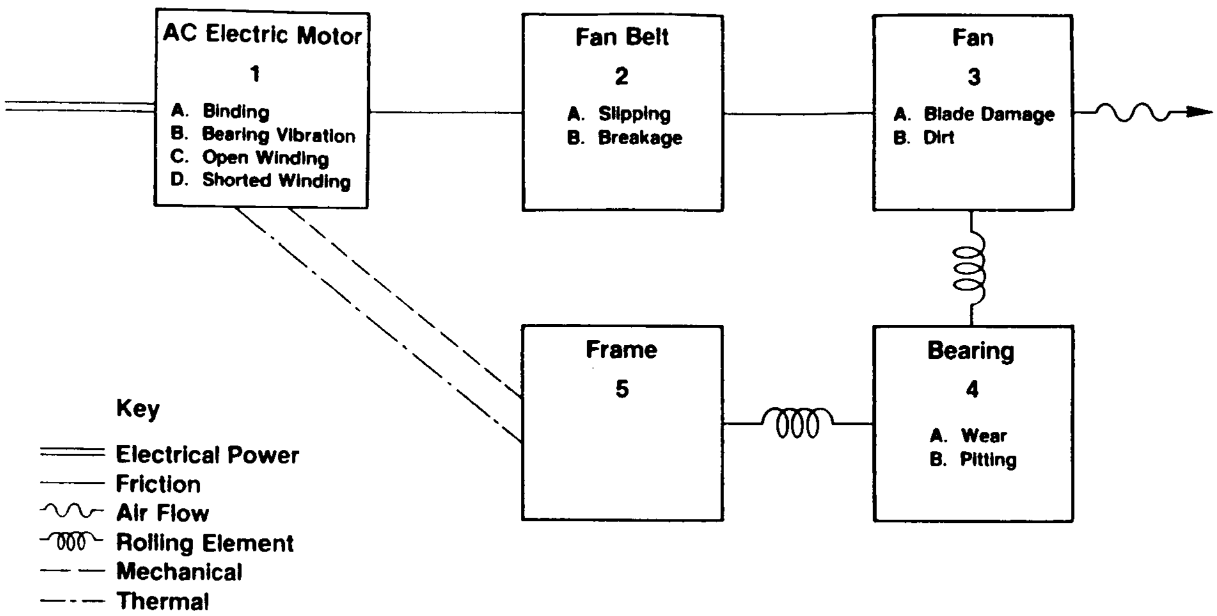

FIGURE 16. ADDITION OF FAILURE MODES TO EXHAUST FAN FIPM

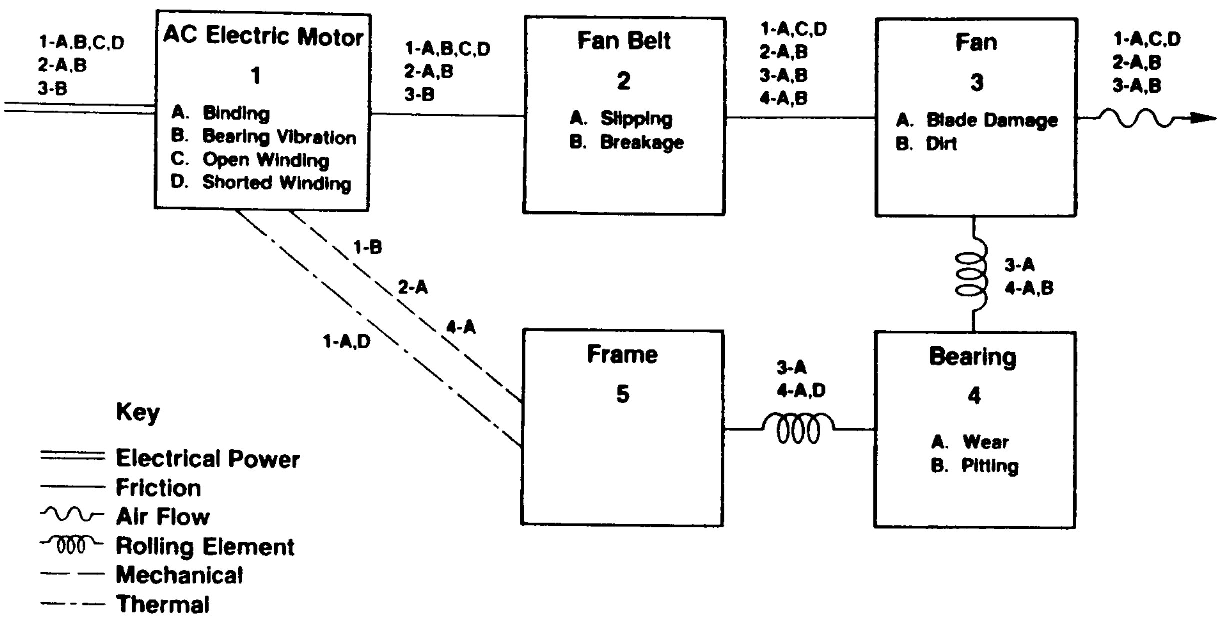

FIGURE 17. FAILURE INFORMATION ASSOCIATED WITH EXHAUST FAN CONNECTIONS

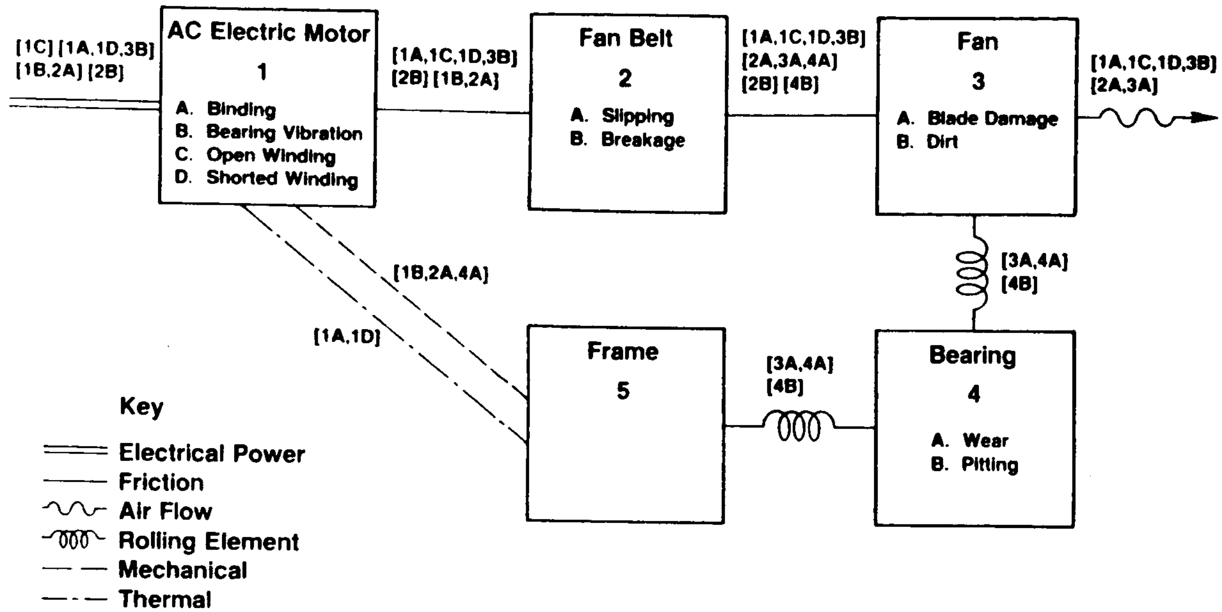

FIGURE 18. FAILURE INFORMATION GROUPED BY SIGNAL TYPE FOR THE EXHAUST FAN FIPM

High-Pressure Oxidizer Turbopump FIPM

The high-pressure oxidizer turbopump (HPOTP) was selected as the initial SSME component for evaluation using the FIPM. An HPOTP FIPM was graphically constructed using the steps outlined in the preceding example. The resulting model was quite large due to the complex nature of the HPOTP. A large portion of the initial representation also was color coded for ease of interpretation. Due to both of these factors, the initial HPOTP FIPM is unsuitable for inclusion in this report. An attempt will, however, be made to describe the significant features of this model and the subsequent analysis which was performed. The version of the FIPM which will be described in this section is no longer the baseline configuration for the HPOTP. The reasons for this situation will be discussed. The revised FIPM approach which is currently being used is outlined in a subsequent subsection.

The original HPOTP FIPM had the following features:

- 46 modules
- 100 module failure modes
- 59 connections
- 2248 failure information propagations.

A small black and white excerpt of this FIPM is shown in Figure 19. A key for this graphic is included as Figure 20. All of the data comprising the FIPM was displayed on the graphic representation.

Subsequent to the development of the HPOTP FIPM, a preliminary analysis of the HPOTP failure information was performed using a failure information matrix. A portion of this matrix is shown in Figure 21. In this matrix, the rows represent connections (test points) between modules. The columns correspond to specific module failure modes. The data entered in the matrix at the intersection of a given row and column is the failure information types associated with the designated failure mode which can be detected at the designated connection. This matrix was used to develop a preliminary set of test signature equations for the HPOTP.

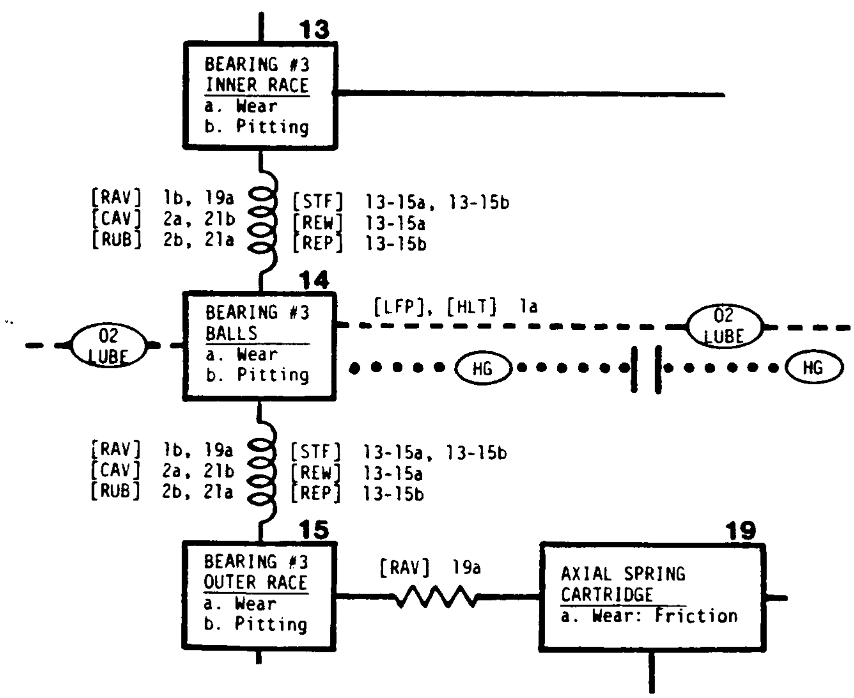

FIGURE 19. EXCERPT FROM INITIAL HPOTP FIPM

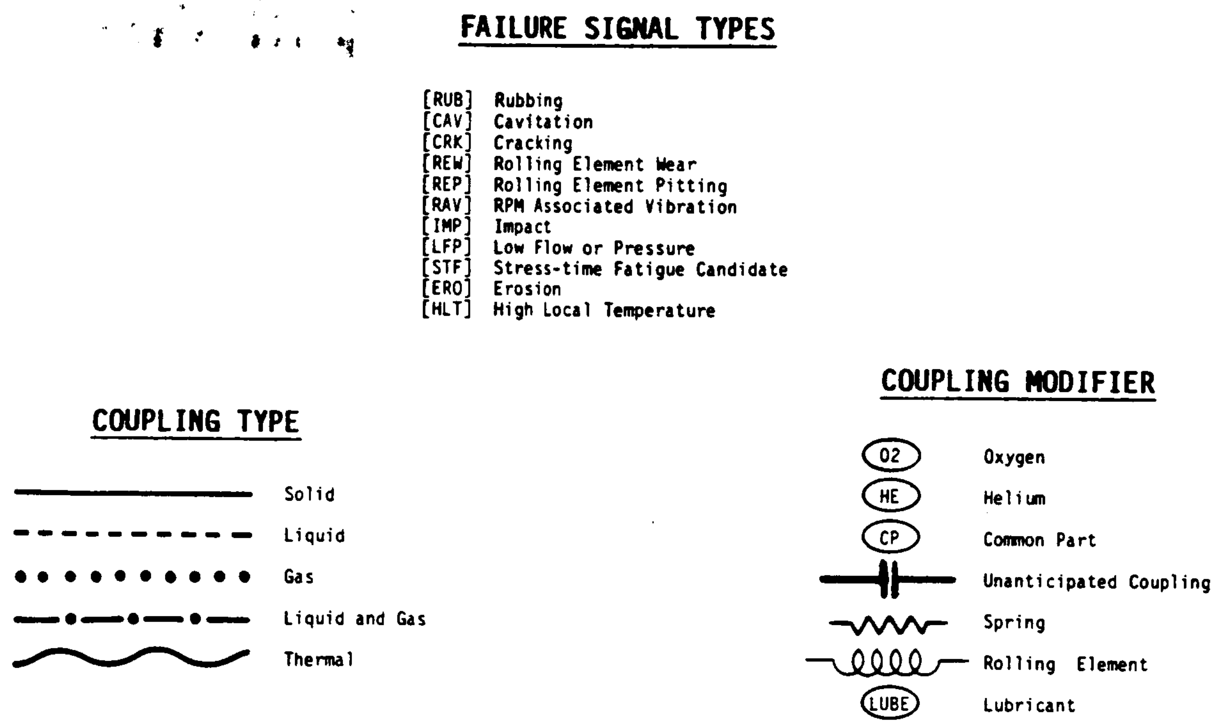

FIGURE 20. KEY FOR INITIAL HPTOP FIPM

The test signatures were formulated by marching through the columns of the matrix. For each column, the rows were examined to determine where failure information resided. The rows also were scanned to identify other failure data present at the connection which exhibited the same signal characteristics (i.e., high temperature, low pressure, etc.). By careful evaluation of the matrix, it was possible to determine sets of signals which could be used to uniquely identify specific failures. Some examples of the initial results included:

- Failure mode 1B = rpm associated vibration @ test point 34 OR
  = rpm associated vibration @ test point 36 OR
  = rpm associated vibration @ test point 38
- Failure mode 2A = cavitation @ test point 5 AND NOT
  cavitation @ test point 1

TEST POINT No.	COMPONENT NUMBERS	COMPONENT INTERFACE	TYPE OF INTERFACE	1. SHAFT: a. LUBE PASSAGE BLOCKED: CONTAMINATION	1. SHAFT: b. VIBRATION: BALANCE	2. PUMP IMPELLER: a. WEAR: CAVITATION	2. PUMP IMPELLER: b. WEAR: RUBBING	2. PUMP IMPELLER: c. IMPELLER DAMAGE: SECONDARY FAILURE	2. PUMP IMPELLER: d. CRACKING: VIBRATION & THERMAL	3. INPUT/OUTPUT MANIFOLD: a. WEAR: RUBBING (2b)	3. INPUT/OUTPUT MANIFOLD: b. WEAR: CAVITATION (2a)	3. INPUT/OUTPUT MANIFOLD: c. CRACKING: VIBRATION & THERMAL	4. OUTLET DUCTING: a. FRACTURE: VIBRATION & THERMAL	4. OUTLET DUCTING: b. CRACK OR LEAK: SECONDARY FAILURE	5. AXIAL BALANCE CAVITY STRUCTURE: a. WEAR: FLUID	5. AXIAL BALANCE CAVITY STRUCTURE: b. LOOSEN: FASTENER	5. AXIAL BALANCE CAVITY STRUCTURE: c. WEAR: RUBBING	6. INLET DUCTING: a. DAMAGE: SECONDARY FAILURE	6. INLET DUCTING: b. FRACTURE: VIBRATION & THERMAL	a. WEA…	
1	3 - 45	INLET/OUTLET MANIFOLD TO PUMP HOUSING	MECHANICAL		RAV		RUB				CAV	STF CRK	CRK STF	CRK IMP		RAV	RUB	CRK IMP	CRK STF	REW STF	I S
2	6 - 45	INLET DUCTING TO PUMP HOUSING	MECHANICAL		RAV		RUB				CAV	STF CRK	CRK STF	CRK IMP		RAV	RUB	CRK IMP	CRK STF	REW STF	REP STF
3	INLET - 6	INLET TO INLET DUCTING	MECHANCIAL															IMP CRK	STF CRK		
4	3 - 5	INLET/OUTLET MANIFOLD TO AXIAL BALANCE CAVITY STRUCTURE	MECHANICAL							RUB	CAV	CRK STF			CAV	RAV	RUB				
5	1 - 2	SHAFT TO PUMP IMPELLER	MECHANICAL	HLT	RAV	CAV	RUB	CRK IMP	CRK STF	RUB						RAV	RUB			STF REW	ST' R'
6	4 - OUTLET	OUTLET DUCTING TO OUTLET	MECHANICAL										STF CRK	IMP CRK							
7	2 - 3	PUMP IMPELLER TO INPUT MANIFOLD	MECHANICAL UNANTICIPATED																		

FIGURE 21. FAILURE INFORMATION MATRIX FOR INITIAL HPTOP FIPM

- Failure mode 2B OR
- Failure mode 3A OR
- Failure mode 5c = rubbing @ test point 4.

No attempt was made to determine a unique signature for certain classes of failure modes. In cases such as the turbopump bearings, it is not necessary to know which particular bearing is bad. An indication that any of the four bearings is experiencing degradation is sufficient cause to remove the turbopump from the engine and overhaul the bearings.

Subsequent efforts to specify a set of diagnostic sensors which would target all of the high-priority HPOTP failure modes, as identified in the SSME failure data review, encountered difficulty due to the need for additional data. The model, as constructed, did not have sufficient detail to adequately describe the failure signals. It was determined that specifying high temperature was insufficient without some sort of associated range. This initial application of the FIPM methodology to a complex mechanical system had also demonstrated the need for more formal definitions and standardized development rules. The definitions and development rules had previously been instituted on an ad hoc basis as the need arose. A decision was reached to restructure the HPOTP FIPM based on a more formal development methodology.

Revised FIPM Methodology

The revised FIPM methodology was prepared by the originator of the FIPM concept with major inputs provided by the participants in the initial FIPM activity. A number of definitions and rules resulted from this process which will be documented at a later date. The definitions, in general, concerned the types of physical connections, failure modes, signals, and signal parameters which can be used in constructing the FIPM. These definitions have been made with respect to fundamental physical properties and laws. Their intent is to reduce the number of arbitrary and possibly confusing choices which must be made during model formulation. The rules relate to the handling of certain situations which otherwise might be ambiguous.

It was also decided that the new FIPM procedure should be implemented in a data base format. This step was necessary to accommodate the large amounts of information which were projected for the SSME models. After consultation with the technical staff at both NASA Headquarters and NASA MSFC, Digital Equipment Corporation's Datatrieve data base management system was selected for use in this application. This system was chosen in large part because of its availability at NASA MSFC and the substantial base of experience which existed at both Battelle and at MSFC.

The revised FIPM methodology still uses a graphical representation of the system. However, the failure information propagations are no longer shown on this diagram. The graphical representation includes only the modules, module failure modes, and the connections between the modules. All of this data is used extensively during the propagation of the failure information throughout the system. The information displayed on the FIPM diagram is also stored in the data base along with the failure information propagations. The data base also allows additional descriptive data to be stored concerning the modules, module failure modes, and connections between the modules. Incorporation of this data would have been impossible with the original graphic model.

FIPM Status

The revised FIPM methodology has been completed. It is recognized, however, that any procedure such as the FIPM must always undergo some expansion and modification. The development methodology does allow for flexibility but such changes should be made only after careful consideration of all the consequences. The methodology will be documented in the final report covering the on-going phase of this study.

The software associated with the FIPM data base is currently under development. This software will be documented at the time of delivery to NASA MSFC. MSFC will be provided with a magnetic tape containing all of the input, modification, and listing procedures developed. All SSME FIPM data generated during the conduct of this study also will be transferred to MSFC.

The revised HPOTP FIPM presently is being formulated in parallel with the development of the FIPM data base software. The completed HPOTP FIPM will be documented in a separate technical report. This report will include the FIPM graphic representation and listings of all the HPOTP information stored in the data base.

The process of implementing the data base and producing the HPOTP FIPM is a highly interactive situation. The data definitions associated with the various data files affect the information which must be generated for the HPOTP. Likewise, situations or problems encountered during the loading of the HPOTP data can affect the design and implementation of the FIPM data base. The completion of the HPOTP FIPM should resolve the majority of these issues and interactions.

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ON-GOING RESEARCH

A number of activities are currently in progress or planned in connection with this study. The tasks which presently are being worked include:

- Development of FIPM data base software (previously discussed)
- Generation and loading of FIPM data for the HPOTP (previously discussed).

The efforts which are currently planned include:

- Generation and loading of FIPM data for the following SSME components:
  - high-pressure fuel turbopump (HPFTP)
  - low-pressure oxidizer turbopump (LPOTP)
  - low-pressure fuel turbopump (LPFTP)
  - oxidizer preburner (OPB)
  - fuel preburner (FPB)
  - main combustion chamber (MCC)
  - heat exchanger (HE)
  - main injector
  - nozzle
- Assessment of candidate diagnostics
- Analysis of existing engine data
- Examination of on-board implications of SSME diagnostics
- Recommendations for diagnostic system development.

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DATA SOURCES

Information for the diagnostic survey was obtained through numerous contacts in government and industry. The following is a listing of many of the government and industry sources used.

Liquid-Fueled Rocket Engine Diagnostics

- Aerojet
- Battelle Columbus Division
- Bentley Nevada
- Honeywell
- NASA LeRC
- NASA MSFC
- Perkins Elmer
- Pratt and Whitney
- Rocketdyne

Aircraft Diagnostics

- Battelle Columbus Division
- Battelle Geneva Division
- Boeing
- Eastern Airlines
- General Electric
- Hamilton Standard
- Pratt and Whitney
- Rolls Royce
- Solar Turbines Incorporated
- Trans World Airlines
- United Airlines
- USAF Griffiss Air Force Base
- USAF Kelly Air Force Base
- USAF Wright-Patterson AFB
- Vibrameter

Non-Aerospace Diagnostics

- ATE Management and Service Company
- Battelle Columbus Division
- Battelle Geneva Division
- Bently Nevada
- Case Western Reserve University
- Department of Defense
- Detroit Diesel Allison
- IRD Mechanalysis
- Marsh-McBirney
- The Ohio State University
- Scientific Atlanta
- Sensor Developments Incorporated
- Solar Turbines Incorporated
- StrainSert
- Universal Engineering
- United States Army MICOM
- Vibrameter

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APPENDICES

APPENDIX A

UCR REVIEW

Preliminary Distribution of UCRs by Component

UCR DATA REDUCTION

Component	Description	Total No. of UCR'S	CRITICALITY 1	2	3	N*
A100	Hot Gas Manifold	80	2		77	1
A150	Heat Exchanger	18	4		12	2
A200	Main Injector	175	5	3	162	5
A330	Main Combustion Chamber	105	1	3	98	3
A340	Nozzle	296		2	285	9
A600	Fuel Preburner	171		2	165	4
A700	Oxidizer Preburner	13			13	
B200	High Pressure Fuel Turbopump	457	3	11	429	14
B400	High Pressure Oxidizer Turbopump	331	7	11	302	11
B600	Low Pressure Fuel Turbopump	59		3	49	7
B800	Low Pressure Oxidizer Turbopump	92			89	3
C100	Check Valves	11			10	1
C200	Pneumatic Control Assembly	7			7	
C210 C250 C270 C300	Solenoid Valves, Pressure Activated Valves, Pneumatic Filter, and Helium Precharge Valve	11			11	
D110	Main Fuel Valve	15			14	1
D120	Main Oxidizer Valve	14			13	1
D130	Fuel Preburner Oxidizer Valve	12			11	1
D140	Oxidizer Preburner Oxidizer Valve	28			27	1
D150	Chamber Coolant Valve	9			9	
D200	Bleed Valves	4			4	
D300	Antiflood Valve	18	2	1	15	

*No criticality.

UCR DATA REDUCTION (CONTINUED)

Component	Description	Total No. of UCR'S	CRITICALITY 1	2	3	N
D500	GOX Control Valve	8			8	
D600	Recirculation Isolation Valve	9			9	
E001	Main Valve Actuator	23		1	22	
E002	Preburner Valve Actuator	20			19	1
E110	Main Fuel Valve Actuator	35		1	33	1
E120	Fuel Preburner Oxidizer Valve Actuator	8			8	
E130	Oxidizer Preburner Oxidizer Valve Actuator	9		1	8	
E140	Main Oxidizer Valve Actuator	5			5	
E150	Chamber Coolant Valve Actuator	25	1	2	22	
E201	RVDT	3			3	
E202	Servovalve	0				
E203	Torque Motor/Servo	0				
F000	Controller	265		167	98	
F500	Software (Not Reviewed)	0				
F600	GSE, Controller	3		1	2	
F700	CADS Software (Not Reviewed)	0				
F800	FASCOS	29		10	17	2
G000	Igniter	76			62	14
H000 H001 H002	Electrical Harnesses	105		15	77	13
J200	Pressure Sensor	84		4	70	10
J300	Temperature Sensor	113		15	96	2

UCR DATA REDUCTION (CONTINUED)

Component	Description	Total No. of UCR'S	CRITICALITY 1	2	3	N
J600	Flow/Speed Pickup	13		2	10	1
J700	Fuel Flowmeter	0				
J800	Accelerometers	7			5	2
K100	Fuel Line/Duct	81		1	79	1
K200	Oxidizer Line/Duct	32	1		31	
K300	Drain Line	5			5	
K400	Hydraulic Line	3			3	
K500	Pneumatic Hose/Line	9			8	1
K600	Controller Cooling Duct	5			5	
L000	Static Seal	18			18	
L200	Stretch Bolts	7			7	
L300	Leakage (Joint)	4			4	
M000	Gimbal	9			9	
N100	Interconnect Hardware	3			3	
N200	Thermal Protection	5			5	
N300	Engine Venicle Interface	0				
N400	POGO Accumulator	3			3	
N600	ASI, Lee Jet Orifices	6			6	
N700	Line Orifices	0				
Q000	GSE (Not Reviewed)	0				
Q500	Closures	0				

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APPENDIX B

UCR REVIEW

Preliminary Listing of Failure Types by Component

A100 HOT-GAS MANIFOLD

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N*
1	Cracks in Liner					
	(a) Thermal & Vibration Loads--Redesigned	18			18	
	(b) Not Heat Treated--Heat Treat	1	1			
2	Weld Cracks--Defective Weld--Fab. Modified	16			16	
3	Contamination					
	(a) Metal Fabrication Chips--None	8			8	
	(b) Adhesive--None	1			1	
	(c) Fluid, Internal--None	2			1	1
4	G-5 Seal Joint--Gouge, Leak--Planning Change	7			7	
5	Flange Corrosion--None	1			1	
6	Stud Keys Broken--Vibration or Tolerances--Plate Keys to Fit	9			9	
7	ASI Chamber Cracks--Thermal Fatigue--None	1			1	
8	Studs					
	(a) Loose-Intallation--Train Tech	2			2	
	(b) Dimension-repeated Stretch-Repair	2			2	
	(c) Soft Keys--Design Change	3			3	
9	Dimension Discrepancy					
	(a) Powerhead Dimension Discrepancy--Open	1			1	
	(b) Igniter Threads--Open	1			1	
	(c) Plug (0.005 Out of Toler.)--Fabrication--None, Rework	1			1	
10	Leak in MCC Ignition Joint--Open	1	1			
11	Bent Flange (FPB) Install--None	1			1	
12	Flange Nuts Galled--Stud Ref. Error--None	1			1	
13	Spacer Gap--Vibration & Installation--None	1			1	
14	Elliptical Plug Plating Missing--Unknown--None	1			1	
15	SML Cracks--Not Config. for FPL	1			1	1
		80	2	—	77	1

*No criticality.

A150 HEAT EXCHANGER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Coil Dings					
	(a) Bracket Clearance--Redesign	1				1
	(b) Tech Mishandling--Mfg. Change	2			2	
2	Coil Crack-Fitting Material Incorrect--National Change	2	2			
3	Coil Leak--Wear--None	1	1			
4	Coil Clearances--Mfg.--Mfg. Changes	6			5	1
5	Coil-Bent Tubes, Clearance Problems--Planning Change	3			3	
6	Coil Leak--Weld Incomplete--Inspection	1	1			
7	Bypass Line--Damaged When Removed--None	1			1	
8	Forward Vane--Inclusion--Open	1			1	2
		18	4	—	12	2

A200 MAIN INJECTOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Heat Shield Retainers					
	(a) Damage--New Heavy Design	8			8	
	(b) Secondary Failure	4			4	
	(c) Gas Turbulence--FPL--Change	19			19	
	(d) Open	3			3	
2	Baffles--Cracks, Erosion (Replace as Needed)	20			20	
3	Lox Posts--Broken, Cracked					
	(a) Broken-Gas Turbulence FPL--Change Structure	2			2	
	(b) Thermal Overload--None	1			1	
	(c) Open	3			3	
16	Lox Post--Erosion					
	(a) Blocked Orifice--Repair	3			3	
	(b) High Cycle Fatigue--Material Change	1		1		
	(c) Braze Joint--Leak--Spec Change	1			1	
15	Lox Posts--Crooked, Bent--Inspect	3			1	2
26	Lox Posts--Plugged	1			1	
25	Braze Joints--Leaks, Cracks--Inspect	3			3	
9	Buffles--Loose Improper Installation--None	2			2	
5	Heat Shield--Cracks, Thermal--New Retainers	1			1	
18	Heat Shield--Cracks @ FPL--Unshaped Structure	3			3	
20	Lox Post Inertia Weld-Spalling (FPL)--None	1			1	
7	Primary Face Plate					
	(a) Erosion--High Cycle Fatigue--Mat'l Change	3		2	1	
	(b) Cracks--Load Distribution--Inspection	3			3	
14	Interpropellant Plate					
	(a) Cracks--Heat Shield Failure--Better Retainers	3			3	
	(b) Cracks--Gas Turbulence FPL--U-Structure Installed	3			3	
	(c) Cracks--Open	1			1	
21	Secondary Face Plates--Chaffed--Improper Assy.	2			2	

c-2

A200 MAIN INJECTOR (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
24	Secondary Face Plate Retainers					
	(a) Cracked--Insufficient @ FPL--Redesign	1			1	
	(b) Cracked--Plugged Post	1			1	
	(c) Not Flush--No Problem	1			1	
6	Face Nuts (Erosion)					
	(a) Local Over Heating--Maintenance	3			3	
	(b) Secondary--Hot Gas Containment--Redesign	4			4	
	(c) Mismachined Orifice--Plugged Post-Repair	4			4	
22	Blocked Fuel Inlet--None	1			1	
23	ASI Supply Line--Cracks, Liquid Embrittlement--Redesign	5	5			
17	Reinforcement Ring Damage					
	(a) Torn-Improper Assy.--Planning Change	4			4	
	(b) Damage--Secondary Failure--None	3			3	
	(c) Damage-Gas Turb. @ FPL--U-Structure Design	4			4	
8	T-Bolts					
	(a) Loose-Improper Assy.--Design Change	4			4	
	(b) Loose--Operation-Maintenance	1			1	
19	Strain Gauges--Inoperative--None	3				3
10	Contaminants--Metal From Other Failures--None	17			17	
11	Broken Fuel Filters--Insufficient Life--Eliminate	25			25	
		175	5	3	162	35

A300 MAIN COMBUSTION CHAMBER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Burst Diaphragm					
	(a) Leak-Rupture, Rise in Temp--UCR A010713	8		1	7	
	(b) Leak, Weld--Redesign Weld	1			1	
	(c) Leak, Improper Plug Install--Planning Change	2			2	
2	Irregular Hot Gas Wall					
	(a) Bulges--Ok--Coolant Holes Enlarged	15			15	
	(b) Blanched, Discolored--None--Normal	16			16	
	(c) Hot Spots, Coolant Flow Restriction--None	2			2	
	(d) Erosion by Contamination--None	2			2	
3	Hot Gas Wall Liner					
	(a) Cracks--Restricted Cooling Channels--Enlarge Channels	5			5	
	(b) Cracks--Normal--None	8			8	
	(c) Crack in Cavity, Crown Weld--Machine	1			1	
	(d) Centerline Crack, Hot Gas Impingement--Under Study	3			3	
7	MCC Coolant Channels--Cracks					
	(a) Delamination--Repair as Needed	1			1	
	(b) Inherent Cracks--None or Open	8			8	
15	MCC Liner--Delamination EDCU Plating--None	3			3	
17	Port--Plugged, Brazing Alloy Contamination--Machining	2			2	
18	Port--Damage, Poor Reliability--Modify Engine	1		1		
10	Coolant Inlet--Missized--Open	1			1	
12	Turb. Drive Support Manifold--Leak by Weld Repair--Discontinue	1	1			
9	Welds					
	(a) Hole Near Exit Manifold--Welding Improved	1			1	
	(b) Microcracks--None, Normal	3				3
	(c) Surface Cracks--Planning Change	1			1	
	(d) Coolant Inlet Welds Mismatch--Open	4			4	
11	Elbow--Cracks, Internal, Radiograph Oversight--Improve	1			1	

A300 MAIN COMBUSTION CHAMBER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
14	Acoustic Cavity--Erosion, Hot Gas Impingement--UCRA015766	2			2	
16	Lee Jet--Tolerance--Planning Change	3			3	
8	Strut Assy.					
	(a) Lugs Cracked, Weld--Change Weld	1			1	
	(b) Clevis Worn--Open	1			1	
19	Retainer Ring--Installed Wrong--Modify Engine	1		1		
6	Contamination					
	(a) Fabrication Contaminant--Alert Personnel	2			2	
	(b) From Outside Engine--None	1			1	
	(c) Internal, Unknown--Ongoing Program	4			4	
		105	1	3	98	3

A340 NOZZLE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
2	Nozzle Tubes					
	(a) Ruptures, Leaks--Local Overheat--Cutoff Sequence Change	5			5	
	(b) Leaks--From Previous Repairs--Repair	44			44	
	(c) Leaks--Braze Bond & Voids--RA 1607--014 Amended	18		1	15	2
	(d) Cracks--Incorrect Braze Alloy--IL-78-CD-3139	3			3	
	(e) Cracks--Local Thermal Strains & Flow Restr.--Thicker Wall Tubes	41			41	
	(f) Cracks--Mishandling--Repair as Necessary	2			2	
	(g) Ruptures--Inadequate Expm. Band Design--Design Change	2			2	
	(h) Leaks--Strains @ Braze Bonds--Fabrication Change	36			33	3
	(i) Leaks--Internal Corrosion--Planning Change	6			6	
	(j) Leaks--Open	4			4	
4	Brazing Voids on Tubes					
	(a) Brazing Voids--Inadequate--Doublers Installed	7			7	
	(b) Separation of Tubes--Thermal Distortion--None	4			4	
	(c) Separation of Tubes--From Previous Repair--None	1			1	
3	Nozzle Plating Failure--Inadequate--Steerhorn--Redesign	1			1	
1	Nozzle Feldline Wall Thickness Undersize--Metal Ground--Redesign	1			1	
14	Nozzle Tubes--Secondary Failure--Injector Post Broke--Repair	1			1	
6	Welds					
	(a) Support Bracket to Hotbend Broke--Vibration--Reinforcement	1			1	
	(b) Aft Manifold Weld--Vibration & Thermal Fatigue--None	5			5	
	(c) Spot Welds--Broken From Drain Bracket--Redesign	4			4	
	(d) Nozzle Bracket Weld Broke--Vibrations--Repair	1			1	
	(e) TPS Spot Welds Broke Welds--Inadequate Welds--None	1			1	

A340 NOZZLE (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
	(f) Broken DFI Bracket Welds--Vibration--Add Clips	2			2	
	(g) TPS Bracket Welds Fail--Added Loads--Eliminate Brackets	9			9	
	(h) Steerhorn Fillet Welds--Transient Loads--None	1			1	
	(i) Spot Welds, Fuel Supply Duct--Unspecified Routing--Spec. Change	3			3	
	(j) Spot Welds DFI, Hyd Drain--Redesign	2			2	
	(k) Spot Welds Broken--Random Failures--Configuration Change	11			11	
	(l) Support Bracket Debonded--New Repair Procedure	1			1	
	(m) Weld Broke--Vibration--Incomplete Weld--Repair	4			4	
	(n) Broken Weld/Open	7			7	
11	Outer Jacket					
	(a) Cracks--Thermal Cycling--Reworked	3			3	
	(b) Cracks--Fabrication--Change Fabrication	1			1	
15	Hyd. Drain Bracket Broken--External Fire--Improved Design	1		1		
9	Hot Band					
	(a) Crack #9 HB--Previous Repair--Prepared	2			2	
	(b) HB #9 Tube--Material Deterioration--Drawing Change	2			2	
	(c) HB Pinholes--Stress Corrosion--None	1			1	
	(d) Hyd. Drain & Hot Bend Leak--Transients--Redesign	9			9	
	(e) Leak, Cold Weld-Inadequate Expm. HB--Design Change	2			2	
	(f) HB Aft Manifold Leak-Strain Crack @ Braze--Fabrication Change	1			1	
10	Filler Weld Wire Incorrect--Mixed Lots by Supplier--Caution	1			1	
7	Joint Leaks					
	(a) Leak @ F6.7--Seal Replaced	1			1	
	(b) Leak @ F6.10--Inadequate Requirements--Improved	1			1	
	(c) Leaks @ F17--Seal Not Positioned--None	4			2	2
19	Tubes Blocked--Contamination--Repair	1			1	

A340 NOZZLE (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
18	TPS Bracket					
	(a) Broken & Spot Welds--Loads--Redesign	4			4	
	(b) Shifted--Open	2			2	
13	DFI Straps Broken--Repair as Needed	1				1
25	TPS Foil Damage--Fab. Handling--Design Mod.	5			5	
5	Contamination					
	(a) In Joint--Inadequate Cleaning--Improve Cleaning	1			1	
	(b) From Previous Repair--None	1			1	
	(c) Deposit From External Source--None	4			4	
20	Steerhorn Fire--Operational Strains--Fabrication Change	1			1	
21	Insulation Damage, Loose--Interference, Thermal--Repair	4			4	
26	Sheet Metal Seal Missing--Seal Thickness Increased	1			1	
23	Joints--Misfit					
	(a) Joint 17 Misaligned--Assembly--New Tool	3			3	
	(b) Joint F6 & F6.4 Misaligned--Open	1			1	
27	Drain Fan Damage--External Fire--Design Change	1			1	
16	Temp. Sensor					
	(a) Defective--Contamination--Replace New Location	2			2	
	(b) Debonded--Handling--Repair	1			1	
17	Radimeter					
	(a) Defective--Contamination	1			1	
	(b) Debonded--Handling--Person Notified	2			2	
8	Installation Error-Bolts Loose--Procedure Change	1				1
12	Broken Studs on Nozzle Assy.--Ref. UCR A014085	1			1	
24	Loose Bolts on Drain/Aft. Manifold--Open	1			1	
		296	—	2	285	9

A600 FUEL PREBURNER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Baffles (Erosion)					
	(a) Erosion-Water & Ice--New Drying Procedures	1			1	
	(b) Erosion--High Local Mixture Ratio--Repair	3			3	
	(c) Erosion--ASI Hot Gas Impingement--None	7			7	
	(d) Erosion--Feed Coolant Channel Blocked--Open Coolant Holes	2			2	
	(e) Erosion--Secondary Failure--Turb. Duct--Ref. UCR A018306	1			1	
2	Baffles Cracked--High Mixture Ratio--Replace As Needed	4			4	
3	Lox Posts Nonconcentric, Blocked					
	(a) Nonconcentric--Improper Installation--Correct As Needed	2			2	
	(b) Slag Blockage--Reworked	1			1	
	(c) Nonconcentric--Thermal Distortion--R&D	1			1	
	(d) Blocked--Installation--Reworked	1			1	
4	Lox Posts Erosion					
	(a) Erosion--Water & Ice--New Drying Procedure	1			1	
	(b) Nibbling--Temp. Spikes, High Mixture Ratio--Repair	14			14	
	(c) Erosion--Contamination--Repair as Needed	1			1	
	(d) Crack in Oxidizer Post--Alternate Design	1			1	
5	Face Plate Erosion					
	(a) Erosion--Flow Inpingement--Divergent Liner Installed	6		2	4	
	(b) Erosion--Water & Ice--New Drying Procedure					
	(c) Box Pin Missing--Erosion--Repair	3			3	
	(d) Erosion--Slag In Fuel Anulus--Improve Design	6			6	
	(e) Bowing Plate--Welding--Repair	1			1	
	(f) Erosion--Fabrication Debris--None	1			1	
	(g) Erosion--Blocked Coolant Orifice	1			1	
	(h) Erosion--Unknown or Open	7			6	1
	(i) Erosion--Secondary Failure--Ref. UCR A018288	7			6	1
6	Face Plate Cracks--Low Cycle Fatigue--Hot Gas--Divergent Liner Added	2			2	

A600 FUEL PREBURNER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
7	Face Plate Deposits--Slags, Hot Gas Flow--Divergent Liner Added	1			1	
8	Liner					
	(a) Cracks--Overheat--Install Divergent Liner	6			6	
	(b) Erosion--Fuel Annulus Restrictions	2			2	
	(c) Erosion Unknown	1			1	
9	Elliptical Plug Locked--Jam Not Installed Wrong--Repair	1			1	
10	Elliptical Plug					
	(a) Erosion--Direct Hot Gas Flow--Revised Installation	3			3	
	(b) Erosion--Ring Installed Wrong--Repair	2			2	
12	Coolant Holes					
	(a) Plugged--Metal Braze Flux Contam.--Braze Discontinued	1			1	
	(b) Blocked High Mixture Ratio, Slag--Repair as Needed	1			1	
	(c) Plugged with Weld Wire--Improper Installation--Repair	5			5	
	(d) Plugged During Cleaning--Change Procedure	1			1	
13	Moly--Shield Cracks Thermal Strains/Pressure Loads--None	9			9	
14	Fuel Sleeve					
	(a) Hole Cracks--Water & Ice--Change Drying Procedure	1			1	
	(b) Hole--Decayed c/o Purge-Change Shutdown Procedure	1			1	
	(c) Cracks--Open	1			1	
15	Contamination					
	(a) Contamination in Coolant & Buffles--External Source--None	3			3	
	(b) Contamination--Wire Brush Pneumatic Tool--Eliminate Tool	1			1	
	(c) Contamination--Introduced During Rework--Alert Field Oper.	1			1	
	(d) Contamination--Unknown	6			5	1
	(e) Contamination--Loose Retainer End--Design Change	1			1	

A600 FUEL PREBURNER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
16	Liner Exit Mismatched--Mfg.--Rework	1				1
17	Air Damp Cap Undersized--Thermal Loads--None	1			1	
18	Inspection Crack-Pressure Cycled (One Engine)--Eng. Removed	4			4	
19	Igniter Cracks--Hot Gas Recirculation--None	1			1	
20	ASI Done Cracks--Hot Gas Recirculation--None	1			1	
21	Support Pins					
	(a) Missing--Misinstalled--Improve Procedure, Design Rod	19			19	
	(b) Extra Pins--Misinstalled	3			3	
22	Coolant Holes Cracked--Distress--Procedure Change	2			2	
23	Plug Weld Closure Eroded--Excess Braze--Procedure Change	1			1	
24	Baffle Weld--Crack in Nicro Filler--Penetration--Welds Improved	15			15	
25	Elliptical Washer Cracks--Residual Stress--Repair	1			1	
		171	—	2	165	4

A700 OXIDIZER PREBURNER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Lox Posts					
	(a) Slight Melting--Normal After PFC Tests--None	1			1	
	(b) Erosion--Contamination in Fuel Annulus--None	2			2	
2	Lox Orifices Cracks--Hot Gas Recirculation--None	2			2	
3	Lox Post, High Eddy Reading--Work Hardened--Spec Change	1			1	
4	Liner Erosion--Contamination in Fuel Annulus--None	1			1	
5	Dome--Void--None	1			1	
6	Welds					
	(a) Weld--Buildup--Revised Drawing	1			1	
	(b) Weld #3 Hairline Crack--Open	1			1	
7	Lox Post Support Pin Dislodged Installation Design Change	1			1	
8	Contamination From Fuel Filter External to Engine--Eliminate Filter	1			1	
9	Contamination From Heat Shield Failure--Redesign	1			1	
		13	—	—	13	—

B200 HIGH-PRESSURE FUEL TURBOPUMP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Liftoff Seal					
	(a) Leakage--Contamination in Bushing Groove--None	5		1	4	
	(b) Dimension Discrepancies--Mfg.--Supplier Notified	4		2	2	
	(c) Low Noise Load--Not Repeating--Repair	2			2	
2	Fishmouth Seal					
	(a) Rubbing or Cracks--Overheat of Turb. Bearing Support--Redesign	6			6	
	(b) Cracks--Thermal Caused--Redesign	6			6	
	(c) Yielding--Inherent Thermal Stress--Ref. UCR A011185	2			2	
	(d) Rubbing--Turbine Blade Platform--Temperature--Redesign	2			2	
	(e) Gouged--Secondary Fail, Dampers--None	1			1	
	(f) Erosion--Temp. From ASI--Coolant Hole Enlarged	2			2	
3	Labyrinth Seals					
	(a) Cracks, Rubbing @ Teeth--High Cycle Fatigue--Clearance Changed	3			3	
	(b) Failure Unknown?	1			1	
	(c) Seal Configuration--Vib, Suction Low, Procedure Changed	2				2
	(d) Erosion--Contamination--None	1			1	
4	Seals					
	(a) Groove Out of Tolerance--Thermal Gradients--Maintenance	9			7	2
	(b) Break Torque High--Rubbing of Seals (Interstage)--None	8			7	1
	(c) Contaminant on F/U Seal--Unknown--None	1			1	
	(d) Fractured Hydrogen Embrittlement--None	6			6	
	(e) Binding G-6 Seal Improper Install.--Planning Change	3			2	1
	(f) Tip Seal Damage--Secondary Failure Contaminated--Fix	3			3	
	(g) Tip Seal--Overheat Fatigue--Material Change	3			3	
	(h) Tip Seal Gauges--Cracked Housing Pilot Lip--Redesign	1			1	
	(i) Max. Leak Rate--Old Configuration--New Configuration	2			2	

B200 HIGH-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
	(j) Seal Separating--Secondary Failure	2			1	1
	(k) Kel-F Seal Damage--Retainer Motion--Redesign	2			2	
	(l) Seal Crack/Leak--Low Cycle Fatigue--None	1			1	
	(m) G5 Seal Grooves Stained--Residual Combustion Products--None	2			2	
	(n) Pitting on G-5 Seal--Secondary--Ref. UCR A014015	1			1	
	(o) Kel-F Seal Failure--Secondary--Special Inspection	1			1	
	(p) Broken Seals--Undetermined	3			3	
	(q) Delaminated Seal--Inadequate Cleaning--Material Change	1			1	
	(r) Leak Joint F-4--Oversize Groove--Planning Change	1			1	
5	Turbine Blades--Erosion					
	(a) Erosion, Burnt--Secondary Failure--Ref. UCR A016031	1			1	
	(b) Erosion, 1st Stage--Transient Thermal Environment--Redesign	4			3	1
	(c) Erosion--Rubbing, Overspeed--None (Normal)	1			1	
	(d) Erosion--Thermal Environment--Redesign	2			2	
6	Blades--Cracked, Damage					
	(a) Deformed/Drawings--Contamination--Seal Redesign	5			5	
	(b) Cracked Blade--Combined HCF/LCF--Inspection	1			1	
	(c) Blade Failures, Premature Cutoff--FPB Configuration--None, Unique Conf.	1		1		
	(d) Cracked Shunks--Low Cycle Fatigue--None	2			2	
	(e) Fracture--Moisture--New Drying Procedure	1			1	
	(f) 2nd Stage Damage--Dislodged Damper--Ref. A013999	1			1	
7	Turbine Platform Erosion--ASI Temp.--Redesign & Coolant Holes Enlarged	12			11	

B200 HIGH-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
8	Sheet Metal					
	(a) Cracking--Fitup Weld Variation--Inspect	8			8	
	(b) Crack in Turbo Shroud--High Cycle Fatigue--Material Change	1			1	
	(c) Crack--Secondary Failure	1			1	
	(d) Cracking--Full Power Level (FPL)--Monitor	2			2	
	(e) Crack-Weld Bead Notch--Design Change	2			2	
	(f) Cracks--Built in Insufficiency--Redesign	35			35	
9	Inlet/Discharge					
	(a) Linear Cracks--Overstressed--Spec Change	1			1	
	(b) Cracks--High Cycle Fatigue--Monitor	2			2	
	(c) Cracks--Insufficient Joint Strength--Spec. Change	2			2	
	(d) Damage--Open	1			1	
10	Synchronous Vibration--Unknown--Limit Unbalance	1			1	
12	Vanes					
	(a) Turbine Edge Damage--Debris, Secondary Failure--Ref. A012653	1			1	
	(b) Erosion, FPB Malfunction--UCR A004402	3			3	
	(c) Erosion, 1st Stage--High/Low Cycle Fatigue--Material Change	6			6	
	(d) Burn Through--Secondary Failure--Ref. UCR A016031	2			2	
	(e) Nick--Weld Operation--Rework	2			2	
	(f) Erosion, Hot Preburner Start-Limit Established	1			1	
	(g) Hole--Open	1			1	
	(h) Erosion--Rapped Gas Pocket--Life Limit Established	5			5	
	(i) Material Missing--Open	1			1	
13	Rub Ring Warped--Misinstalled--Notified Person	1			1	
14	Contamination					
	(a) Self-Generated--No Problem	5			5	
	(b) Installation--None	12			12	
	(c) Unknown, Minor, Gold--None	26			25	1
	(d) Bearing Debris--None	1			1	
	(e) Spring Debris--Vibration--None	2			2	
	(f) Blade Rubbing Redesign	1			1	
	(g) Heat Shield Damage--Secondary, UCRA015968	5			5	
	(h) Unknown--Suspect Seal Wear	5			5	
	(i) Ref. UCR A004585	1			1	

B200 HIGH-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
16	Struts/Posts					
	(a) Cracks--Sheet Metal Fitup & Weld Variations--Inspect	47			47	
	(b) Cracks--High Cycle Fatigue, FPL--Posts Modified	15			14	
	(c) Cracked--Oversized Electrode Repair	3			3	
	(d) Cracks--Weld Bend Notch--Design Change	3			3	
17	Nickel Insulation Damage--Repair as Needed	9			9	
18	Bolt Holes Cracks--Internally Induced--Redesign Turbine	8			8	
19	Impeller Broken--Internal Rubbing--Material Change	1			1	
20	Bellows Shield					
	(a) Cracks--Thermal Spikes--Inspect	1			1	
	(b) Crack--High Cycle Fatigue--ECR 09689	5			5	
	(c) Crack--Machining--None	3			3	
	(d) Weld Crack--Tolerances--Change Planning	1			1	
	(e) Cracks--Open	1			1	
21	T/A Manifold					
	(a) Cracks--Thermal Gradients--Repair	3			3	
	(b) Damage--Weld Failure--Planning Change	1		1		
22	Bearing Balls					
	(a) Thrust Ball Cracks--Dry Lube Overheat--Maintenance	4			4	
	(b) Loose--Improper Swage--Planning Change	1			1	
	(c) Streaks Eccentric Wear--Tooling--Correct	2			2	
	(d) Wear--Cantom. Unknown?	1			1	
23	Shaft Insert Wear with Balls--Ref. UCR A003411	1			1	
24	Bearing Race					
	(a) Wear--Contamination--None	1			1	
	(b) Scoring--Outer Race Preload--Ref. A011480	1			1	
	(c) Cracked--Misalignment Planning Change	1			1	
25	Turbine End Ring					
	(a) Cracks--Sheet Metal & Weld Variations--Maintenance	2			2	
	(b) Plating & Peeling--Ambiguous Rework Specs--Change Specs.	1			1	

B200 HIGH-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
26	Coolant Liner Bulged High Pressure--Thicker Liners	2			2	
27	Dog Bone Wt. Fragmented--High Cycle Fatigue--Specs Change	1			1	
28	Cav. Sense Line Damage--Installed Wrong--Redesign	1			1	
29	Slag Erosion G-5 Ft. Fuel Annulus--Improved Design	1	1			
30	Subsynchronous Vibration					
	(a) Increasing--Pump End Imbalance--Limit Allowable	1			1	
	(b) High Vib--Wear on Preload Springs--Seals Modified	1			1	
31	Shaft Travel					
	(a) Excessive--Unknown Reason--None	8			6	2
	(b) Excessive Wear on Balance Piston Orifice--OK	3			3	
	(c) Low--None--Within Toler.	2			2	
32	Fuel Drain Leak--Excessive--None (Within New Specs)	1			1	
33	Fuel Discharge Part Crack (Weld)--Penetration--Planning Change	1			1	
34	Preload Springs Worn--Vibrations--Interstage Seal Change	1			1	
35	Blacking Pin					
	(a) Sheared--High Torque--Planning Change	2			2	
	(b) Missing--ASI High Temp.--New Material	8			8	
36	Diffuser					
	(a) 2nd Stage Broken--Interference Fit--Planning Change	3		1	2	
	(b) Broke--Overaging During Heat Treat--Repair	2		2		
	(c) Gouge--Machining--Alert Tech	2			2	

B200 HIGH-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
37	Nozzle Cracks					
	(a) Crack--Thermal Low Cycle Fatigue--Change FPB	1			1	
	(b) Erosion--High Transients--Redesign	2			2	
38	High Accelerometer Signals					
	(a) Vibration (16g) Cavitation Wrong Labyrinth Seal Conf.--Procedure Change	2		2		
	(b) High Levels--Unknown--None	1			1	
39	Inlet Cap Nut					
	(a) Crack/Erosion-ASI Temperature--Redesign	13			13	
40	Saureisen Material Washed Out--ASI Temp.--Cool Hole Mode	4			4	
41	Nuts & Washers					
	(a) Missing From Shield--Unknown--Interim Design	2	2			
	(b) Loose Nut--Typical--None	4			3	1
	(c) Discharge Bolt Loose--Open	1			1	
	(d) Lugs Missing--Open	1			1	
42	HPFT (Water Contamination)					
	(a) Water Trapped in Pump--None	2			2	
	(b) Water in Bellows--New Drying Procedure	3			3	
	(c) Moisture in Bearing Support--None	1			1	
44	Inlet Failure--Pump Cavitation--Requirements Change	1		1		
45	Bearing Support					
	(a) Crack--Open	1			1	
	(b) Crack--Insufficient Joint Strength--Limits Estab.	2			2	
46	Missing Damper--Damaged Blades--Open	2			2	
47	Dimension Discrepancies--Afterburn--New Specs	1			1	
48	Seal Tabs					
	(a) Cracked--Load--Redesign	1			1	
	(b) Missing--Hot Gas Impingement--Redesign	1			1	
		457	3	11	429	14

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
1	Bearings--Balls					
	(a) Discoloration--Superficial--None	2			2	
	(b) Spalling--Transient Axial Forces--Redesign	14		7	7	
	(c) Surface Distress & Spalled--Bearing Loading--Solid Film Lab. Added	14			11	3
	(d) Undersized Ball--Loading Condition--Solid Film Lab	4			4	
	(e) Surface Distress, Wear--Secondary Fail.--UCRA006806	1				1
	(f) Gold Contamination--Temp. Aggravation of AU Plate--Studies	1			1	
	(g) Surface Distress--Fluid Jet Impinge on Cage--Redesign	2			2	
	(h) Spalling/Surface--Distress--Bearing & Vib. Problems IL 170TM-1594	4			4	
	(i) Spalled/Undersized--Open	3			3	
2	Bearing Cage/Cartridge					
	(a) Contamination in Cartridge--Improved Cleaning	5			5	
	(b) Fretting--High Transient Axial Loads--Acceptable	2			2	
	(c) Cage Delamination--Drawing Change	1			1	
	(d) Cage Frayed--Fluid Environment--Limit Established	11			11	
	(e) Cage Damage--Machining--None	1			1	
	(f) Cage Delamination--Loading Condition--IL 170TM-1594	3			3	
	(g) Wear/Cartridge--Secondary Failure--A006806	1			1	
	(h) Cartridge Dry--Lubeworn-Bearing Loading--IL 170TM-1594	2			2	
	(i) Cage Delamination Fluid Jet Impinge--Redesign	1			1	
	(j) Cage Delamination--Open	1			1	
	(k) Rub Mark--Bearing & Vib.--IL 170TM-1594	1			1	
3	Bearing Races					
	(a) Wear--Loading Condition--IL 170TM-1594	4			4	
	(b) Inner Race Raised--Bearing & Vibration IL 170TM-1594	1			1	
4	Isolator Fretting--Insufficient Clamping Load--None	1			1	

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
5	Impeller					
	(a) Rust Deposits--Moisture--Precaution	2			2	
	(b) Cavitation Erosion--Normal--None	7			6	1
	(c) Rubbing Secondary Failure--UCR A004664	1			1	
6	Primary Seal					
	(a) Breakway Torque High--Rubbing of Seal--Spec. Change	3			3	
	(b) Yield of Seal--Design Change	2			2	
	(c) Leakage--Ref. UCR A006374	2			2	
7	Tip Seal--Breakaway Torque High--No Problem	2			2	
8	K-Seal Leak-Improper Installation--Personnel Lateral	2			2	
9	Labyrinth Seal					
	(a) Metal Contam. @ Teeth--Planning Error--Change	1			1	
	(b) Rubbing--Paddles Oversized--Part Elevated	1			1	
10	Seal (Other)					
	(a) Seal Wear--Old Shaft Sleeve--New Design	1			1	
	(b) Secondary Seal, Leak--Roughened Shaft Sleeve--New Material	2			2	
	(c) Seal Leak--Improper Installation--Planning Change	1			1	
	(d) Int. Seal Pressure Dropped--Coolant Blockage--Redesign	1			1	
	(e) Pits on Seal Washer Crack--Improper Staking Tool--New Tool	1			1	
	(f) Seal Groove to Deep--Inspection Advised	2			2	
11	Bellows Shield					
	(a) Scratches--Normal Installation--None	1			1	
	(b) Crack Thermally Induced--Design Change	1			1	
	(c) Compressed Improper Installation--Adhere	1			1	

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
12	Nozzle Vane					
	(a) Erosion--Installation Damage--None	1			1	
	(b) Cavitation Wear--Normal--None	2			2	
	(c) Erosion--c/o Purge Eliminated--None	1			1	
	(d) Eroded--Hot Gas Imbalance--OPB/FPB Modified	1			1	
	(e) Erosion--FPB Injector Failure--None	1			1	
	(f) Metal Folded Over Vane--Machining--None	1			1	
	(g) Erosion--Modified Start Sequence--Modify OPOV Command	1			1	
	(h) Crack--Erosion--Open	3			3	
13	Shaft Sleeve Wear--Old Configuration--New Design	1			1	
14	Contamination					
	(a) Metal Contam.--Unknown--None	23			23	
	(b) Krytox Excess-Leak--Techs Alerted	4			3	1
	(c) Contam. From Other Failures--None	4			3	1
	(d) Contam. From Turbine Damper Failure--None	1			1	
	(e) Gold Rub on Housing--High Thrust @ Shutdown--None	2			2	
	(f) Contamination Material During Machining--Personnel Alerted	7			7	
	(g) Gold Splatter on Turb. Blades--Bonding of AU (Temp.)--Study	8			7	1
	(h) Oil Contam.--Transport of Aircraft--Add Inspection	1			1	
	(i) Metal--Filter Breakdown ECR 10370 & 10347	1		1		
	(j) Contamination--Improper Staking Tool--New Tool	1			1	
15	High Break Torque					
	(a) Rubbing of Seals--None	18			18	
	(b) Out of Spec.--Old Shaft Sleeve--New Configuration	1			1	
	(c) Primary Seal Rubbing--Heated Krytox--New Spec.	2			2	
	(d) Yield of Primary Seal--New Design	2			2	
	(e) Particles of Dampers Floating--Change Dampers	2			2	
17	Strut Assembly					
	(a) Damage--Assenbly/Disassembly--None	3			3	
	(b) Erosion--Leaky OPOV--UCR A017523	1			1	
	(c) Cracks--Unknown--Estimate Limits	6			6	

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
18	Drain Line					
	(a) Mux Leakage Exceeded--UCR A011981	2			1	1
	(b) Draw Line Tan Tube Leak--Unknown--Material Change	2			2	
19	Housing					
	(a) Pin Leak @ Pump Hsg.--Lock Wire Hole Inadequate--Redesign	1			1	
	(b) Rubbing--High Thrust Loads @ Shutdown--Study	1			1	
	(c) Cracks--Unknown/Open--Plan to Determine Life Limits	10			10	
20	Turbine Blades--Cracks					
	(a) Cracks--High Cycle Fatigue--Periodic Inspection	19			19	
	(b) Chips--Fabrication/Manufacturing--None	2			2	
	(c) Broken--High Cycle Fatigue--Design Improved	1			1	
	(d) Slay & Cracks--Main Injector Failure--None	1			1	
	(e) Damage--Bearing Loading Condition--IL-1/UIM-1594	1			1	
21	Blades Erosion					
	(a) Erosion--Unknown--None	1			1	
	(b) Erosion--Secondary Failure--UCR A010631	1			1	
	(c) Erosion--Hot Start--OPOV Command Change	1			1	
22	Sheetmetal					
	(a) Burnt--Main Injector Failure--None	1			1	
	(b) Cracking Establish Life Limits	6			5	1
23	Shaft Rubbing--High Axial Thrust--Design Change	1			1	
24	Locks Broken--Ductile Overload--Change	2			2	
25	Eccentric Ring--Installation Error--None	1			1	
26	Bearing Support					
	(a) Fretting--Not Detrimental--Add Preload Spring	3			3	
	(b) Pitting--Open	2			2	
27	Inducer Vane Out of Contour Handling--Person Alerted	1			1	

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
28	Diffuser Vane Damage--High Cycle Fatigue--Redesign	3			3	
29	Jet Ring					
	(a) Flow Tubes Damaged--High Cycle Fatigue--Life Limits Established	1			1	
	(b) Cracks Residual Welding Stress--None	1			1	
	(c) Obstructed--Open	2			2	
30	Wave Preload Spring					
	(a) Improper Installation--Planning Change	2			2	
	(b) Worn Spring--Secondary Failure--UCR A006806	1			1	
	(c) Spring Land Worn--Loading Problems--IL-170TM-1594	1			1	
31	Carbon Seal Ring Worn--Coolant Blockage--Design Mod	1			1	
32	Turb. Blade Dampers Broken--High Cycle Fatigue--Revision	1			1	
33	Subsynchronous Vibration					
	(a) Bearing Loading Condition--IL-170TM-1314	5	5			
	(b) Bearing & Vibration Problems--Development Plan IL-170TM-1594	1	1			
34	Synchronous Vibrations					
	(a) Bearing & Vibration Problems--IL-170TM-1594	7	1		6	
	(b) Instrumentation Problem--None	2			1	1
	(c) Inadequate Balance--Green Run	1		1		
35	Isolater Dri Lube Wear--Secondary Failure--None	1			1	
36	Nuts & Washers					
	(a) Nut Cavitation--Installation/Disassembly--Maintenance	2			2	
	(b) Nut Cavitation--Pumping Action of Lobes--Design Change	1			1	
	(c) Washers Broken--Improper Staking Tool--New Tool	3			3	

B400 HIGH-PRESSURE OXIDIZER TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
37	Roll Pin Cracked--Suspect Grain Bonding Carbides--None	1			1	
38	Turbine Disk					
	(a) Damage Surface--Jet Ring Secondary Failure--UCR A006735	1			1	
	(b) Cracks on Au Plating--Low Cycle Fatigue--None	1			1	
	(c) 2nd Stage Rubbing--High Thrust Loads @ Shutdown--Study	2			2	
39	G-3 Area, Water Trapped--New Drying Procedure	1		1		
40	Liver Erosion--Open	1		1		
41	Bolt Hole Flange Cracks--Open	1			1	
42	Weld Cracks--Fatigue--Add Dye Penetrant Inspection	1			1	
43	Turbine Inlet					
	(a) Plating Worn--High Thrust Loads--None	1			1	
	(b) Cracks--Casting Defect--Improve Casting	1			1	
	(c) Cracks--Determine Life Limits (Fatigue)	8			8	
44	Fir Tree					
	(a) Gold Missing--Poor Adhesion--None	1			1	
	(b) Cracks in Gold--Open	1			1	
45	Shaft Travel--Bearing Loading--IL-170TM-1594	1			1	
		331	7	11	302	11

B600 LOW-PRESSURE FUEL TURBOPUMP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Turbine Blades					
	(a) Dings--Engine Generated Ding--None	1			1	
	(b) Dent--Fabricated--None	1			1	
2	Pump Inlet Gauge--Open	1			1	
3	Bearings--Improper Installation--Planning Revision	1			1	
4	Labyrinth Seal Rubbing--Max. Torque Excessive--Redesign	10		1	9	
5	Liftoff Seal					
	(a) Carbon Nose Rubbing--High Torque--None	1			1	
	(b) Carbon Nose Failure--None	1				1
	(c) Squeal--Rubbing--None	2				2
6	Turbine Inlet Nicks--Temp. Sensor Debonded--A017772	1			1	
7	Vibration					
	(a) Suction Pressure--None Found	1		1		
	(b) Synch Vibration	1			1	
	(c) Rubbing @ Labyrinth Seals--Design Change	2			2	
9	Nickel Insulation					
	(a) Ruptured--Mishandled--Silicon Repair	1			1	
	(b) Split--Engine Generated Ding--None	1			1	
	(c) Crack--Moisture Entry--Field Repair	6			6	
	(d) Insulator Boots Loose--Installation--None	2			2	
10	Contaminated					
	(a) Suspect Dust Cover--Awareness	2			2	
	(b) Contamination--Inadequate Clearing--Alert	2			2	
11	Excessive Torque					
	(a) Torque Anomality--Not Failure	1				1
	(b) Copper Plate Buildup--Labyrinth Seal Redesign	7			7	
	(c) Excessive Torque--None	1			1	
12	Housing Copper Plate Damage--Unknown Repair	1			1	
13	Omniplate Crack-Previous Repair Damage--None	1			1	
14	Joint F2 Cut--Installation Error--None	1				1

B600 LOW-PRESSURE FUEL TURBOPUMP (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
15	Locking Tubs Loose--Improper Handling--Tech Alert	1			1	
16	Fuel Feed Leak--Thermal Cycling--None, Repair	1			1	
17	Impeller/Inducer					
	(a) Scuff Mark--Not Detrimental	1				1
	(b) Ding--Open	1			1	
18	R&V Patch Loose--Moisture None, Repair	1			1	
19	Nuts--Rub Marks--Open	1			1	
20	Stator Shroud Low Pressure Misbraze--Revise Drawing	1		1		
21	Nozzle					
	(a) Erratic Pressure--New Nozzle Conf.--Not Detrimental	1			1	
	(b) High Pressure Drop--Excessive Nozzle Block--Rework	1			1	
	(c) High Pressure Drop--Open	1				1
22	Leak Not Detrimental--None					
		59	—	3	49	7

B800 LOW-PRESSURE OXIDIZER PUMP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Bearing Balls					
	(a) Worn Thrust Balls--High Torque--Track Bearings	1			1	
	(b) Coating Contaminated During Installation, Notify Techs	1			1	
2	Bearing Cage Friction--None	16			16	
3	Bearing Journal Vibration--Journal Undersized--Planning Change	1			1	
5	Seals Groove Oversized-Hand Lapping--Planning Change	1			1	
6	Stator Silver Plate--Lifted--Open	1			1	
7	Bolt Hole Rust Deposits--Iron Bolts--Replace	1			1	
9	Contamination					
	(a) Metal--Transducer Base--Ref. UCR A012678	4			3	1
	(b) Steel Chip--Main Vane Assembly--None	2			2	
	(c) Teflon Pieces @ Ring Nozzle--Tool--None	1			1	
	(d) Shop Debris--Ref. UCR A015786	3			2	1
	(e) Contamination--Unknown Source--Awareness	16			16	
	(f) Coatings on Bearings--Glove Fragments--Mfg. & Inspect	1			1	
	(g) Silver in Turbine Section--None	1			1	
	(h) Contamination-Discharge Duct Failure--UCR A011506	1			1	
	(i) Grease--Assembly Error--None	1			1	
	(j) Metal on Rotor Arm--Open	1			1	
	(k) Deposit on Nozzle Vanes & Surface--Open	2			2	
10	High Break Torque					
	(a) Ball Speed Variation at Low Speed--OK	3			3	
	(b) Bearing Ball Wear--Truck Bearing Wear	1			1	
	(c) Cage-Bearing Friction--None	17			17	
	(d) Silver in Turb Section--None	1			1	
11	Shaft Travel					
	(a) Bearing Wear--Track Wear	1			1	
	(b) High Axial Load--Reduced m/s Axial Thrust	4			4	
	(c) Wear--Not a Failure--R&D	2			2	
12	Erroneous Cutoff-FASCOS Inaccurate Redline--New Red Line	1				1

B800 LOW-PRESSURE OXIDIZER PUMP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
13	Flange					
	(a) Undercut on Surface--Misalign--None	1			1	
	(b) Raised Metal, Nick--Open	2			2	
14	Inducer Leading Edge Rolled Over--Improper Handling--None	1			1	
16	Plating Chipped--Interference Fit--Revise Spec.	1			1	
17	Shim Discoloration--Open	1			1	
18	Pitting on Spline--Open	1			1	
		92	—	—	89	3

C100 CHECK VALVES

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	FPB Purge Check Valve Leak-Dri-Lube From Flange Bolts--Alert	2			2	
2	OPB Purge Check Valve Leak--Leak Not Verified	1				1
3	Oxidizer Dome Purge Check Valve					
	(a) Reverse Leak--Contamination, Unknown Source--None	1			1	
	(b) Leak--Not Verified	1			1	
4	Fuel Purge Check Valve Leak--Momentary Stuck--None	1			1	
5	Fuel Purge Ch. Valve Pressure Spike--Closed?	1			1	
6	FPB ASI Check Valve					
	(a) Leak Sticky Poppet, Fabrication, Add Inspection	1			1	
	(b) Seat Leakage--Contamination--None	1			1	
	(c) Leak--Open	1			1	
7	OPB ASI Check Valve Leak--Poppet Bore Interference Inspect	1			1	
		11	—	—	10	1

C200 PNEUMATIC CONTROL ASSEMBLY

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Helium Burst Diaphragm--DVS Test Induced Fatigue--Test Change	1			1	
2	Vent Seat, DVS Testing Leak--Inter. Seal Purge Pav--A017367	2			2	
3	Inlet Seat--Suspect Instrument Error--New Test Procedure	1			1	
4	Pneumatic Solenoid Leak--Seal Impressions--None, Repair	1			1	
5	Contamination					
	(a) White Residue in Inserts--Galvanic Corrosion--None	1			1	
	(b) Lub Oil in PAVs--Source Unknown--Cleanliness	1			1	
		7	—	—	7	—

C210, C250, C270, C300-SOLENOID VALVES, PAV, PNEU FILTER, HELIUM PRECHARGE VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Emergency Shut Solenoid Sent Leak--Allowable Leak Rate	1			1	
2	FPB Purge PAV Inlet Seat Leak--Not Substantiated--OK	1			1	
3	Fuel Purge PAV (Pressure Activated Valve)					
	(a) Leak--Leak Rate Allowable--Change Limits	1			1	
	(b) Inlet Seat Leak--Transient Contam.--Clean and Use	1			1	
4	HPOT Inter. Purge PAV					
	(a) Leak--Inlet Seat Distortion--Poppet Seal Redesign	4			4	
	(b) Dynamic Seal Leak--DVS Test Induced--None	1			1	
5	PAV Internal Leak--Open	1			1	
6	Man Chamber Dome PAV Vent Leak--Trans. Contamination--None	1			1	
		11	—	—	11	—

D110 MAIN FUEL VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks					
	(a) Ball Seal Leak--Scaling Factor Error--Person Alerted	1			1	
	(b) Valve to Actuator Misclock--Change to Std. Height Blind Tooth	1			1	
	(c) Internal--Suspect Contamination--Not Determined	1			1	
	(d) Ball Seal Leak, Downstream Temp High--Contaminated--Leak Check	1			1	
	(e) Leak, Static Seal--Defect--Isolated Incident	1			1	
	(f) Primary Seal Leak--Dri--Film Particles--None	1			1	
2	Throat Sleeve Nicks--No Problem	3			2	1
3	Housing Crack--Thermal Stress @ Mfg.--Add Inspection	1			1	
4	Metal Contamination--Unknown Source--None	1			1	
5	Bearing					
	(a) Washer Damage--Vibration, Fatigue None, Isolated	1			1	
	(b) Race Cracked--Not Determined Why	1			1	
6	Plating Separation--Handling Damage--Material Change	1			1	
7	Broken Cam Follower Guide--Cryogenic Temp.--None	1			1	
		15	—	—	14	1

D120 MAIN OXIDIZER VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks					
	(a) Deformed Bellow--Unknown--None, Isolated Case	1			1	
	(b) Ball Seal Leak--Contamination--Unknown Source--None	1			1	
	(c) Ball Seal Leak--Dri-Lube on Surface--OK	1			1	
	(d) Ball Seal Leak Installation Position Marginal--Redesign	1			1	
2	Inlet Discharge Sleeves Nicked--Debris--OK	2			1	1
3	Bearing Retainer Hub Broke--Fatigue--Mov Spec. Change	2			2	
4	Contamination Source Unknown--Inspection	1			1	
5	Follow Guide Omitted in Assembly--Mfg. Oversight--Notify Person	1			1	
6	Drift Open Installation Error Procedures Change	1			1	
7	Bearing, Rusty--Isolated Case--None	1			1	
8	Excessive Pressure @ Hotfire--UCR A008305	1			1	
9	Water in Joint 07--Inadequate Closure--New Closure	1			1	
		14	—	—	13	1

D130 FUEL PREBURNER OXIDIZER VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks--Ball Seal					
	(a) Ball Seal Leak--Particle Contamination, Unknown--None	1			1	
	(b) Leak--Cracked Ball Seal, Poor Material Spec. Change	1			1	
	(c) Leak--Discrepant Bellows--None, Isolated Case	1			1	
2	Leak (Other)					
	(a) Suspect Leak--Marginal Bellows--Spec. Change	1			1	
	(b) Internal Leak--Particle Backflow--Closing Rate Change	2			1	1
3	Ball Seal Damage--ASI Combustion Backflow--Personnel Alert	2			2	
4	Contamination--Unknown Source--None	1			1	
5	Bolt Stretch Error Caused Low Flow Rate--Personnel Alert	2			2	
6	Suspect Over Pressurization--UCR A008305	1			1	
7	Excessive Flowrate During Test--Normal	1			1	
		13	—	—	12	1

D140 OXIDIZE PREBURNER OXIDIZER VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Ball Seal Leak, Hot Fire--Flow Reversed Combustion--Software Change	1			1	
2	Flow Reading Low--None	1			1	
3	Ball Seal Melting--ASI Combustion Backflow--Software Change	20			20	
4	Contamination					
	(a) Secondary From Steerhorn Failure--UCR A010997					
	(b) Oily Substance on Flange--Unknown--None	1			1	
5	Studs Overtorqued--No Failure--None	2			1	1
6	Overpressure--UCR A008305	1			1	
7	Excessive Flow Rate--Incorrect Test--Spec Change	1			1	
8	Wall Sleeve Scratches--Unknown Source--Not Detrimental	1			1	
		28	—	—	27	1

D150 CHAMBER CHART VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Slider Corrosion--Brown Dust None, OK	1			1	
2	Roll Pin Broken Interference--Installation Changed	2			2	
3	Studs					
	(a) Overtorqued Improper Tool Use--Train Person	1			1	
	(b) Overtorqued--Unknown--Repair	1			1	
4	Contamination					
	(a) Metal Clip--Handling--None, Clean	1			1	
	(b) Unknown Source--Clean	3			3	
		9	—	—	9	—

D200 BLEED VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leak--Isolated Incident--None	2			2	
2	LVDT Voltage Oscillation--Vibration, Fatique--Redesign	2			2	
		4	—	—	4	—

D300 ANTIFLOOD VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	LVDT & Wiring					
	(a) Output Voltage Low--Wire Fatigue--Spec. Change	2			2	
	(b) Output Voltage Low-Handling Damage--None	2			2	
	(c) Position Signal Eratic--Broken Probe, Vibs--None	1			1	
	(d) Open Circuit--High Cycle Fatigue--Hys Fillet Increased	1		1		
	(e) Erratic Position Indication--Broken Wire--UCR A012535	2			2	
	(f) Erratic Position Indication--Open	1			1	
2	Poppet					
	(a) Cracked Suspect Handling--Assembly Change	1	1			
	(b) Cracked--Open	1	1			
4	Separation @ Weld--Defective--Weld Schedule Review	1			1	
5	Piston Spring Broke--High Cycle Fatigue--Redesign	1			1	
6	Valve Remained Open @ Shutdown--Not Lodged--Inspection Alerted	1			1	
7	Indicator Bolts Incorrect Type--Supplied--Notified	1			1	
3	Contamination					
	(a) Particle--Tapping Debris--Inspection Added	1			1	
	(b) Source Unknown--Cleanliness	2			2	
		18	2	1	15	—

D500 GOX CONTROL VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Seal--Leak					
	(a) Leak, Reverse Flow--Seal Crack, Machining--Drawing Change	1			1	
	(b) Leak--Insufficient Sealing Strength--Leak OK	2			2	
	(c) Leak--Source Not Determined--Inspect	1			1	
	(d) Leak Cracked Seal, High Cycle Fatique Not to Print, Change	1			1	
	(e) Seal Leak--Particle Contamination--None, In Spec.	1			1	
	(f) Leak @ Part 024.1--Open	1			1	
2	Supply Pressure Low--Open	1			1	
		8	—	—	8	—

D600 RECIRCULATION INSULATION VALVE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leak					
	(a) Internal Leak--Allowable Rate, OK	2			2	
	(b) Leak--Fabrication--Planning Change	1			1	
	(c) Upper Shaft Seal Leak--Thermally Induced, DVS Test, None	1			1	
2	LVDT					
	(a) Output Voltage Low--Shim Install Error Mfg. Alerted	1			1	
	(b) Output Erratic--Armature Fracture, Fatigue--Redesign	1			1	
3	Contamination					
	(a) Metallic--Source Unknown--None	1			1	
	(b) Brown Deposits--Unknown--None	1			1	
4	Housing to Shaft Wedging Wear--Open	1			1	
		9	—	—	9	—

E001 MAIN VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leak					
	(a) Pin Plug Leak--Inadequate Seal--Add Leak Test	1			1	
	(b) Wireway Leak--Epoxy Did Not Adhere--Process Change	3			3	
	(c) Internal Leak--Tolerance Stackup--Detectable in Test	2			2	
	(d) Hyd Oil Leak--Excessive Proof Test Cycling--None	2			2	
	(e) Static Seal Leak--Burr Induced Scratch--New Inspection	1			1	
	(f) Vent Port Leak--Defective O-Ring--Open	2			2	
	(g) Wireway Leak--Inadequate Epoxy Coverage--Spec. Change	2			2	
2	Hydraulic Lockup Drift--Mfg. Error--Detectable--None	5			5	
3	Slew Rate Error--Contamination--None	2			2	
4	Servo Switch Failed--Thermal Damage--Ref. UCR A001737	1		1		
5	RVDT Error--Mismatch to Actuator--Personnel Alerted	1			1	
6	Activator Failed to Close--Design Life Exceeded	1			1	
		23	—	1	22	—

E002 PREBURNER VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks					
	(a) Wireway Leak--Inadequate Joint Seal-Surface Finish Change	1			1	
	(b) Failsafe Servoswitch Leak--Not Determined--Replace, Detectable	2			1	1
	(c) Wireway Leak--Epoxy Sealant Did Not Adhere--Process Change	6			6	
	(d) Servoswitch Leak--O-Ring Omitted--Personnel Alerted	1			1	
	(e) Wireway Leak--Open	4			4	
	(f) Leak--Shaft Seal Surface Scratch, Handling--Inspect Change	1			1	
2	RVDT Channel Error--Bearing Freeplay--Configuration Change	1			1	
3	Bent Terminal, Dielectric Test Failure--Supplier Changed	1			1	
4	Silicone Oil Contamination on Shaft--Unknown--Persons Alerted	1			1	
5	Vent Port Pitting--Unknown Cause--Personnel Alerted	1			1	
6	Pneumatic Sequence Test Failure--Open	1			1	
		20	—	—	19	1

E110 MAIN FUEL VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks					
	(a) Wireway Leak--Epoxy Did Not Adhere--Process Change	2			2	
	(b) Vent Port Leak--Scratched Piston--None, Detectable	1			1	
	(c) Vent Port Leak--Out of Round--Isolated Case, None	1			1	
	(d) Servo Valve Leak--Dirt on O-Ring, Assembly-Alert	1			1	
	(e) Vent Port Leak--O-Ring Nibbled by Movement--New Backup Ring	3			3	
	(f) Wireway Leak--Insufficient Epoxy Coverage--Procedure Change	5			5	
	(g) Vent Port Leak--Open	1			1	
	(h) Leak--Open	2			2	
2	Heater Blanket					
	(a) Damage Handling--Technicians Alerted	2			2	
	(b) Open Circuit--Defective Spot Welds--Inspection Added	1			1	
3	Servoswitch					
	(a) Erratic--Insulation Damage by Pitting--Persons Alerted	1			1	
	(b) Pull In-Drop Out Test Failure--Open	1			1	
	Servoswitch					
	(a) Erratic--Insulation Damage by Pitting--Persons Alerted	1			1	
	(b) Pull In-Drop Out Test Failure--Open	1			1	
4	Contamination					
	(a) Suspect Contam--UCR A018556	1			1	
	(b) Particle in Shaft Cavity--Unknown--None	1			1	
5	Position Indicator Failure--Open	1			1	
6	Actuator					
	(a) Handling Damage-Not Determined--Procedure Change	1			1	
	(b) Improper Installed Warmer Insert--Procedure Change	1			1	
	(c) Slow to Respond--Coil Short Circuit--Procedure Change	1		1		

E110 MAIN FUEL VALVE ACTUATOR (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
7	Actuator to Valve Mating Proc. Error--Wrong Instructions--New Instructions	1			1	
8	Hyd. Oil Wetting @ Servo-Anomaly--Tech Alerted	1			1	
9	Washer and Spring Bent--Mfg. Procedure Error--Procedure Change	1			1	
10	Failsafe Performance Test Failure--Open	1			1	
11	Seal Damage--Housing Fab. Error--Tech Alerted	2			1	1
		35	—	1	33	1

E120 MAIN OXIDIZER VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leak					
	(a) Leak--Contamination, Source Unknown--None	1			1	
	(b) Hyd Oil Contaminated Induced Wear--Clean	1			1	
	(c) Contam. Induced Cap Seal Scratches--Source Unknown--None	1			1	
	(d) Leak--Housing to Actuator Cylinder--Pending Analysis	1			1	
2	Contamination					
	(a) Contam.--See UCR A018556	1			1	
	(b) Hyd. Reservoir and Supply (Facility)--Purge Added	1			1	
3	Wireway Nut Broken--Undetermined--None	1			1	
4	Wire Insulation Cold Flow Marks--Vibration--Not Detrimental	1			1	
		8	—	—	8	—

E130 FUEL PREBURNER OXIDIZER VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
1	Leak					
	(a) Dynamic Seal--Hyd. Oil Contam. Induced Wear--Clean and Maintain	2			2	
	(b) Seq. Valve Seal Leak--O-Ring Shift--Redesign	1			1	
2	Contamination					
	(a) Suspect--UCR A018556	1			1	
	(b) Contam. Facility Hyd. Reservoir--Drum Purge Added	1			1	
3	Pretest Check Out FIDs--Suspect Contam.--None	1		1		
4	O-Ring Defect--Personnel Alerted	1			1	
5	Crank Failure--Obsolete Configuration--Replace	1			1	
6	Sequence Valve Anomaly--Open	1			1	
		9	—	1	8	—

E140 OXIDIZER PREBURNER VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
1	Forward Servo Leak--Not Determined--OK Use As Is	1			1	
2	Contamination					
	(a) Contamination--See UCR A018556	1			1	
	(b) Facility Hyd. Reservoir Contam.--Drum Purge Added	1			1	
3	Bolts Rusty--Cosmetic Condition--Change Bolts	1			1	
4	Actuator Would Not Close--Crank Failure, Obsolete Conf.--Replace	1			1	
		5	—	—	5	—

E150 CC VALVE ACTUATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Leaks					
	(a) Internal--Tolerance Stuck Up--None Detectable	1			1	
	(b) Pneumatic Seal Leak--Scratched Piston, Contam.--None, Detectable	1			1	
	(c) Servo Valve Leak--Not Determined--OK, Use As Is	2			2	
	(d) Wireway Leak--Insufficient Epoxy Coverage--Spec. Change	3			3	
	(e) Vent Port Leak--Damaged Orifice O-Ring--Back Up Ring Added	1			1	
2	Contamination					
	(a) Contam.--Source Unknown--Personnel Alerted	1			1	
	(b) Fac. Hyd. Reservoir Contam.--Drum Purge Added	1			1	
3	Post Shutdown Purge Terminated Early--O-Ring Shift--Redesign	4	1		3	
4	RVDT					
	(a) Comparison Limit Exceeded--Engine Flashback--None, Unique	1		1		
	(b) Adjustment Error, Obsolete Design, Redesign	1			1	
	(c) Insulation Resistance Low--None, Isolated, Detectable	1			1	
5	Error Position FID, Suspect Contamination--None	1		1		
6	Actuator Failure--Design Life Exceeded--Replace	2			2	
7	Solenoid Screw Loose--Handling--Inspection Added	1			1	
8	Servo Coil Open Circuit--None, Isolated Case	1			1	
9	Servo Switch Land Wire Worn--Vibration--None, OK	1			1	
10	Spring Guide Chaffed--Material Deficiency--Material Change	1			1	
11	Pneu. Shutdown Out of Spec--Sleeve Not Per Drawing--Check Added	1			1	
		25	1	2	22	—

E201 RVDT

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	RVDT Coil Voltage Erratic--Design Problem--New Design	2			2	
2	Strength Test Failure--Add Insulation Tape	1			1	
		3	—	—	3	—

FOOO CONTROLLER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Transistor					
	(a) Memory Altered Ch. A or B--Lugs Too Long--Now Measure	2		2		
	(b) Short Circuit--Sensitive to High Voltage/Temp--None	1		1		
	(c) Ch. A P/S Shutdown--Shorted Transistor--Inspection Faded	1		1		
	(d) Ch. A P/S Shutdown--Trans. Shorted to Chassis--None, Isolated	1		1		
	(e) 400 Hz Input Power Overload--Emitter/Collector Short--New Requirement	2		2		
2	Circuit Board					
	(a) Fails to Execute Skip Instruct.--Loose Board--None	1		1		
	(b) Ch. A P/S and Halt--Inproper Board Seating--None	1		1		
	(c) Noise Coupling--Ungrounded Substrate--Grd. Strap Added	2		2		
	(d) Ch. A Parity Error--Improper Board Seating--Board Ht. Measure	1		1		
	(e) Ch. B Halt--IEGB S/N 19 Card--None Possible	1		1		
3	Wire					
	(a) Open Circuit, Broken Wire--None	11		9	2	
	(b) Open Circuit, Broken Wire--Handling--Alert Mfg.	1		1		
	(c) Short-Pinched Wire Caused Xistor to Short-Use Tie Cord	1		1		
	(d) Failed Self Test--Broken Land--None	1			1	
	(e) Damaged Insulation--Enhanced Inspection	3		1	2	
	(f) Parity Error--Wire Fractured by Rework--None	4			4	
	(g) MOVA Failsake Servovalve Wire Break--Tooling Change/X-Ray	5		2	3	
	(h) Short to Chassis--Insulation Cold Flow--Insulation Tape	2		2		
	(i) Ch. B MFV Failure Reported--MIB Wire Broke--None	5		2	3	
	(j) H/S Wire Output Low--Contam. Damage--None Applicable	1		1		
	(k) DCUA Halt--Multiple Insulation Scrapes--Defective Tool Removed	1		1		
	(l) DPOT Disch. Press. Fail.--Twisted, Pair Wire Damage--None	1		1		

FOOO CONTROLLER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
	(m) DCUB Failed Accept. Test--Shorted Wire, Insulation--Caution Note	1			1	
	(n) DCUB Address Error--Pinched Wire @ Closure--Procedure Change	1		1		
	(o) Excessive Power Draw--Power Wire--Pinched--Wire Removed	1			1	
4	Miscellaneous Open/Short Circuit					
	(a) Failure--Open Circuit--None	1		1		
	(b) Failure--Short Circuit to Chassis--None	2			2	
	(c) DCUB--Failure--Hex Inverter Short	1		1		
	(d) Ch. B Halt--Contamination Caused Short--None	2		2		
	(e) Not Able to Load Memory--Short by Wire Clippings--Add Procedure	1			1	
	(f) Failure--Short Due to Tight Wires--Inspection Added	1			1	
	(g) Failure--Open Circuit--Overstrussed IC--None	1			1	
5	Connector Pins					
	(a) Cannot Load Ch. A--Mismatched Pins--Change Procedure	1			1	
	(b) Error Reading--Broken Pin--None	1			1	
6	Assembly Error (Miscellaneous)					
	(a) Loss of Ch. A Power--Assembly Error--None	1			1	
	(b) Heater Power Shorted--Careless Assembly--Amend Instructions	1			1	
8	Noise					
	(a) Interrupt--Noise in Interrupt Current--Already Handled	1			1	
	(b) Ch. B., Temp. Calibration Low Voltage--Noise From 500 Hz Gen.--None	1			1	
	(c) Command Failure--Noise on 12 MHz Clock--Add Filter	1		1		
9	Unknown Cause					
	(a) Various Small Problems--Unknown Cause--None	130		82	48	
	(b) Same as Above--Open	27		21	6	
10	Miswired					
	(a) Simulated +5V DC Undetected--Unsoldered Lead--None	1			1	
	(b) Ch. 6 6V Supply was -9V--MiB Miswire--None	1		1		

FOOO CONTROLLER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
	(c) Ch. B VEEI Not Copying--Miswired Pulse Transd.--Test Change	1		1		
	(d) Failure--Incorrect Rework Wiring--None	1		1		
	(e) Heater Failure--P/S Terminals Miswired--None	1			1	
	(f) Command Ch. C Failed--Miswired Connection--None	1		1		
	(g) Int. Temp A, FID, Incorrect Resistor--Redesign Adapter	1			1	
	(h) Command Channel C--Part Installed Wrong--Alert Person	1		1		
	(i) FPOV Miscompare and Interrupt--Unsoldered Joint--Open	1		1		
11	Defective Plating--CCV FID--Improve Inspection	1			1	
12	OP Amps					
	(a) Bad Reading--Low Op Amp Slow Rate--New Type Op Amp	4		3	1	
	(b) Miscompare--Bad Op Amp--None, Replace	1		1		
	(c) Miscompare--Particle In Op Amp--New Test	2			2	
	(d) Sensor Failures, Out of Range--DC Offset--None	1		1		
	(e) A/D Conversion FIDs--Amp Failure--None	2		2		
	(f) Ch. B P/S Not Power Up--Op Amp Short, Particle Add X-Ray Test	1			1	
13	Wrong Indication--Heated Circuit--Add Jumpers	1			1	
14	Contaminated Contacts					
	(a) Current Out of Tolerance--None	1			1	
	(b) MOVA Feedback Miscompare--Sockets Contam.--None	1		1		
15	Diode					
	(a) Premature Heat--Diode, High Junct. Cap.--Change Diode	1			1	
	(b) DCUB PRI w/o PFI--Damaged Zener Diode--None	1		1		
16	Bad Bonding					
	(a) Erroneous FID.--Loose Lead Bond in IC--None	1		1		
	(b) Voltage Failure--Debonded Resistor Lead--None	1		1		
	(c) Ch. A WDT2 Failure--Debonded Socket--Inspection	1		1		

FOOO CONTROLLER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
17	Corrosion					
	(a) Solenoid Hold Voltage Low--Corroded Capacitor--New Cap	1		1		
	(b) Pressurant Leak Rate High--Corroding Seals--OK, None	1			1	
18	Voltage Error--Hardware Timing Condition--S/W Patch Delay	1			1	
19	Oscillation					
	(a) Miscompare Design Causes Oscill.--Ferrite Beads Added	2		1	1	
	(b) OPOV Oscillation @ Hotfire--Open	1		1		
20	Capacitor					
	(a) Voltage Dropped--Capacitor Short to Grid--None	1		1		
	(b) A/D Conversion Failure--Defective Cap.--None	1			1	
	(c) Compare FIDs--Capacitor Momentary Short--None	1		1		
21	Pressure Miscompare--PR Bridge 2mV Offset--Put Cap. in Bridge	1			1	
22	Pressure Sensor Failure--High Resistance Conductor Path--None	1		1		
		265	—	167	98	—

F600 GSE CONTROLLER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Two ICs bad--None Applicable	1			1	
2	CADS Circuit Breaker Dropout, Other Equipment--Separate Power Supply	1		1		
3	CAPS Halt--Improperly Seated Card--None Applicable	1			1	
		3	—	1	2	—

F800 FASCOS

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Cable/Wire					
	(a) FID--Intermittent Coax Cable--Redesign and Change Installation	1			1	
	(b) Chaffed Wires--Poor Surface Preparation and Routing--Repair	1			1	
2	12V Power Supply Low--Defective Resistor--None, Isolated	1		1		
3	Failed Propagation Delay Test--Capacitor Defect--X-Ray Caps	1			1	
4	FIDs on Ch. 2--Short Circuit in Signal Cond. Module--Spec. Change	1			1	
5	FIDs--Combined Accelerometer and Mount Resonance--None, Redundancy	10		8	2	
6	Torque Anomaly--Defective Tooling--None, New Tools	1				1
7	Failed Stability Test--Fatigue Fracture Capacitors--Better Adhesive	1				1
8	Contacts/Connectors					
	(a) Connector Failed Capacitance Test--Die Cracked @ Bonding--None	1			1	
	(b) No Volts to Accelerometer--Poor Solder Joint--Personnel Alerted	1			1	
	(c) Connector Min. Gap to Small--Drawing Problem--Change Drawing	2			2	
9	Pressure					
	(a) Internal Pressure Low--Solder Crack, Thermal Exp.--Change Material	1			1	
	(b) Pressure Leak--Coax Connector Leak--Change Leak Requirements	1			1	
10	Unknown Cause					
	(a) Intermittent FIDs--Unknown--Personnel Alert	4			4	
	(b) Receptacle Threads Dented--Unknown--None	1			1	
11	Design--Erroneous Output When Power Off--Software Change	1		1		
		29	—	10	17	2

GOOO IGNITER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Ignitor Tip Cracks					
	(a) Surface Cracks--Extended Service--OK, Normal	3			1	2
	(b) Copper Tip Damage--Extended Service--Past Design Life	1			1	
	(c) Output Failure--Suspect Physical Damage--None	2			2	
2	Igniter Tip Erosion					
	(a) Tip Erosion--Off Combustion, ASI Contamination--OK As Is	13			7	6
	(b) Tip Erosion--Off Normal Combustion--None, Replace	8			8	
3	No Spark--Contamination (ASI)--None OK As Is	1				1
4	Igniter Tip Melting--ASI Contamination--OK As Is	1				1
5	Insulator Crack					
	(a) Cracked Ceramic--ASI Contamination--None, OK As Is	11			7	4
	(b) Ceramic Flaking--Off Normal Combustion--Repair or Replace	6			6	
	(c) Ceramic Failure--Spark Quenches--Add Criteria	1			1	
6	Electric Connections					
	(a) Output Voltage Off--Bad Connection--Isolated, None	1			1	
	(b) Ch. B Igniter Malfunction--Inadequate Ground--Mfg. Process Change	1			1	
	(c) Intermittent--Internal Ground Strap Not Attached--Mfg. Notified	1			1	
7	Igniter Tip--Moisture					
	(a) Spark Failure--Moisture on Tip--Drying Procedure	2			2	
	(b) FID During Checkout--Moisture--None	2			2	
8	Intermittent--Transformer Short, Void-Change Mfg.	3			3	
9	Monitor Voltage High--Transistor Failed--None, Detectable	1			1	
10	Igniter Tip Debonding--Plating Deficiency--Mfg. Improved	1			1	

G000 IGNITER (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
11	Cause Unknown--Various					
	(a) Erratic Output--Cause Unknown--None	2			2	
	(b) Low Insulator Resistance--Suspect--Spec. Change	6			6	
12	Potting Void--Erratic Operation--Mfg. Process Change	4			4	
13	Low Resistance Pin--F2 Filter Failed--Change Cleaning Solvent	2			2	
14	Output Failure, Electrode Short-Off Combustion--None	1			1	
15	Quench Problem--Off Normal Combustion--None	2			2	
		76	—	—	62	14

HOOO, HOO1, HOO2 ELECTRICAL HARNESSES

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Harness Braid Birdcaged--Handling Damage--Repair Procedure	17			17	
2	Ground Wire Lug Broken--Handling Damage--Heat Shrink Added	5			4	1
3	Connectors					
	(a) Connector Loose--Open	1			1	
	(b) Rust in Connector--Rain Water--None, Proc. Adequate	3			3	
	(c) Connector Defective--Pin Hole Misplacement--None, Isolated	1			1	
	(d) Unlocked Connector--Unknown Cause--Remove Bout Requirement	1			1	
	(e) Defective Connector--Particle Contam. Unknown--None	2			2	
	(f) Connector Disengaged--Suspect Improper Torque--ECP 416	6		4	2	
	(g) Connector Backshells Loose--Normal Condition--None	6				6
	(h) Loose Backshells--Handling Damage--New Design	7			7	
	(i) Connector Disengaged--Unknown, FPL--New Design	3		2	1	
	(j) Incorrect Connector Mating--Human Error--Person Alerted	1			1	
	(k) Backshell Broken--Inadequate Cleaning--Techs Alerted	2			2	
	(l) Loose Connector--Installation Error--New Instructions	2			2	
4	Pin Recessed--No Failure--None	2				2
5	Wire					
	(a) Broken @ Connector--Excessive Bending--Not Flight Conf.	1		1		
	(b) Broken--Suspect Handling Damage--Alert Tech.	5		1	4	
6	Open/Short Circuit					
	(a) Open Circuit--Handling Damage--Techs Alerted	2		1	1	
	(b) Short Circuit/Insulator Sleeve and Leads--Open	1		1		

H000, H001, H002 ELECTRICAL HARNESSES (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
7	Improper Harness Support--Support Requirements Added	1		1		
8	Torque Lock					
	(a) Debonded--Surface Contamination--None, Isolated Case	1			1	
	(b) Missing--Defective Material--New Material	2			2	
	(c) Missing Connector Loose--Inadequate Torque--Increase Torque	3		1	2	
	(d) Torque Lock Debonded--Bad Surface Preparation--Spec. Change	6			6	
9	Birdcaged @ Connector					
	(a) Birdcaged--Not Determined--None, Repair	1			1	
	(b) Birdcaged--Handling Damage--None, Repair	5			4	1
10	Loss of Continuity--Handling Damage--Personnel Alerted	2		1	1	
11	Retainer Ring					
	(a) Broken--Stress Corrosion--No Functional Problem	1			1	
	(b) Retainer Cracked--Stress Corrosion--Redesign	3				3
12	Undetermined Problems					
	(a) FIDs @ Flight Readiness Test--Unknown--None Applicable	2		2		
	(b) Noisy, Low Signal--Unknown--Field Signts Notified	2			2	
13	Insulation Low Resistance--Moisture in Connector--None	1			1	
14	Material/Elastomer Problems					
	(a) Material Moisture Contam.--New Supplier	1			1	
	(b) Elastomer Abnormal--Humid Environment--Spec. Change	2			2	
	(c) Material Defective--Moisture Sensitivity--New Packaging	3			3	
15	Broken Strain Relict Rope--Hardened by Epoxy--Mfg. Notified	1			1	
		105	—	15	77	13

J200 PRESSURE SENSORS

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
1	Wire Fatigue (Vibrations)					
	(a) Open Circuit--Wire Fatigue--Redesign	3			3	
	(b) Output Failure--Gold Wire Fatigue--Redesign	3			3	
	(c) Output Failure--Gold Wire Fatigue--Redesign ECP454	18		3	7	8
2	Wire Break					
	(a) Sensor Output Failure--Wire Break--Terminal to be Welded	1			1	
	(b) Sensor Output Failure--Wire Break--Inadequate Putting--Insp.	2			2	
3	Output Failure--Thermal Induced Gold Wire Break--NASA Decision	2			2	
4	Low Insulation Resistance--Shorted Diode--None, Detectable	1			1	
5	Assembly Error					
	(a) Connector Misaligned--Assembly Error--Inspection Added	1			1	
	(b) Bent Pin--Handling Error--None Applicable	2			2	
	(c) Error Band Deviation--Improperly Set Overload Screw--None	1			1	
	(d) Output Failure--Assembly Defects--Document Revised	1			1	
6	Output Failure--Thermal Induced Resistance Change--NASA Decision	1			1	
7	Manufacturing Problem					
	(a) Erroneous Output--Shop Aid Plug Not Removed--Supplier Caution	1			1	
	(b) Input/Output Resistance Low--Supplier Data Oversight--Techs.	1			1	
8	Thermal Problems--Miscellaneous					
	(a) Zero Offset--Thermal Gradients--Improve Characteristics	1			1	
	(b) Output Failure--Thermal Environment--NASA Decision	1			1	
9	Open/Short Circuit					
	(a) Open--Unknown, Suspect Hot Gas Leak--None	1			1	
	(b) Short--Pin to Case--Documents Changed	1			1	
	(c) Erratic Output--Open Circuit--Replace	1			1	

J200 PRESSURE SENSORS (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
10	Undetermined Output Errors					
	(a) Error Band Deviation--Unknown--None, Unit Compensated	16			16	
	(b) Erroneous Output--Suspect Cold Environment--None	1			1	
	(c) Bad Output--Unknown, Maybe Gold Wire--Redesign	3			2	1
	(d) Pressure Rise--Not Known, Suspect Ice-Drying and Purge Added	1			1	
	(e) Sensor FIDs--Unknown--None	1		1		
	(f) Output Drift--Unknown--None	3			3	
	(g) Output Failure--Unknown--None	2			2	
	(h) No Output on Flights, Low Input Capacitance--Unknown; Replace	2			2	
	(i) Calibration Test Failure--Unknown--Sensor Redesign	1			1	
	(j) Noisy or Hot Fire or Flight--Open	2			2	
11	Internal Failure--Gold Wire Bond Parted None, Not Used Now	1			1	
12	Welds					
	(a) Output Failure--Weld Defect--None, Isolated	1			1	
	(b) Bad Output--Link Pin Weld Cracks--Weld Inspection Added	3			3	
13	Output 100 psi High--Overheated @ Hot Fire--Thermal Isolation	1			1	
14	RC Error--Resistor Compartment Failure--None	1			1	
15	FIDs During Shutdown--Coefficient Error--Correct Coefficient	1				1
16	Thermal Block Cracked--Installed Under Stress--QA Advised	1			1	
		84	—	4	70	10

J300 TEMPERATURE SENSORS

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
1	Sensor Tip Erosion--Suspect Contamination--Improved Cleaning	1			1	
2	Sensor Tip Broken/Damage					
	(a) Tip Broken--Hot Gas Flow Impact--Redesign Pending	4		1	3	
	(b) Tip Bent--Over Temp.--None Applicable	1			1	
	(c) Erroneous Output--Flow Debris Impact--Shield Added	7		2	5	
	(d) Tip Broken--High Flow Velocity--Probe Retracted	1			1	
	(e) Sensor Tip Broken--Vibration, Fatigue--Redesign	4		4		
	(f) Erratic Output--High Cycle Fatigue--Check Added	1			1	
3	Output Problem--Unknown Cause					
	(a) Erratic Output--Unknown--None	15		1	12	2
	(b) Output Failure, Cracks in Pressure Seal--Unknown--Redesign	1			1	
	(c) Erroneous Output--Open	1			1	
4	Open/Short Circuit (Miscellaneous)					
	(a) Open Circuit--Handling Damage--Personnel Alerted	1			1	
	(b) Open Circuit--Suspect Debris Impact--None	1			1	
	(c) Erroneous Output--Open	1			1	
5	Open/Short Circuit (Miscellaneous)					
	(a) Open Circuit--Handling Damage--Personnel Alerted	1			1	
	(b) Open Circuit--Suspect Debris Impact--None	1			1	
	(c) Short to Case @ Test--Overheat--Techs Alerted	1		1		
	(d) Off Scale Output--Circuit Not Isolated--Redesign	4			4	
	(e) Short Circuit--Open	1			1	
6	Erratic Output--Braze Joint Defects--Check Added	3			3	
7	Insulation					
	(a) Open Circuit--Fatigue, Sheathing Contam.--Redesign	4			4	
	(b) Low Insulation Resistance--Moisture--None	3			3	
	(c) Low Insulation Resistance--Overheating--None	5			5	
	(d) Isolation Insulation Test Failure--Open	1			1	

J300 TEMPERATURE SENSORS (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
8	Wire Break					
	(a) Open Circuit--Wire Break--Redesign	1			1	
	(b) Performance Shift, Wire Break--Flow Debris--None	2			2	
	(c) Erratic Output--Wire Break, Fabrication--Mfg. Procedure Change	2			2	
	(d) Open Circuit, Element Wire Break--Handling Damage--Techs. Alerted	2		1	1	
	(e) Output Failure, Element Wire Break, Assembly--Assembly Change	2		2		
	(f) Erratic Output--Wire Break--Design Investigation	1		1		
9	Electrical Connector Damage--Unknown--None, Repair	1			1	
10	Miscellaneous Handling Damage					
	(a) Resistance Off--Handling Damage--Techs Alerted	1			1	
	(b) Ground Short--Handling Damage--Persons Alerted	1			1	
	(c) Skin Temp. Erroneous--Handling Damage--Repair	1			1	
11	Missing Receptacle Insert--Requirement Not Defined--Add Requirements	3			3	
12	Sensor Debonding					
	(a) Improper Epoxy Cure--Epoxy, Instructions	1			1	
	(b) Handling Damage/Inadequate Bond--None, Repair	26			26	
13	Coax Cable					
	(a) Electrical Leak to Case--Cable Crack--None	2			2	
	(b) Output Failure--Coax Fracture--Assembly Procedure Change	2		1	1	
14	Moisture					
	(a) Noisy--Moisture Contamination--None	1			1	
	(b) Resistance Test Failed--Moisture, Fabrication--Assembly Change	1		1		
		113	—	15	96	2

J600 FLOW/SPEED PICKUP

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Low Insulation Resistance--Wire Insulation Damage/Fabrication--None, Detectable	2			2	
2	Speed Sensor Tip Contact Housing--Dimension Error--Change Drug	1				1
3	Broken Wire--Suspect Thermal Induced--Thermal Test Revised	1			1	
4	Miscellaneous Output Failure					
	(a) Output Failure--Unknown--None	4			4	
	(b) Output Failure--Suspect Thermal Shock--Test Change	1			1	
	(c) Erratic Output--Suspect Sensor Nut Variations--Evaluation	1			1	
5	Open Circuit, Encapsulment Cracks--Assembly--Assembly Change	2		2		
6	Open Circuit--Cracked Epoxy--Assembly Change	1			1	
		13	—	2	10	1

J800 ACCELEROMETER

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Accelerometer Debonded--Not Detrimental--None	2				2
2	Noisy Accel.--Accel. and Mount Resonance--None, Redundant	2			2	
3	Dielectric Insert Missing--Cause Unknown--None	1			1	
4	High Readings					
	(a) High Amplitude Output--Unknown--None	1			1	
	(b) Off Scale Spikes (STS7)--Failure Could Not be Reproduced--None	1			1	
		7	—	—	5	2

K100 FUEL LINE DUCT

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Bellows Flex Joint					
	(a) Collapsed During DVS Test--Leakage @ Weld--New Design	2			2	
	(b) Frost Formed--Handling Damage--None, Repair	1			1	
	(c) Frost Formed on Bellows--Bond Seal, RTV Cure--Specification Change	1			1	
	(d) Spring Rate High--Excessive Epoxy--None	1			1	
	(e) Exp. Joint Boot Torn--Cause Unknown--None, Repair	1			1	
	(f) Frost on Bellows--Open	1			1	
2	Rust in LPFT Discharge Duct--Open	2			2	
3	Fuel/Seal Leak					
	(a) Fuel Leak--Cause Unknown--None Applicable	1			1	
	(b) Seal Leak--Defective Seal--None Required	1			1	
	(c) Leak @ Joint F4.2--Open	1			1	
4	Nickel Insulation Plating					
	(a) Damaged--Handling--Improve Procedure	1			1	
	(b) Cracked--Inadequate Repair--New Specs.	2			2	
	(c) Cracked--Unknown Cause--OK	1			1	
	(d) Damaged--By People in Area--Test Personnel Advised	2			2	
	(e) Insulation Damage--Open	1			1	
5	Contamination					
	(a) Contamination--Source Unknown--None, Clean	5			5	
	(b) Contamination--Human Error, Shop Debris--Advise Techs	11			10	1
6	Flange Insert					
	(a) Backed Out--Key Not Fully Engaged--Procedure OK	1			1	
	(b) Damaged--Incorrect Branching of Slots--Planning Change	1			1	
	(c) Key Not Flush--Suspect Tolerance Buildup--None, OK	1			1	
7	Joint Holes Damaged--Repeated Use--Improve Product	1			1	
8	Pinhole Leaks in Flow Meter--Carburization--Redesign	1			1	

K100 FUEL LINE DUCT (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality			
			1	2	3	N
9	Dimension Errors					
	(a) Orifice Size Error--Inspection Error--Planning Improved	1			1	
	(b) Seal and Groove Misfit--Groove Undesize--Managers Notified	1			1	
	(c) Joint Misalign--Tolerance Stackup--Revise Report	2			2	
	(d) Flange ID Undersize--Blend Oper. Omitted--Add Blend Oper.	1			1	
10	Burst Diaphragm Broke--Handling and Vibration--None	10			10	
11	Accel. Debonded--Improper Adhesive Prep.--Advise Tech.	1			1	
12	Duct Cracks--Were Not Detected--Revise NDT Drawings	1			1	
13	Seals					
	(a) Seal Groove Edge Damage--Bad Installation--Persons Alerted	1			1	
	(b) Cut and Chatter Marks--Machining--None	1			1	
	(c) Tolerance Problem--Rework--Acceptable	1			1	
	(d) Discoloration and Pitting--High Humidity and Salt--None--Polish	4			4	
14	Nuts/Screws					
	(a) Nuts Yielded--Increasing Stresses--None Required	1			1	
	(b) Sheared Screwhead--Impact, Unknown--None	1			1	
15	Joints--Overmold					
	(a) Split in Overmold--Ice, Thawing--Test Stand Notified	1			1	
	(b) Debonded--Improper Adhesive--Change Adhesive	3			3	
	(c) Overmold Raised--Not to Print--Use Silicone Tape	4			4	
	(d) Missing--Accidental Impact--Person Cautioned	1			1	
16	Cracks in Weld--Improper Technique--Train Welder	2			2	
17	Excessive Copper Plate--Planning Change	1			1	

K100 FUEL LINE DUCT (CONTINUED)

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
18	F/M					
	(a) High Fuel Indication--F/M Constant Bad--Change	1			1	
	(b) F/M Calib. Bad--Synchronous Wake Pulse--Redesign	1			1	
	(c) F/M Calib. Const. Low--Fuel Prediction Error--Conduct Tests	1		1		
		81	—	1	79	1

K200 OXIDIZER LINE DUCT

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Duct Cracks					
	(a) Failure, Pressure Test--Seam Weld Crack--Develop Detection Method	1	1			
	(b) Crack @ Weld Ft. 7--Inspector Inattentive--Improve Inspect.	1			1	
	(c) Possible Crack--Open	1			1	
	(d) Leak/Crack @ Weld 14--Open	1			1	
2	Duct--Damage					
	(a) Nicks on ID Surface--Debris Impact--None OK	1			1	
	(b) Worn Spot--Handling Damage--None	1			1	
3	Duct Leaks					
	(a) High Leakage--Unknown Cause--None, OK	1			1	
4	Installation Error/Misfit					
	(a) Port @ Joint 9.1 Off Drilled Incorrect Hole--Advise Person	2			2	
	(b) Crack @ Support Link--Flex Joint Backwards--Repair	1			1	
	(c) Seal Groove Tolerance--Inspection Alerted	1			1	
5	Contamination					
	(a) Weld Debris in Duct Joint--Procedure--OK As Is	3			3	
	(b) Contamination Throughout--Unknown--Cleanliness	12			12	
	(c) Metal Inside Joint--Bolts Stripped None, Replace Bolts	1			1	
	(d) Tape on Flange--Improper Use of Lox Tape--Change Process	1			1	
	(e) Brown Residue--Open	1			1	
	(f) Metal Sliver in Seal Groove--Measure Error--Alert	1			1	
6	Bulge in 039 Tube--Local Explosion--c/o Sequence Change	1			1	
7	Impression Marks on Ring--Improper Installation--Alert	1			1	
		32	1	—	31	—

K300 DRAIN LINE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
2	Line Damage					
	(a) Damaged Drain Manifold--Repeated Removal HPOT--Replace	1			1	
	(b) Gouges on Flange--Dropped in Assembly--No Further Action	1			1	
4	Misalignment					
	(a) Drain Line to PCA Improper Handling Procedures Clarified	1			1	
	(b) Misalign Joint--Unknown Cause--Inspect	1			1	
5	Contamination @ Joint--Sample Too Small--None	1			1	
		5	—	—	5	—

K400 HYDRAULIC LINE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
3	Line Leak					
	(a) Leak @ Joint 1/16--Elastomer Damage--OK As Is	1			1	
	(b) Hydraulic Leak @ Joint H-1--Relax of Torque--None, OK	1			1	
4	Joint Misaligned--Exchange of Nozzle--None, OK	1			1	
		3	—	—	3	—

K500 PNEUMATIC HOSE/LINE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
2	Damaged Line					
	(a) Kink, Bent or Twisted--Improper Handling--Procedure Change	3			3	
	(b) One Compressed--Installation Error--Person Cautioned	1			1	
4	Misaligned Joint--Cause Unknown--Inspection	1			1	
5	Contamination					
	(a) Joint and Seal Contamination--Source Unknown--None	2			2	
	(b) Residue in Joints--Dry Lube Residue Mfg. Alerted	2			1	
		9	—	—	8	1

K500 PNEUMATIC HOSE/LINE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Duct Cracks					
	(a) Cracks--Improper Installation--Personnel Alerted	3			3	
	(b) Side Panels Cracked--Open	1			1	
5	Coolant Holes Plugged, Debris--Nozzle Removal--Non-Flight Problem	1			1	
		5	—	—	5	—

LOOO STATIC SEAL

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	Criticality 2	Criticality 3	Criticality N
1	Seal Damage					
	(a) Seal Sliver in Joint--Assembly Mistake--Personnel Alerted	1			1	
	(b) Seal Surface Blistered--Cause Unknown--None	2			2	
	(c) Chatter Marks--Turbine Housing Moved Radially--None	2			2	
	(d) Damage--Seal Came Loose--Revised RF004-146	1			1	
	(e) Protrusion on Seal--Open	2			2	
2	Contamination in Seal Groove--Mfg. Error--Improve Inspection	1			1	
3	Tolerance Problems					
	(a) Kel F Dimension Small--Measurement Error--Planning Change	1			1	
	(b) Discrepent Dimensions--Material Characteristics--Drawing Revised	1			1	
	(c) Seal Diameter Out of Toler.--Unknown Cause--None	2			2	
	(d) Seal Oversized--Drawing Error--Correct Drawing	1			1	
	(e) Seal Size Anomaly--Improper ID--Vendor Alerted	1			1	
	(f) Seal Undersized When Cryogenic--Calculated Wrong--Planning Change	1			1	
4	Low Leak Rate--Heat Marks on Sealant--None Needed	2			2	
		18	—	—	18	—

L200 STRETCH BOLTS

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Bolt Preload Error					
	(a) Studs Not Stretched--Assembly Error--Procedure Change	1			1	
	(b) Damaged Bolts on Removal--Preload Error--None	1			1	
	(c) Bolt Found Loose--Overload at Installation--None	1			1	
2	Bolt Damage					
	(a) Nicked--While Slotting HGM--Person Alerted, Superficial	1			1	
	(b) Broken Bolt--Suspect Excessive Torque--NSTL Alerted	1			1	
3	Stud Keys					
	(a) Piece of Key Missing--Improper Installation--Persons Alerted	1			1	
	(c) Keys Protrude--Improper Installation--Persons Alerted	1	—	—	1	—
		7			7	

L300 LEAKAGE--JOINT

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Joint Leaks--Scratches, Unknown Cause--Alert	4	—	—	4	—
		4			4	

M000 GIMBAL

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Fretting & Galling					
	(a) On Block and Body--Vibrations--None	5			5	
	(b) Wear, Interference Condition--Eliminate Interf.	1			1	
2	Bushing Cracks--Low Ductility Material--New Purchasing	3			3	
		9	—	—	9	—

N100 INTERCONNECT HARDWARE

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Missing Locking Clip--Removed for Test--Reinstalled	3			3	
		3	—	—	3	—

N200 THERMAL PROTECTION

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Insulation Separation--Application Technique--None, Repair	4			4	
2	Insulation Debond--Improper Cleaning--Eliminate Tools	1			1	
		5	—	—	5	—

N400 POGO ACCUMULATOR

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Cracks					
	(a) Cracks in Welds--No Failure--MRD091051, None	1			1	
	(b) Crack in Baffle--Gas Pure Defect--None, Inspect OK	1			1	
	(c) Cracks in Slotted Wall--Open	1			1	
		3	—	—	3	—

N600 ORIFICES--ASI, LEE JET

Fail. ID	Failure Mode - Failure Cause - Recurrence Control	Total No.	Criticality 1	2	3	N
1	Orifice Deformed--Open	3			3	
2	Tolerance Problems					
	(a) Orifice Not Per Print--Rework Wrong--Personnel Alerted	1			1	
	(b) Lee Jet Pin Not to Print--Installation--Alert	1			1	
3	Low Torque Value--Installation Lee Jet Error--Alert	1			1	
		6	—	—	6	—

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APPENDIX C

UCR REVIEW

List of High Occurrence/Criticality Failure
Types by Component

HOT GAS MANIFOLD

Comp. A100 Failure	1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	3	1	2	4	2	4	1	1	--	--	18	Crack in lined transfer tube-vib & Thermal Loads-Redesign-1981
1b				1					1	--	--	Duct Ruptured-Not heat treated-heat treat req'd.
2			5	3	3	1	4		--	--	16	Weld cracks-defective welds fabrication modifications
3a	1	2		2	1	2			--	--	8	Fabrication contamination, other failure debris-none
4		2		1	3	1			--	--	7	G-5 seals, gouges, leaks-Install problems-planning change
6				1	2	3	3		--	--	9	Stud Keys, brake, missing-Vib. & toler.-plate keys to fit
7					1				--	--	1	ASI orifice cracks - Thermal Fatigue-None
8a						1	1		--	--	2	Studs loose-torque tech trained
8b								2	--	--	2	Studs oversized-repeated stretching-maintenance
8c						3			--	--	3	Studs loose-soft keys design change
10								1	1	--	--	MCC ignition jt. leak OPEN

HEAT EXCHANGER

Comp. A-150 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1						1	1		--	--	2	Tube dings-mishandled Mfg change
2	2								2	--	--	Crack in coil-fitting mat'l incorrect-material verif.
3			1						1	--	--	Coil leak-wear on primary tube-none
4*				1	1	2	2		--	--	5	Various clearance problems-mfg-mfg. changes
5						3			--	--	3	Bracket clearance-thermal cycling-mfg. planning change
6							1		1	--	--	Coil leak-incomplete weld mfg. insp. improvement
8							1		--	--	1	Inclusion on fwd. vane OPEN

*Criticality N UCRs are included in the distribution for the time periods shown.

MAIN INJECTOR

Comp. A-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	2	3	Description - Cause Resolution
1a	5	3							--	--	8	H.S. Retainer damager-old configuration-new design
1b			1	2		1			--	--	4	Damage-secondary failure none
1c					10	8		1	--	--	19	Damage-gas turbulence @ FPL U-shaped structure install.
1d								3	--	--	3	Damaged-OPEN
2	5	2	11	1				1	--	--	20	Baffle cracks, erosion-environment; repair as needed
3a	1				1				--	--	2	Lox posts broken-gas turbulence Q FPL-change structure
3b						1			--	--	1	Broken lox posts-thermal overload - none
3c								3	--	--	3	Leak or broken lox posts OPEN
16a	1	1		1					--	--	3	Erosion-blocked orifice repair
16b	1								--	1	--	Erosion lox posts-high cycle fatigue-mat'l change
16c						1			--	--	1	Erosion lox posts-braze joint leak-spec. change
15*				2				1	--	--	1	Crooked lox posts-not failure conditions

*Criticality N UCRs are included in the distribution for the time periods shown.

MAIN INJECTOR (Continued)

Comp. A-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
25						1	2		--	--	3	Braze joints-leaks or cracked spec. change-inspect
9		2							--	--	2	Baffles loose-improper install.-none
5	1								--	--	1	Heat shield cracks-thermal loads-new retainers
18			1		1	1			--	--	3	Heat shield cracks @ FPL - gas turbulence-u-shaped structure
7a		2		1					--	2	1	Primary fact plate erosion-high cycle fatigue-new mat'l.
7b		1		1	1				--	--	3	Primary face plate cracks-load distri.-inspection
14a	1	1	1						--	--	3	INTER PROPELLANT PLATE CRACKS-heat shield fail.-new retainers
14b					3				--	--	3	Interpropellant plate cracks-gas turb. @ FPL-Unshaped struc.
14c								1	--	--	1	Interpropellant plate cracks-OPEN
21						1	1		--	--	2	Secondary face plate chaffed improper assy.-none
24a					1				--	--	1	Cracked sec. face plate retainers -insuf. @ FPL-redesign

MAIN INJECTOR (Continued)

Comp. A-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
24b							1		--	--	1	Cracked sec. face plate retainers plugged lox post-Ret. modi.
6a	2	1							--	--	3	Face nuts erosion-local overheat-ing-maintenance
6b			1	1	1	1			--	--	4	Face nuts erosion-hot gas contam-inant-heat shld. redesign
6c				4					--	--	4	Face nut erosion-mismachined orifice post plugged
23							5		5	--	--	ASI supply line cracks-liquid embrittlement-redeisgn
17a			3	1					--	--	4	Reinforcement ring turn-improper assy.-design change
17b				3					--	--	3	Reinforcement ring damage-second-ary fail.-ret UCR A018310
17c				2	2				--	--	4	Reinforcement ring damage-gas turb. @ FPL-u-shaped structure
8a	1	3							--	--	4	Loose T-bolts-inadequate install. new configuration
8b						1			--	--	1	Loose T-bolts-operation-maintenance
10		1	4	3	1	2	5	2	--	--	18	Metal contaminants-secondary failure-unknown sources-none

MAIN COMBUSTION CHAMBER

Comp. A-330 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	2	3	Description - Cause Resolution
1a	4			1	1	2			--	1	7	Burst diaphragm leak, rupture-rise in temp.-ref UCR A010713
1c	1					1			--	--	2	Leak-improper plug install. planning change
2a	1		8	4		1	1		--	--	15	Hot gas wall irregularities-thermal distor.-coolant holes enlarged
2c			1	1					--	--	2	Hot spots in hot gas wall-high coolant flow resistance-none
2d						2			--	--	2	Hot gas wall erosion-contamination-none
3a	3		1		1				--	--	5	Hot gas wall cracks-restricted coolant channels-channels enlar.
3b		4			1	2	1		--	--	8	Hot gas wall cracks-normal-none
3c							1		--	--	1	Hot gas wall cavity crack-bad crown weld-machining
3d								3	--	--	3	Hot gas wall centerline crack-hot gas impingement-under study
7a	1								--	--	1	MCC coolant channel cracks, de-lamination-repair as needed
7b				3		1	1	3	--	--	8	MCC coolant channel cracks-inherent-none or open

MAIN COMBUSTION CHAMBER (Continued)

Comp. A-330 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
15		1	1				1		--	--	3	MCC liner delamination of EDCu plate-none-study
17	1	1							--	--	2	Plugged port-contamination from braze alloy-EDM machining
18		1							--	1	--	Port damage-poor reliability-modify engine ECR09981
12							1		1	--	--	Turb. drive support manifold leak-weld repr.-discont. type rpr.
9d							1	3	--	--	4	Coolant inlet welds mismatch OPEN
14		1			1				--	--	2	Acoustic cavity erosion-hot gas imping.-ref. UCR A015766
86								1	--	--	1	Strut assy. clevis worn-OPEN
19		1							--	1	--	Retainer ring installed wrong-modify engine
6a			1			1			--	--	2	Contamination, fabrication-alert personnel
6b					1				--	--	1	Contamination from outside engine-none
6c						4			--	--	4	Contamination-unknown source-ongoing program

NOZZLE ASSEMBLY

Comp. A-340 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2a	5								--	--	5	Ruptures, leaks in nozzle tubes-local overheat-cuttoff ser. chgd.
2b	5	13	6	9	4		6	1	--	--	44	Leaks from previous repairs (tubes) repair
2c*	8	7			1	2			--	1	15	Tube leaks-braze bonds & voids RA 1607-014 amended
2d	3								--	--	3	Cracks in tubes-incorrect braze alloy-ref. 12 78-CD-3139
2e	8	14	10	5		4			--	--	41	Tube cracks-local strains (thermal) thicker wall tubes
2f		1	1						--	--	2	Tube cracks/leaks-mishandling-repair as necessary
2g				2					--	--	2	Tube ruptures-inadequate expm bond design-change design
2h*					8	4	18	6	--	--	33	Tube leaks-operation strain @ braze bonds-fabrication change
2i					6				--	--	6	Tube leaks-internal corrosion-planning change
2j								4	--	--	4	Leaks in tubes/OPEN
4a	4	2	1						--	--	7	Brazing voids-inadequate-doubler installed

*Criticality N UCRs are included in the distribution for the time periods shown.

NOZZLE ASSEMBLY (Continued)

Comp. A-340 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
4b		1	1		1	1			--	--	4	Separation of tubes-thermal distortion-none
4c							1		--	--	1	Separation of tubes from previous repair-none
14		1							--	--	1	Tubes-secondary failure, inject. post brake-repair
6b	2	2							--	--	4	Aft. manifold weld-vib. & thermal loads-none
6c	3	1							--	--	4	Spot welds broken from drain brkt.-vib. & therm. fat.-redes.
6d	1								--	--	1	Nozzle bracket welds broke-vib.-repair as needed
6e	1								--	--	1	TPS spot welds-inadequate welds-none
6f	1				1				--	--	2	Broken DFI Bracket weld-vib.-add clips
6g		2	1			1		5	--	--	9	TPS bracket welds failed-added loads-eliminate bracket
6h		1							--	--	1	Steerhorn bracket fillet welds transion & loads-none
6i		3							--	--	3	Fuel supply duct spotwelds-unspecified routing-specify rtg.

NOZZLE ASSEMBLY (Continued)

Comp. A-340 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
6k				2		2	7		--	--	11	Spot welds broke-random failures-repair
6m					1	2		1	--	--	4	Weld failure-vib./weld incom-plete-repair
6n								7	--	--	7	Broken welds/OPEN
11a	2				1				--	--	3	Outer jacket cracks-thermal cycling-reworked
11b						1			--	--	1	Outer jacket crack-fabrication-change fab.
9a	1	1							--	--	2	Crack #9 hat band-previous repair-repaired again
9b*		2							--	--	--	Hat band & tube mat'l deteriora-tion, drawing change
9c		1							--	--	1	Hat band pinholes-stress corro-sion-none
9d			9						--	--	9	Hyd. drain & hat band leak-trans-ients-redesign
9e				2					--	--	2	Hat band leak-cold weld-inadeq. expm HB-design change
9f					1				--	--	1	Hat band aft/manifold leak-strain crack @ braze-fab. change

*Criticality N UCRs are included in the distribution for the time periods shown.

NOZZLE ASSEMBLY (Continued)

Comp. A-340 Failure	Time Period (Months) 1980		1981		1982		1983		Criticality			Description - Cause Resolution
	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12	1	2	3	
7c*						1	3		--	--	2	Joint F17 leak-seal mt positioned -none
19				1					--	--	1	Tubes blocked-contamination-repair as necessary
18a			1				1	2	--	--	4	Tps bracket broken-loads-repair & redesign
18b								2	--	--	2	Bracket (TPS) shifted/OPEN
25							5		--	--	5	Tps foil damage-fabrication loads & handling-design change
5c			3	1					--	--	4	Contamination deposit. from external source-none
21					1	2	1		--	--	4	Insulation damage, loose-interference fit, thermal-repr.
23a						2	1		--	--	3	Joint 17 misaligned-assembly error-new tool
23b								1	--	--	1	Misalignment at joint F6 & 6.4, OPEN
16a			2						--	--	2	Defective temp. sensor-contamination-replace as needed
16b						1			--	--	1	Debonded temp. sensor-handling-repair as needed

*Criticality N UCRs are included in the distribution for the time periods shown.

NOZZLE ASSEMBLY (Continued)

Comp. A-340 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
17a			1						--	--	1	Defective radiometer-contamination-replace as needed
17b			2						--	--	2	Damaged radiometer-location personnel notified
24								1	--	--	1	Loose bolts on draw/aft manifold-OPEN

FUEL PREBURNER

Comp. A-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b	1	1	1						--	--	3	Baffle erosion-high local mixture ratio-repair
1c		1	4		1	1			--	--	7	Baffle erosion-ASI hot gas impingement-none
1e				1					--	--	1	Baffles erosion-secondary failure, turb. duct.
2	1	1			1		1		--	--	4	Baffles cracks-high mixture ratio-repair/replace as needed
3b				1					--	--	1	Lox posts blocked-slag-repaired
3c				2	2	7			--	--	11	Lox posts nonconcentric-thermal distortion-none, R&D
3d				1					--	--	1	Lox posts blocked-installation error-repaired
4b	2	5	3	1		1	2		--	--	14	Lox post nibbling-temp. spikes-none
4c		1							--	--	1	Lox post erosion-contamination-repair
5a*	6	1							--	2	4	Face plate erosion-hot gas flow-divergent liner installed
5c	1		2						--	--	3	Face plate erosion-lox pin missing-repair

*Criticality N UCRs are included in the distribution for the time periods shown.

FUEL PREBURNER (Continued)

Comp. A-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
5d*		3	1	1					1	--	3	Erosion-slag in fuel annulas-improved design
5f			1						--	--	1	Face plate erosion-fabrication debris-none
5h				1	4			1	--	--	6	Face plate erosion-unknown or OPEN
5i				1					--	--	1	Erosion-secondary failure ref. UCR A018288
6	1		1						--	--	2	Face place cracks-low cycle fatigue-install divergent liner
7	1								--	--	1	Face plate slag deposits-hot gas flow-divergent liner installed
8a	6								--	--	6	Liner cracks-overheating-install divergent liner
8c		1							--	--	1	Liner erosion-unknown-none
9	1								--	--	1	Elliptical plug locked-jam nut misinstalled-repair
10a	3								--	--	3	Elliptical plug erosion-direct hot gas flow-install. revised
10b	2								--	--	2	Elliptical plug erosion-ring installed wrong-replace part

*Criticality N UCRs are included in the distribution for the time periods shown.

FUEL PREBURNER (Continued)

Comp. A-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
12b		2	3						--	--	5	Plugged coolant holes w/weld wire-improper install.-repair
12c				1					--	--	1	Plugged coolant holes during cleaning-change procedure
13		3	5				1		--	--	9	Moly-shield cracks-thermal strains/press. loads-none
14c								1	--	--	1	Fuel sleeve cracks-OPEN
15a	2	1							--	--	3	Contamination in coolant ch. & baffles-external source-none
15d*						5	1		--	--	5	Contamination-unknown source
16		1							--	--	1	Liner exit mismatched-mfg.-repair
17		1							--	--	1	Air dome cap undersized-thermal loads-none
19		1							--	--	1	Igniter cracks-hot gas recircula-tion-none
20			1						--	--	1	ASI dome cracks-hot gas recircu-lation-none
21a				5	3	4	7		--	--	19	Missing support pins-misinstal.-improve procedure, desgn. mod6183
21b					1	1	1		--	--	3	Extra support pins installed-inspection stricter

*Criticality N UCRs are included in the distribution for the time periods shown.

FUEL PREBURNER (Continued)

Comp. A-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
24						10	5		--	--	15	Baffle weld crack in filler-penetration incomplete-impr. wld.
25							1		--	--	1	Elliptical washer cracks-residual stress-repair

OXIDIZER PREBURNER

Comp. A-700 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
16	1				1				--	--	2	Erosion of lox posts-contam. in fuel annulus-none
2			1				1		--	--	2	Cracks in lox posts-hot gas recirculation-none
3							1		--	--	1	Lox posts high eddy reading-work hardening-spec. change
4	1								--	--	1	Liner erosion-contaminant in fuel annulus-none
5	1								--	--	1	Dome-void-none
66								1	--	--	1	Weld #3-hairline crack-OPEN

HIGH PRESSURE FUEL TURBOPUMP

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	2				2	1			--	1	4	Leak (liftoff seal)-contamination in bushing group-inspect
1b	3					1			--	2	2	Dimension discrepancies, liftoff seal-supplier notified
1c					2				--	--	2	Low liftoff seal nose load-not reseating-ref A004280
2b*		4	1	1	1				--	--	6	Fishmouth seal, cracks-thermal stress-study
2c					2				--	--	2	Yielding of fishmout seal-thermal stress-UCR A011185
2e								1	--	--	1	Gouged FM seal-secondary failure (damper)-none
2f					2				--	--	2	Fm seal erosion-ASI temp. coolant hole enlarged
3a	1					2			--	--	3	Labyrinth seal cracks-high cycle fatigue-increase clearance
3d*	1						1		--	--	1	Labyrinth seal erosion-none
4a*	5	2	1		1				--	--	7	Seal groove tolerance-thermal gradients-maintenance
4b*	2	2			1	1	1	1	--	--	7	Break torque high-rubbing of interstage seals-none

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
4d	2						4		--	--	6	Fractured seals-liquid embrittlement-none
4f		1	1		1				--	--	3	Tip seal damage-secondary failure-ref. UCR A008339
4n					1				--	--	1	Seal pitting-secondary failure-UCR A014015
4o					1				--	--	1	Kel-f seal-secondary failure-special inspection
4p					3				--	--	3	Broken seals-undetermined
5a				1					--	--	1	Turb. blade burnt away-secondary Ref A016031
5b	1				2	1			--	--	4	Blade erosion-transient temps.-redesign
5d						1	1		--	--	2	Erosion-thermal environment-redesign FPB
6a	1	1	2	1					--	--	5	Blades dings/deformed-unknown contaminant-seal redesign
6c				1					1	--	--	Blade failures-FPB configuration-none configuration unique
6d					2				--	--	2	Cracked shanks (blades)-low cycle fatigue-none

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
6f								1	--	--	1	Blade failure-dislodged damper-UCR A013999
7*					2	7	1	2	--	--	11	Turbine platform erosion-ASI temp.-redesign, enlarge cool. hol
8a*	4	2	1	2					--	--	8	Sheet metal cracks-fit-up & weld variations-inspect
8c				1					--	--	1	Crack-secondary failure
8d					2				--	--	2	Sheet metal cracking @ FPL-monitor
8f						9	19	6	--	--	34	Sheet metal cracks-insufficient strength-redesign
9b			1		1				--	--	2	Inlet duct cracks-high cycle fatigue @ FPL-inspect
12a	1								--	--	1	Vane, turb. edge damage-secondary failure-ref UCR A012653
12b			2	1					--	--	3	Erosion of 1st stage vane-FPB malfunctions-UCR A004402
12c			2		4				--	--	6	Vane erosion-high/low cycle fatigue-mat'l change
12d*		1		1	1				--	--	2	Vane burn thru-secondary failure-UCR A0160131

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
12e						1	1		--	--	2	Nick in vane weld operation-repair
12y							1		--	--	1	Hole in vane-OPEN
12h*							3	2	--	--	2	Vane damage-unknown, suspect seal wear-none
12i*							3		--	--	1	Vane mat'l missing-OPEN
14b*	3		1		2		5	1	--	--	15	Contamination-installation caused -none
14c*	5	5	1	1	4	3	2	5	--	--	25	Contamination-minor unknown source (gold, other)-none
14d	1								--	--	1	Bearing debris-none
14e		1	1						--	--	2	Spring debris-vibration-none
14y					1	1			--	--	2	Contamination-heat shield damage UCR A015968
14h						2			--	--	2	Contamination-unknown suspect seal wear-none
14i							1		--	--	1	Contamination-ref. UCR A004585
16a	11	5	5	1		10	10	4	--	--	46	Struts/posts cracks-sheetmetal fitup & weld variations-inspect

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
16b*			2	3	8	2			--	--	14	Strut cracks-high cycle fatigue-posts modified
16c					1	2			--	--	3	Struts cracked-oversized electrode, install.-repair
17	3	3				2	1		--	--	9	Nickel insulation damage-repair as needed
18	3		1	2	1	1			--	--	8	Bolt holes cracked-thermally induced-redesign turbine
20b	2		1		1		1		--	--	5	Bellows shield crack-high cycle fatigue-ref ECR09689
20c				2		1			--	--	3	Bellows shield crack-install., machining-none
20e							1		--	--	1	Bellows shield cracks-OPEN
21a	1				2				--	--	3	T/A manifold cracks-thermal gradients-repair
21b				1					--	1	--	T/A manifold damage-weld failed-planning change
22a		2	1			1			--	--	4	Bearing ball cracks-dry lube overheat-repair
22d							1		--	--	1	Bearing ball wear-unknown
23						1			--	--	1	Shaft insert wear-ref. UCR A008411

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
24a							1		--	--	1	Bearing race wear-contam.-none
24b			1						--	--	1	Race scored-preload spring wear-ref. UCR A011480
25a	1				1				--	--	2	Cracks in turbine end ring-sheet metal & weld variations-rpr.
29		1							1	--	--	G-5 jt. erosion-slag in fuel annulus/noncon-redesign
31a*		2			1	2	1	2	--	--	6	Shaft travel excessive-unknown-none
31b			2			1			--	--	3	Shaft travel excessive-wear on balance pistons orifice-ok
35b					4	3	1		--	--	8	Missing locking pins-ASI temp.-new mat'l
36a				3					--	1	2	Diffuser broken-interference fit-planning changes
36b					2				--	2	--	Diffuser broken-overaging during lent & vent-redo
37b				1		1			--	--	2	Nozzle erosion-high transient temp.-redesign
38a				1			1		--	2	--	16 g. vib. level, low suction, cavity-wrong laby. seal conf.-proc. change

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
38b							1		--	--	1	High acceleration levels-unknown-none
39					10	3			--	--	13	Inlet cap nut cracks-ASI temp.-redesign
41a		2							2	--	--	Nuts & washers missing from shield-unknown-redesign
41c								1	--	--	1	Discharge nut/bolt loose/OPEN
41d								1	--	--	1	Lugs missing/OPEN
42a*						1		1	--	--	3	Water trapped in pump-none
42c							1		--	--	1	Moisture in bearing support-none
44c							1		--	1	--	Inlet failure-cavitation-change design
45a								2	--	--	2	Bearing support-joint strength-establish limits
46								1	--	--	1	Missing damper-damaged blade-OPEN

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE OXIDIZER TURBOPUMP

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b	6	4	4						7	--	7	Bearing balls, spalling-transient axial forces-redesign
1c*					11	3			--	--	11	Ball surface distress-bearing loading-solid film lube added
1h						2	2		--	--	4	Balls spalling/surface distress-bear. & vib.-IL 170 TM-1594
1i							2	1	--	--	3	Balls spalling & undersized-OPEN
2a	1	2			1		1		--	--	5	Bearing cage contaminants-improve cleaning
2c		1							--	--	1	Cage delamination-drawing change
2d				4	6	2			--	--	12	Cage frayed-fluid environment-life limit established
2f					2		1		--	--	3	Cage delamination-loading condi-tion-IL 170 TM-1594
2g					1				--	--	1	Bearing cartridge wear-secondary failure-A006806
2h					1	1			--	--	2	Cartridge drilube worn-loading condition-IL 170 TM 1594
2i						1			--	--	1	Bearing cage delamination-fluid jct. impinge.-redesign

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2j								1	--	--	1	Cage delamination/OPEN
2k								1	--	--	1	Rub mark-bearing & vib. loading-IL 170 TM-1594
3a					2	2			--	--	4	Bearing race wear-loading condi-tion-IL 170 TM-1594
3b							1		--	--	1	Inner race raised-bearing & vib. loading-IL 170 TM-1594
5b*	3	1				2	1		--	--	6	Impeller cavitation erosion-normal-none
5c					1				--	--	1	Impeller-rubbing-secondary failure
10f			1			1			--	--	2	Seal groove too deep-inspection added
11c	1								--	--	1	Bellows shield compressed-improper installation-none
12e				1					--	--	1	Nozzle vane erosion-modified start sequence-modify OPOV comm.
12h							1	2	--	--	3	Nozzle vane crack/erosion/OPEN
14a	2			2	8	7	3	1	--	1	22	Metal contamination-unknown source-none
14b		3	1						--	--	4	Krytox excess-alert technicians

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
14c			3	1					--	--	4	Contamination-from other failures -none
14d			1						--	--	1	Contamination-turb. damper failure-none
14e			1	1					--	--	2	Gold rub o-housing-high thrust loads @ shutdown-none
14f					2	2	2	1	--	--	7	Contam.-mat'l during machining-personnel alerted
14g*					2	3	2	1	--	--	7	Gold splatter on blades-bad AU bonding-study
14h						1			--	--	1	Oil contam.-transport of aircraft-add inspection
14i						1			--	--	1	Metal contam.-filter-breakdown ECR 10370
15a	5	5			3	5			--	--	18	High break torque-rubbing seals-none
15d			2						--	--	2	High torque-primary seal yield-redesign
15e						2			--	--	2	High-torque-broken dampers-change dampers
17a	1			1			1		--	--	3	Damaged strut-assembly-none

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
17b					1				--	--	1	Strut erosion-leaky OPOV UCR A017523
17c						2	3	1	--	--	6	Strut cracks-unknown-estimate life limits
18a*	2								--	--	1	Drain line leak-UCR A011981
19b					1				--	--	1	Housing rubbing-high thrust loads @ shutdown-study
19c							10		--	--	10	Housing cracks-unknown or open-determine life limits
20a	4	4		1	2	2	4	1	--	--	18	Turb. blade cracks-high cycle fatigue-inspection
20b			1	1					--	--	2	Turb. blade chips-fab & mfg-none
20d				1					--	--	1	Turb. blades cracked & slag-main injector failure-none
21a			1						--	--	1	Turb. blade erosion-unknown-none
21b				1					--	--	1	Blade erosion-secondary failure-UCR A010631
22a				1					--	--	1	Sheet metal burnt-main injector failed-none
22b*					1		3	2	--	--	5	Sheet metal cracking-establish life links

*Criticality N UCRs are included in the distribution for the time periods shown.

HIGH PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
26b					1		1		--	--	2	Bearing support pitting-OPEN
29a				1					--	--	1	Jet ring flow tubes damaged-high cycle fat.-life limits
29b					1				--	--	1	Jet ring crack-residual welding stress-none
29c							1	1	--	--	2	Jet ring obstructed-OPEN
30b					1				--	--	1	Worn preload spring-secondary failure-UCR A006806
30i								1	--	--	1	Spring lands worn-secondary failure-IL-170TM-1594
33a				1	2	2			5	--	--	Subsynchronous-vib.-bearing load condition-IL-170TM-1314
33b						1			1	--	--	Subsynch. vib.-bearing & vib. problems-IL 170 TM-1594
34a					1	4	2		1	--	6	Synch. vib.-brg. & vib. problems-IL 170 TM-1594
34c						1			--	1	--	Synch. vib.-balance inadequate green run-balance
35				1					--	--	1	Isolator dri-lube wear-secondary failure-none

HIGH PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
37					1				--	--	1	Roll pin cracked-inspect grain boundary carbides-none
38a				1					--	--	1	Turb. disk-secondary failure, jet ring-UCR A006735
38b					1				--	--	1	Turb. disk cracks in air plate-low cycle fatigue-none
38c						2			--	--	2	Rubbing-high thrust loads @ shutdown-study
40*								1	--	1	1	Liner erosion-OPEN
41								1	--	--	1	Bolt hole flange cracks-OPEN
42								1	--	--	1	Weld cracks-fatigue-add dye penetrant inspection
43a						1			--	--	1	Turb. inlet plating worn-high thrust loads-none
43c							8		--	--	8	Turb. inlet cracks-fatigue-determine life limits
44a					1				--	--	1	Fir tree gold missing-poor adhesion-none
44b							1		--	--	1	Crack in gold-OPEN
45							1		--	--	1	Shaft travel-bearing loading-IL 170 TM-1594

*Criticality N UCRs are included in the distribution for the time periods shown.

LOW PRESSURE FUEL TURBOPUMP

Comp. B-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2							1		--	--	1	Pump inlet gouge/OPEN
4					4	6			--	1	9	Labyrinth seal rubbing-max. torq. excessive-redesign
5b			1						--	--	1	Liftoff seal carbon nose failure-carbon ring-none
6		1							--	--	1	Turbine inlet nicks-dische temp. sensor debonded-A017772
9a	1								--	--	1	Ruptured insulation-mishandling-silicone repair
9b	1								--	--	1	Insulator (nickel) split-engine generated ding-none
9c					2	1	3		--	--	6	Crack in insulation-moisture entry-field repair
9d					2				--	--	2	Insulator boots loose-install. error-none, repair
10a		1					1		--	--	2	Contamination-suspect dust cover-alert personnel
10b					2				--	--	2	Contamination-inadequate cleaning-none, alert
11b					3	4			--	--	7	High torque-excessive copper plate-redesign

LOW PRESSURE FUEL TURBOPUMP (Continued)

Comp. B-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
11c								1	--	--	1	Excessive torque-OPEN
12						1			--	--	1	Housing copper plating damage-unknown-repair
13			1						--	--	1	Omniplate crack-previous repair damage-none, repair
16			1						--	--	1	Fuel feed tank-thermal cycling-none
17b							1		--	--	1	Impellar ding/OPEN
18					1				--	--	1	Loose patch (RTV)-moisture-none, repair
19						1			--	--	1	Nut has rub marks/OPEN
20							1		--	1	--	Stator shroud misbrazed-low pressure-revise drawing
21b							1		--	--	1	High pressure drop-excessive nozzle blockage-rework
21c								1	--	--	1	High pressure drop/OPEN
22			2						--	--	2	Leak-not determined-none

LOW PRESSURE OXIDIZER TURBOPUMP

Comp. B-800 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	1								--	--	1	Worn bearing balls-high torque track bearing wear
2			2		12	1	1		--	--	16	Bearing cage friction-none
6								1	--	--	1	Stator silverplate-lifted-OPEN
9a*	1					2	1		--	--	3	Metal contam.-ref. UCR A012678
9b	1				1				--	--	2	Steel chip contam.-main vane assy.-none
9c	1								--	--	1	Teflon pieces @ edy ring nozzle-tool problem-none
9d*		2				1			--	--	2	Contam.-shop debris-mfg. UCR A015786
9c*		4	1	1	4	5	1		--	--	14	Contam.-unknown-awareness
9f					1				--	--	1	Contam. coat on bearing balls-glove fragments-alert personnel
9g					1				--	--	1	Silver contam. in turbine section-none
9h						1			--	--	1	Contam.-discharge duct failed-A011506
9j							1		--	--	1	Metal contam. on rotor arm-OPEN
9k								2	--	--	2	Deposit on nozzle vanes-OPEN

*Criticality N UCRs are included in the distribution for the time periods shown.

LOW PRESSURE OXIDIZER TURBOPUMP (Continued)

Comp. B-800 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
10b	1								--	--	1	High break torque-bearing wear-track wear
10c			3		12	1	1		--	--	17	High break torque-cage, brg. friction-none
11a	1								--	--	1	Shaft travel-bearing wear-track bearing wear
11b			4						--	--	4	Shaft travel high-high axial loads-reduced m/s axial thrust
13a			1						--	--	1	Flange surface undercut-misalignment-none
13b							1	1	--	--	2	Flange raised metal-OPEN
14			1						--	--	1	Plating-chipped-interference fit relaxed-redesign
17							1		--	--	1	Shim discoloration-OPEN
18							1		--	--	1	Spline pitting/OPEN

CHECK VALVES

Comp. C-100 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1	1				1				--	--	2	FPB purge chk. valve leak-dri lube from flange bolts-alert tch.
3a				1					--	--	1	Oxidizer dome purge chk. valve rev. leak-contam., unknw-none
5						1			--	--	1	Fuel purge chk. valve pres. spike-source unknown-closed
6a						1			--	--	1	FPB ASI chk. valve leak-sticky poppet, fab.-add inspect.
6b							1		--	--	1	FPB ASI chk. valve seat leak-contam.-unknown
6c								1	--	--	1	FPB ASI chk. valve leak--open
7						1			--	--	1	OPB ASI chk. valve leak-poppet bore interference-inspect

PNEUMATIC CONTROL ASSEMBLY

Comp. C-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2	1					1			--	--	2	Vent seat, dvstest leak-inter. seal purge pav-A017367
4						1			--	--	1	Pneum. solenoid-leak-seal impressions-repair
5b						1			--	--	1	Lube oil contam. in pav's-source unknown-cleanliness

SOLENOID VALVES, PRESSURE ACTIVATED VALVES, PNEUMATIC FILTER, HELIUM PRECHARGE VALVE ASSEMBLY

Comp. C-210 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
3b						1			--	--	1	Fuel purge pav seat leak-transient contam.-clean
4a					1		3		--	--	4	HPOT INTER. purge pav leak-inlet seal distorted-redesign
5								1	--	--	1	Internal leak, pav/OPEN
6						1			--	--	1	Main chamber dome pav vent leak-trans. contam.-none

MAIN FUEL VALVE

Comp. D-110 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c			1						--	--	1	Internal leak-suspect contam.-not determined
1d				1					--	--	1	Ball seal leak, downstream temp. high-contam.-leak check
1e				1					--	--	1	Static seal leak-defect-none, isolated case
1f								1	--	--	1	Primary seal leak-dri film particles-none
3			1						--	--	1	Housing crack-thermal stress @ mfg.-inspection
4						1			--	--	1	Metal contam.-unknown source-none
5a	1								--	--	1	Bearing damage & torn washer-vibration, fatigue-none, isolate
5b					1				--	--	1	Bearing race cracked-not determined

MAIN OXIDIZER VALVE

Comp. D120 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	1								--	--	1	Deformed bellows caused leak-unknown-none, isolated case
1b	1								--	--	1	Ball seal leak-contam., unknwn. source-none
4				1					--	--	1	Contamination-source unknown-none
5							1		--	--	1	Follower guide omitted @ assy.-mfg. oversight-alert personnel
7						1			--	--	1	Rust on bearing-unknown-isolated case, none
8						1			--	--	1	Excessive pressure @ hot fire-UCR A008305

FUEL PREBURNER OXIDIZER VALVE

Comp. D-130 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	1								--	--	1	Ball seal leak-particle contam.-unknown source-none
1c			1						--	--	1	Ball seal leak-discrepant bellows-none, isolated case
2b					1				--	--	1	Internal leak-particle contam.-unknown source-none
3*	1				1				--	--	1	Ball seal damage-ASI combustion backflow-closing rate change
4		1							--	--	1	Contam.-unknown source-none
5*		1							--	--	2	Bolt stretch error caused low flow rate-personnel alerted
6						1			--	--	1	Suspect overpressurization-UCR A008305

*Criticality N UCRs are included in the distribution for the time periods shown.

OXIDIZER PREBURNER OXIDIZER VALVE

Comp. D-140 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1					1				--	--	1	Ball seal leak-ASI combustion backflow-software change
3	1				13	6			--	--	20	Ball seal melting-ASI combust. backflow-software change
4a	1								--	--	1	Secondary contamination-steerhorn failure-UCR A010997
6						1			--	--	1	Overpressure-A008305

CHAMBER COOLANT VALVE

Comp. D150 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
3a					1				--	--	1	Studs overtorqued-improper tool-train person
3b							1		--	--	1	Studs overtorqued-cause unknown-repair
4a		1							--	--	1	Metal chip-handling damage-none, clean
4b					2		1		--	--	3	Contamination-source unknown-clean valve

BLEED VALVE

Comp. D-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1						1	1		--	--	2	Leak-isolated case-none

ANTIFLOOD VALVE

Comp. D-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b	1		1						--	--	2	LVDT output voltage low-handling damage-none
1c					1				--	--	1	Position signal erratic-broken probe, vibrations-none
1e								1	--	--	1	Erratic position indication-broken wire-UCR A012535
1f								2	--	--	2	Erratic position indication-OPEN
2a	1								1	--	--	Poppet cracked-suspect handling-assembly change
2b							1		--	--	1	Poppet cracked-OPEN
6							1		--	--	1	Valve remained open @ shutdown-nut lodged in poppet-inspection
3a						1			--	--	1	Particle contam.-tapping debris-inspection added
3b						1	1		--	--	2	Contam.-source unknown-cleanliness

GOX CONTROL VALVE

Comp. D500 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c						1			--	--	1	Leak-source not determined-inspect
1f							1		--	--	1	Leak @ port 024.1-open
2							1		--	--	1	Supply pressure low-open

RECIRCULATION ISOLATION VALVE

Comp. D600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2a							1		--	--	1	LVDT voltage low-shim install. error-mfg. alerted
3a						1			--	--	1	Metallict contam.-not determ.-none
3b						1			--	--	1	Brown material deposit-not determined-none
4								1	--	--	1	Wedge ring wear-open

MAIN VALVE ACTUATOR

Comp. E-001 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b		3							--	--	3	Wireway leak-epoxy did not adhere -process change
1e						1			--	--	1	Static seal leak-burr induced scratch-inspection added
1f							1	1	--	--	2	Vent port leak-defective O-ring-open
1g						1		1	--	--	2	Wireway leak-inadequate epoxy coverage-spec. change
2	1	2		1			1		--	--	5	Hydraulic lockup drift-mfg. error -detectable, none
3	2								--	--	2	Slew rate error-contamination-none
4	1								--	1	--	Servoswitch failure-thermal damage-UCR A010737

PREBURNER VALVE ACTUATOR

Comp. E-002 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c		4	1		1				--	--	6	Wireway-leak-epoxy sealant did not adhere-process change
1d		1							--	--	1	Servoswitch leak-O-ring omitted-personnel alerted
1e								4	--	--	4	Wireway leak-OPEN
1f						1			--	--	1	Shaft seal leak-surface scratch, handling-inspection changes
4					1				--	--	1	Silicone oil contamination on shaft-unknown-alert personnel
5					1				--	--	1	Vent port pitting-unknown cause-personnel alerted
6								1	--	--	1	Pneumatic sequence test failure-metering slot deformed-alert people

MAIN FUEL VALVE ACTUATOR

Comp. E-110 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a	1	1							--	--	2	Wireway leak-epoxy did not adhere-process change
1d				1					--	--	1	Servovalve leak-dirt on O-ring-assembly problem-alert personnel
1e					2	1			--	--	3	Vent port leak-O-ring nibbled by movement-new backup ring
1f						1	2	2	--	--	5	Wireway leak-insuffıcent epoxy coverage-procedure change
1g							1		--	--	1	Vent port leak-OPEN
1h								2	--	--	2	Leak ?-OPEN
2a	1	1							--	--	2	Heater blanket damage-handling-technicians alerted
3a		1							--	--	1	Servoswitch erratic-insulation damage-persons alerted
3b								1	--	--	1	Pull on-drop out test failure-OPEN
4a	1								--	--	1	Suspect contamination-UCR A018556
4b							1		--	--	1	Particle in shaft cavity-unknown-none
5								1	--	--	1	Position indicator failure-OPEN

MAIN FUEL VALVE ACTUATOR (Continued)

Comp. E-110 Failure	Time Period (Months) 1980		1981		1982		1983		Criticality			Description - Cause Resolution
	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12	1	2	3	
6c		1							--	1	--	Actuator slow response-coil short circuit-procedure change
8							1		--	--	1	Hyd. oil wetting @ servo valve-anomaly-techs. alerted
10								1	--	--	1	Failsafe performance test failure-OPEN
11*				1	1				--	--	1	Seal damage-housing fabricate error-techs. alerted

*Criticality N UCRs are included in the distribution for the time periods shown.

MAIN OXIDIZER VALVE ACTUATOR

Comp. E-120 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a		1							--	--	1	Leak-contam., source unknown-none
1b			1						--	--	1	Hyd. oil contam. induced leak-clean
1c					1				--	--	1	Leak-contam. induced scratches-source unknown-none
1d							1		--	--	1	Leak, housing to actuator cylinder-pending analysis
3	1								--	--	1	Wireway nut broken-undetermined-none

FUEL PREBURNER OXIDIZER VALVE ACTUATOR

Comp. E-130 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a			2						--	--	2	Dynamic seal-hyd. oil contam. induced wear-clean & maintain
2a		1							--	--	1	Suspect contam.-see UCR A018556
3		1							--	1	--	Pretest checkout FID's-suspect contam.-none
4			1						--	--	1	O-ring defect-person alerted
6								1	--	--	1	Sequence valve anomaly-OPEN

OXIDIZER PREBURNER OXIDIZER VALVE ACTUATOR

Comp. E-140 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2a		1							--	--	1	Contam.-see UCR A018556

E-150 CC VALVE ACTUATOR

Comp. E-150 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1d								3	--	--	3	Wireway leak-insufficient epoxy coverage-spec. change
2d	1								--	--	1	Contam.-source unknown-personnel alerted
3			4						1	--	3	Early post shutdown purge termination-O-ring shift-redesign
4a		1							--	1	--	RVDT limit exceeded-engine flashback-none
4c						1			--	--	1	Insulation resistance low-none-isolated case
5	1								--	1	--	Position error FID-suspect transient contam.-none
8						1			--	--	1	Servo malfunction-servo coil open circuit-none, isolated
10							1		--	--	1	Spring guide chaffed-mat'l deficiency-mat'l change
11				1					--	--	1	Pneu. shutdown not in spec.-sleeve not per drwg.-inspect. add

CONTROLLER

Comp. F-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b	1								--	1	--	Transistor short circuit-sensitive to high voltg. temp.-none
1d						1			--	1	--	Ch. AP/s shutdown-transistor shorted to chassis-none
2a	1								--	1	--	Fails to execute skip instruct-loose circuit board-none
2b	1								--	1	--	Ch A P/S+HLT-improper board seating-none
2e						1			--	1	--	Ch B Hal+-IE6B S/N 19 card-none possible
3a	1				3	7			--	9	2	Open Circuit-broken wire-none
3b		1							--	1	--	Open circuit-broken wire, handling-alert mfg.
3e				1		1	1		--	1	2	Damaged insulation-enhanced inspection
3f				1		3			--	4	--	Parity error-wire fractured by rework-none
3g				1	1		3		--	2	3	Mova failsafe servo wire break-tooling change, x-ray
3i				1	1	2	1		--	2	3	Ch. B MFV failure reported-M1B wire broke-none

CONTROLLER (Continued)

Comp. F-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
3j						1			--	1	--	H/S wire output low-contam. damage-none applicable
3l						1			--	1	--	LPOT Disch. pressure failure-twisted pr wire dam.-none
3m						1			--	--	1	DCUB failed acceptance test-shorted wire, insul.-caution note
3o							1		--	--	1	Excessive power draw-power wire pinched-wire removed
4a	1								--	1	--	Failure-open circuit-none
4b		1					1		--	--	2	Failure-short circuit to chassis-none
4c		1							--	1	--	DCUB failure-hex inverter short
4d		1				1			--	2	--	Ch. B h/t-contam.-caused short
4e				1					--	--	1	Unable to load memory-short by wire clippings-add procedure
4g						1			--	--	1	Failure-open circuit, overstressed IC-none
5b	1								--	--	1	Error reading-broken pin (connector)-none
8b	1								--	--	1	Ch. B temp. calib. low voltage-noise-none

CONTROLLER (Continued)

Comp. F-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
10a*	26	21	18	18	15	21	8	2	--	82	48	Various small problems-unknown cause-none
10b							20	7	--	21	6	Various small problems-OPEN
11a			1						--	--	1	Simulated 5V PIC undetected-unsoldered lead-none
11b				1					--	1	--	Ch. B 6 volts supply was -9V.-MB miswire-none
11d					1				--	1	--	Failure-incorrect rework wiring-none
11e						1			--	--	1	Failure-incorrect rework wiring-none
11f						1			--	1	--	Command Ch.C failure-miswire connection-none
11h						1			--	1	--	Command Ch.C-part installed wrong-alert personnel
11i							1		--	1	--	FPOV miscompare & interrupt-unsoldered joint-OPEN
13b				1					--	1	--	Miscompare-bad Op amp-none, replace
13d						1			--	1	--	Sensor failures, out of range-DC offset in Op amp-none

*Criticality N UCRs are included in the distribution for the time periods shown.

CONTROLLER (Continued)

Comp. F-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
13e						2			--	2	--	A/D conversion FID's-Op amp Failure-none
15b						1			--	1	--	MOVA feedback miscompare-sockets contam.-none
16b				1					--	1	--	DCUB PRI w/o PFI-damaged zener diode-none
17a					1				--	1	--	Erroneous FID-loose lead band in Ic
17b						1			--	1	--	Voltage failure-debonded resistor lead-none
17c						1			--	1	--	Ch.A WDT2 failure-debonded socket-inspection
18a			1						--	1	--	Solenoid hold voltage low-corroded capacitor-new cap
20b								1	--	1	--	OPOV oscillation @ hot fire-OPEN
21a						1			--	1	--	Voltage dropped-capacitor shorted to grid-none
21c						1			--	1	--	Compare FID's-capacitor momentary short-none
23						1			--	1	--	Pressure sensor failure-high resistance conductor path-none

FASCOS

Comp. F-800 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b			1						--	--	1	Chaffed wires-poor surface prep. and routing-repair
2		1							--	1	--	12 v. power supply low-defect resistor-none, isolated case
4	1								--	--	1	FID's or Ch.2-short circuit in signal cond. module-spec. change
5	2	8							--	8	2	FID's-combined accelerometer & mount resonance-none
8b		1							--	--	1	No voltage to accelerometer-poor solder jt.-personnel alerted
10a	2	2							--	--	4	Itermittent FID's-unknown-personnel alerted
10b	1								--	--	1	Receptacle threads dented-unknown-software change

IGNITER

Comp. G-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c			1				1		--	--	2	Ignited output failing-tip damage-none, repair
2b		1		1		3	3		--	--	8	Igniter tip erosion-off normal combustion-repair or replace
5b				1	1	1	3		--	--	6	Ceramic flaking-off normal combustion-repair or replace
6a	1								--	--	1	Output voltage off-bad connection-isolated case
6c						1			--	--	1	Intermittent-internal ground strap loose-mfg. notified
7a		1		1					--	--	2	Spark failure-moisture on igniter tip-drwing procedure
7b					2				--	--	2	FID during checkout-moisture-none
11a			2						--	--	2	Erratic output-cause unknown-none
11b					6				--	--	6	Low insul. resistance-unknown suspect-spec. change
12					2	2			--	--	4	Erratic operation-potting void-mfg. process change
14					1				--	--	1	Output failure, electrode short-off normal combustion-none
15							2		--	--	2	Quench problem-off normal combustion-none

ELECTRICAL HARNESSES

Comp. H000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1		8	1		3	5			--	--	17	Harness birdcaged-handling damage-repair procedure
2*	2				1	1	1		--	--	4	Ground wire lug broken-handling dam.-heat shrink added
3a								1	--	--	1	Connector loose-OPEN
3c			1						--	--	1	Connector defective-pin hole misplaced-none, isolated case
3e	1			1					--	--	2	Defective connector-particle contamination-none
3f	2	2	2						--	4	2	Connector loose-suspect improper torque-ECP416
3i					5	2			--	--	7	Connector disengaged-unknown-FPL-new design
3j						1			--	--	1	Incorrect connector-mating, human error-person alerted
3k							1	1	--	--	2	Backshell broken-inadequate cleaning-techs. alerted
3l	1					1			--	--	2	Loose connector-installation error-new instructions
5b	1			1	1	1		1	--	1	4	Wire broken-suspect handling damage-alert technicians

*Criticality N UCRs are included in the distribution for the time periods shown.

ELECTRICAL HARNESSES (Continued)

Comp. H000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
6a			1					1	--	1	1	Open circuit-handling damage-techs. alerted
6b								1	--	--	1	Short circuit insulator sleeve & leads-OPEN
8a			1						--	--	1	Torque lock debonded-surface contamination-none, isolated
8c			3						--	1	2	Torque lock missing-inadequate torque-increase torque specs.
8d						6			--	--	6	Torque lock debonded-bad surface preparation-spec. change
9a				1					--	--	1	Harness birdcaged @ connector-not determined-none
9b*						5			--	--	4	Harness birdcaged @ connector-handling damage-none
10			2						--	1	1	Loss of continuity-handling damage-personnel alerted
11a			1						--	--	1	Retainer ring broken-stress corrosion-no problem
11b*					3				--	--	--	Retainer ring cracked-stress corrosion-redesign
12a								2	--	2	--	FID's @ flight readiness test-unknown-none applicable

*Criticality N UCRs are included in the distribution for the time periods shown.

ELECTRICAL HARNESSES (Continued)

Comp. H000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
12b*						2			--	--	3	Noisy, low signal-unknown-field sights notified
13						1			--	--	1	Insulation-low resistance moisture in connector-none
14b				1	1				--	--	2	Elastomer abnormal-humid environment-spec. change
14c					3				--	--	3	Mat'l defective-moisture sensitive-new packaging
15							1		--	--	1	Broken strain relief rope-hardened by epoxy-mfg. notified

*Criticality N UCRs are included in the distribution for the time periods shown.

PRESSURE SENSOR

Comp. J200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b	2	1							--	--	3	Output failure-gold wire fatigue-redesign
1c*		2	7	1	5	3			--	3	7	Output failure-gold wire fatigue-redesign ECP454
2b		1			1				--	--	2	Sensor output failure-wire break, bad potting-inspc. added
3				2					--	--	2	Output failure-thermal induced gold wire break-NASA decision
5b				1	1				--	--	2	Bent pin-handling error-none applicable
5c			1						--	--	1	Error band deviation-improperly set overload screw-none
6			1						--	--	1	Output failure-thermal induced resistance change-NASA decision
7a	1								--	--	1	Erroneous output-shop aid plug not removed-caution supplier
7b				1					--	--	1	Input/output resistance low-supplier data oversight
8b					1				--	--	1	Output failure-thermal environment-NASA decision
9a*	1					1			--	--	1	Open circuit-unknown, suspect hot gas leak-none

*Criticality N UCRs are included in the distribution for the time periods shown.

PRESSURE SENSOR (Continued)

Comp. J200 Failure	1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
9c							1		--	--	1	Erratic output-open circuit-replace
10a	4	4		4	2	2			--	--	16	Error band deviation-unknown-none unit compensated
10b	1								--	--	1	Erroneous output-suspect cold environment-none
10c*	1		1	1					--	--	2	Bad output-unknown, maybe gold wire-redesign
10e		1							--	1	--	Sensor FID's unknown-none
10f		1	1			1			--	--	3	Output drift-unknown-none
10g			2						--	--	2	Output failure-unknown-none
10h					2				--	--	2	No output on fight, low input capacitance-unknown-replace
10i						1			--	--	1	Calibration test failure-unknown-sensor redesign
12a				1					--	--	1	Output failure-weld defect-none, isolated case
14				1					--	--	1	RC error-resistor compartment failure-none
16					1				--	--	1	Thermal block crack-installed under stress-QA advised

*Criticality N UCRs are included in the distribution for the time periods shown.

TEMPERTURE SENSORS

Comp. J-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2c	4	2	1						--	2	5	Sensor tip broken-flow debris impact-shield added
2e		3	1						--	4	--	Sensor tip broken-vib., fatigue-redesign
2f					1				--	--	1	Sensor tip broken-high cycle fatigue-check added
4a*		4	2	3	4	1	1		--	1	12	Erratic output-unknown cause-none
4b						1			--	--	1	Output failure, cracks in pressure seal-unknown-redesign
4c							1		--	--	1	Erroneous output-OPEN
5a	1								--	--	1	Open circuit-handling damage-personnel alerted
5b			1						--	--	1	Open circuit-suspect debris impact-none
5c					1				--	1	--	Short to case @ test-overheat-techs. alerted
5e								1	--	--	1	Short circuit-open
6	2				1				--	--	3	Erratic output-braze joint defects-check added
7a	4								--	--	4	Open circuit, fatigue, insulat. contam.-redesign

*Criticality N UCRs are included in the distribution for the time periods shown.

TEMPERTURE SENSORS (Continued)

Comp. J-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
7b			1			2			--	--	3	Low insulation resistance-moisture-none
7c					5				--	--	5	Low insulation resistance-overheating-none
7d								1	--	--	1	Isolation, insulation test failure-open
8b*	1			1				1	--	--	2	Performance shift-wire break flow debris-none
8d					1	1			--	1	1	Open circuit, element wire break-handling dam.-alert techs.
8e						2			--	2	--	Output failure-element wire break, assy.-assy. change
8f						1			--	1	--	Erratic output, wire break-unknown-none, repair
10a		1							--	--	1	Resistance off-handling damage-techs. alerted
10b				1					--	--	1	Ground short-handling damage-persons alerted
10c						1			--	--	1	Skin temp. error-handling damage-repair
12b*				1	2	11	8	4	--	--	37	Sensor debonding-handling/inadequate bond-none, repair

*Criticality N UCRs are included in the distribution for the time periods shown.

TEMPERTURE SENSORS (Continued)

Comp. J-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
13a				2					--	--	2	Electrical leak-coax cable crack-none
13b				1			1		--	1	1	Output failure-coax cable fracture-assy. change
14a					1				--	--	1	Noisy signal-moisture contamination-none
14b						1			--	1	--	Resistance test failure-moisture fabrication-assy. change

FLOW/SPEED PICKUP

Comp. J-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1							2		--	--	2	Low insulation resistance-damage @ fabrication-none
3					1				--	--	1	Broken wire-suspect thermal induced-thermal test revised
4a	1	2			1				--	--	4	Output failure-unknown-none
4c				1					--	--	1	Erratic output-suspect sensor nut variations-evaluation
5		2							--	2	--	Open circuit, encapsulement cracks-assembly-assy. change

ACCELEROMETER

Comp. J-800 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
3		1							--	--	1	Dielectric insert missing-cause unknown-none
4a							1		--	--	1	High output-unknown cause-none
4b								1	--	--	1	Off scale spikes (STS 7)-nonreproducible failure-none

FUEL LINE DUCT

Comp. K-100 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1d						1			--	--	1	Bellows flex jt. stiff-excessive epoxy-none
1c					1				--	--	1	Exp. jt. boot torn-cause unknown-none, repair
1f							1		--	--	1	Frost on bellows-OPEN
3a				1					--	--	1	Fuel leak-cause unknown-none possible
3b				1					--	--	1	Seal leak-defective seal-none required
3c							1		--	--	1	Leak @ jt. F4 2-OPEN
4c		1							--	--	1	Nickel insulation plating cracked-unknown-ok, none
4e							1		--	--	1	Insulation damage-open
5a	1	1	1	1		1			--	--	5	Contamination-source unknown-none, clean
5b*				2	5	1	3		--	--	10	Contamination-shop debris-advise techs.
9b				1					--	--	1	Seal & groove misfit-groove undersize-managers notified
9c					2				--	--	2	Joint misaligned-tolerance stackup-revise report

*Criticality N UCRs are included in the distribution for the time periods shown.

FUEL LINE DUCT (Continued)

Comp. K-100 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
10	6	3	1						--	--	10	Burst diaphragm broke-handling & vibration-none
13a					1				--	--	1	Seal groove edge damage-bad install.-persons alerted
13b					1				--	--	1	Seal cut & chatter marks-machining error-none
13d							4		--	--	4	Discoloration & pitting on seal-high humidity-none, polish
14a					1				--	--	1	Nuts yielded-increased stresses-none required
14b						1			--	--	1	Sheared screw head-impact, unknown-none
15b						3			--	--	3	Jt. overmold debonded-improper adhesive-change adhesive
15c						4			--	--	4	Overmold raised-not to print-use silicone tape
16						1	1		--	--	2	Cracks in weld-improper technique-train welder
19c							1		--	1	--	F/M calibration constant low-error-conduct tests

OXIDIZER LINE DUCT

Comp. K-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a			1						1	--	--	Duct failure, pressure test-seam weld crack-detection method
1d							2		--	--	2	Leak/crack @ weld 14-OPEN
2b						1			--	--	1	Worn spot-handling damage-none
4a					1	1			--	--	2	Part @ jt. 9iT off-drilled-incorrect hole-advise person
4b						1			--	--	1	Crack @ support link-flex jt. backwards-repair
4c								1	--	--	1	Seal groove tolerance-inspection alerted
5b		4	2			3	3		--	--	12	Contamination throughout-unknown cause-cleanliness
5c						1			--	--	1	Metal inside jt.-bolts stripped-none, replace bolts
5e								1	--	--	1	Brown residue-OPEN
5f					1				--	--	1	Metal sliver in seal groove-measure error-alert person
7						1			--	--	1	Impression marks on ring-bad installation-alert

DRAIN LINE

Comp. K-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2a	1								--	--	1	Damaged drain manifold-repeated removal HPOT-replace
4b					1				--	--	1	Misaligned jt.-unknown-cause-inspect
5		1							--	--	1	Contamination @ jt.-sample too small-none

PNEUMATIC HOSE/LINE

Comp. K-500 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
2a		2			1				--	--	3	Kink or bent line-improper handling-procedure change
2b							1		--	--	1	Line compressed-installation error-person cautioned
4					1				--	--	1	Misaligned joint-cause unknown-inspection
5a	1	1							--	--	2	Joint & seal contam.-source unknown-none
5b*		2							--	--	1	Residue in joints-dry lube residue-mfg. alerted

*Criticality N UCRs are included in the distribution for the time periods shown.

CONTROLLER COOLING DUCT

Comp. K600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a						3			--	--	3	Duct cracks-improper install.-personnel alerted
1b							1		--	--	1	Side panel cracks-OPEN

STATIC SEAL

Comp. L-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1b			1	1					--	--	2	Seal surface blistered-delamination, unknown-none
1c				1	1				--	--	2	Chatter marks on seal & turb. hsg.-moved radially-none
1d						1			--	-	1	Damaged seal-seal came loose-revised RF 0004-146
1e							2		--	--	2	Protrusion on seal-OPEN
3c						1		1	--	--	2	Seal diameter out of tolerance-unknown cause-none
3e							1		--	--	1	Seal size anomaly-improper I.D.-vendor alerted
3f							1		--	--	1	Seal undersize when cryogenic-incorrect calculation-planning change

STRETCH BOLTS

Comp. L-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c	1								--	--	1	Bolt loose-installation overload-none
2b			1						--	--	1	Broken bolt-suspect excess torque-NSTL alerted
3a		1							--	--	1	Piece of stud key missing-installation-persons alerted
3b		1							--	--	1	Keys protrude-installation occur-persons alerted

LEAKAGE - JOINTS

Comp. L-300 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1	4								--	--	4	Leaks-scratches, unknown cause-alert personnel

GIMBAL

Comp. M-000 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1a		1				2		2	--	--	5	Fretting on block & body & vibration-none
1b						1			--	--	1	Wear & galling-interference condition-eliminate interf.
2							3		--	--	3	Crack in bushing-low ductility mat'l-new purchasing

THERMAL PROTECTION

Comp. N-200 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1			4						--	--	4	Insulation separation-application technique-none, repair

POGO ACCUMULATOR

Comp. N-400 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1c							1		--	--	1	Cracks in slotted wall-OPEN

ASI/LGG JET ORIFICE

Comp. N-600 Failure	Time Period (Months) 1980 1-6	1980 7-12	1981 1-6	1981 7-12	1982 1-6	1982 7-12	1983 1-6	1983 7-12	Criticality 1	Criticality 2	Criticality 3	Description - Cause Resolution
1							3		--	--	3	Orifice deformed-none
2a				1					--	--	1	Orifice not per print-rework wrong-personnel alerted
2b				1					--	--	1	Lee jet pin not per print-installation-alert persons
3				1					--	--	1	Low torque value-install. error of lee jet-alert persons

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APPENDIX D

UCR REVIEW

Summary of Component Failure Types Data

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SSME FAILURE INFORMATION MATRIX

Failure Types	Components																									
	A100	A150	A200	A330	A340	A600	A700	B200	B400	B600	B800	C100-C270	D110-D600	E001-E150	F800	G000	H000-H002	J200	J300	J600	J800	K100-K600	L000	L200	M000	N600	Total
Leaks	8	2	0	11	115	0	0	5	0	0	0	9	29	27	0	0	0	0	0	0	0	3	0	0	0	0	209
Cracks	35	4	43	3	86	34	2	127	42	7	0	0	2	0	0	0	0	0	0	0	0	12	0	0	3	0	400
Frosion	0	0	7	2	0	44	3	27	2	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	99
Separation or Delamination	0	0	0	3	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
Loose Parts (Fasteners)	7	0	5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	37	0	0	3	0	1	0	0	54
Broken Parts	5	0	0	0	0	0	0	27	0	0	0	0	0	1	0	0	0	0	5	0	0	10	0	0	0	0	48
Dings, Dents, Damage	0	0	0	0	0	0	0	14	3	0	3	0	0	5	0	0	0	2	0	0	0	1	7	0	0	3	38
Wear	0	0	0	1	0	0	0	1	40	0	6	0	0	1	0	0	0	0	0	0	0	0	0	0	6	0	55
Electrical	0	0	0	0	3	0	0	0	0	0	0	0	7	6	16	18	61	27	32	4	3	0	0	0	0	0	177
Contamination	8	0	18	7	0	5	0	40	45	2	20	0	7	5	0	0	0	0	0	0	0	17	0	0	0	0	174
Geometric Anomalies Missing/Spare Parts	4	0	0	0	0	22	0	13	0	0	0	0	0	1	0	0	0	0	0	0	1	4	0	0	0	0	45
Torque	0	0	0	0	0	0	0	0	22	8	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	48
Vibration	0	0	0	0	0	0	0	2	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
Excess Travel Pressure & (Burnt: 3 only on HPFTP-B200)	0	0	0	0	0	0	0	12	1	0	0	0	4	0	0	0	0	0	0	0	0	1	0	0	0	0	18
Tolerances & Clearances	0	9	0	4	4	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	2	34
Total	67	15	73	31	208	116	5	268	185	17	46	9	50	46	16	32	61	29	74	4	4	55	7	1	9	6	1434
Risk Factor >0.20	1	6	5	1	1	0	0	10	49	0	0	0	3	5	0	0	0	0	0	0	0	3	0	0	0	0	(79)

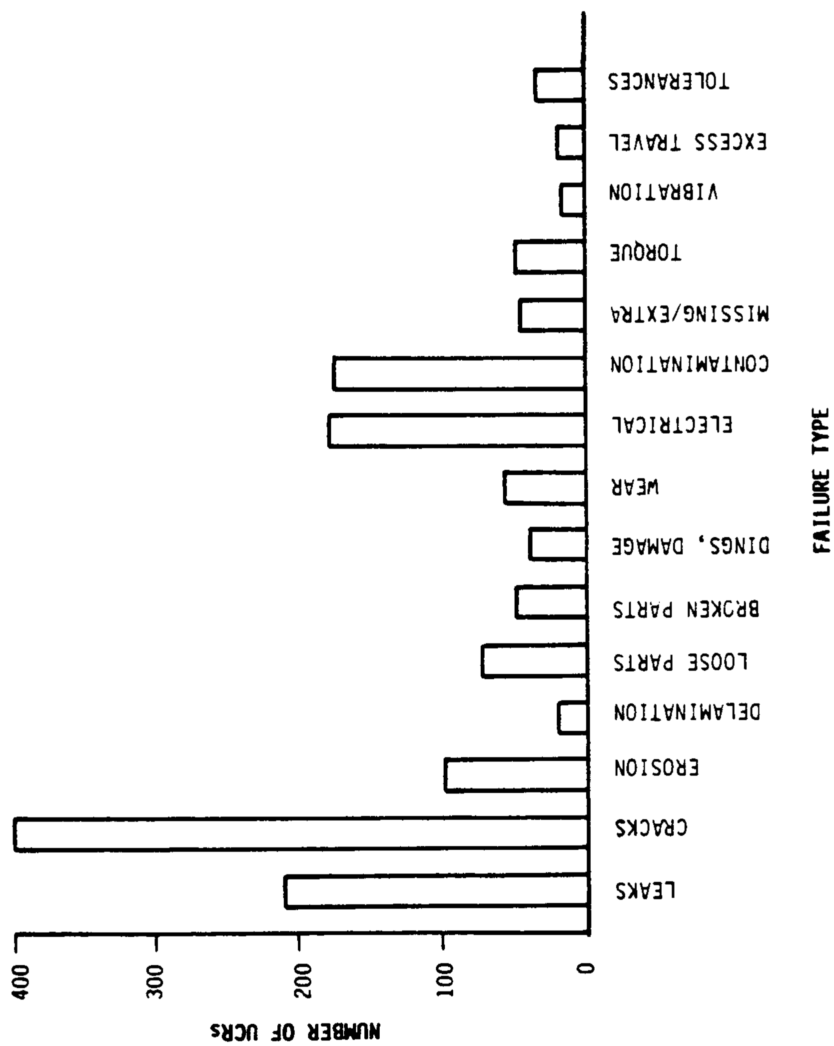

FIGURE D-1. NUMBER OF UCRS BY FAILURE TYPE

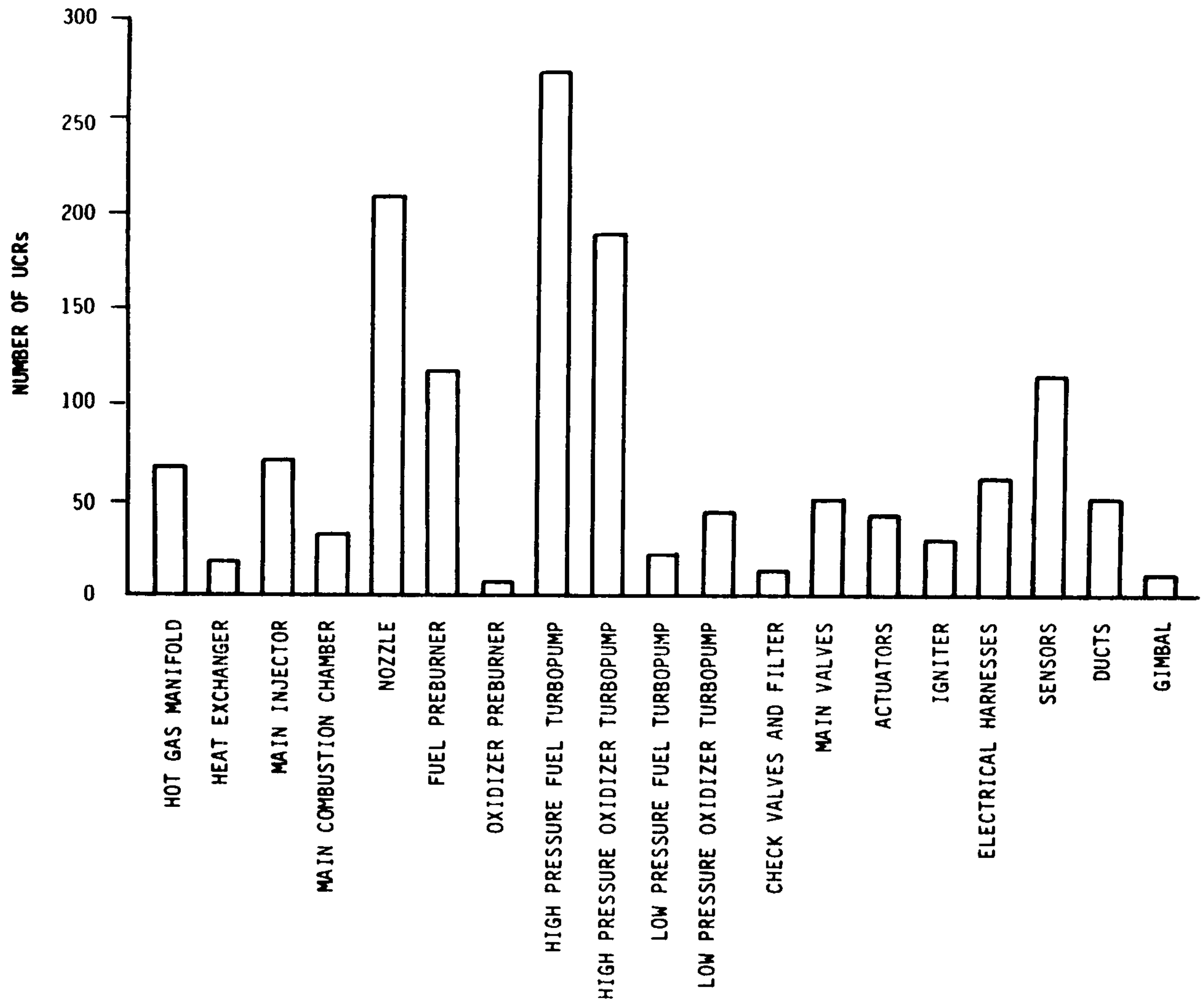

FIGURE D-2. NUMBER OF UCRS BY COMPONENT

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APPENDIX E

UCR REVIEW

Listing of High Occurrence/Criticality Failure
Types and Probable Causes by Component

UCR REVIEW SUMMARY

COMPONENT	FAILURE TYPE	PARTS	CAUSE
A100	Cracks, Rupture	Ducts, Liner	Vibration and Thermal(d)
		ASI Orifice	No Heat Treatment(p)
HOT-GAS MANIFOLD			Defective Welds(f)
	Loose Fasteners	Studs	Wrong Torque(t)
			Repeated Stretching(m)
			Soft Keys(d)
	Gouges,Leaks	G-5 Seals	Installation Problems(p)
	Contamination		Fabrication
A150	Dings	Coil Tubes	Mishandling(p)
	Cracks		Wrong Mat'l(p)
HEAT EXCHANGER	Leaks		Wear(n)
			Bad Weld(i)
	Clearance	Brackets & Tubes	Thermal Cycling(p)
			Fabrication(p)
	Inclusion	Vane	OPEN
A200	Cracks, Broken	Retainer	Gas Turbulence @ fpl(d)
		Baffles	Environment(n)
MAIN INJECTOR		LOX Posts	Gas Turbulence @ fpl(d)
			Thermal Overload(n)
		Braze Joints	Spec. Change(i)
		Primary Face Plate	Load Distribution(i)
		Interpropell. Plate	Heat Shield Failed(d)
			Gas Turbulence @ fpl(d)
		Secondary Face Pla.	Gas Turbulence @ fpl(d)
		ASI Supply Line	Liquid Embrittlement(d)
		Reinforcement Ring	Gas Turbulence @ fpl(d)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
A200 (cont.)	Erosion	LOX Posts	High-Cycle Fatique(d)
		Interpropell. Plate	
		Face Nuts	Local Overheating(m)
			Hot gas contaminant(d)
	Loose Fasteners	T-bolts	Installation(d)
			Operation(m)
	Contamination,metal		Unknown Source(n)
A330	Cracks	Hot-gas Wall	Restr. Coolant Chan.(d)
			Normal(n)
MAIN COMBUSTION CHAMBER			Bad Crown Weld(f)
			Hot-gas Impingement(s)
		Coolant Channels	Normal(n)
	Leak	Burst Diaphragm	Temperature Rise(d)
			Installation(p)
	Leak	Turb. Drive Manifold	Weld Repair(f)
	Delamination	Liner Plating	Unknown(s)
	Erosion	Hot-gas Wall	Contamination(n)
		Acoustic Cavity	Ref. UCR A015766
	Hot Spots, Irregularity	Hot-gas Wall	Thermal Distortion(d)
			Coolant Flow Resis.(n)
	Wear	Strut Assy. Clevis	OPEN
	Contamination		Fabrication(t)
			Unknown Source(n)
			Previous Repairs(m)
A340	Leaks	Tubes	Local Overheat(c)
			Braze Voids(p)
NOZZLE ASSEMBLY			Oper. Strains & Braze(f)
			Internal Corrosion(p)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
A340 (cont.)			Mishandling(n)
	Cracks, Separation	Tubes	Wrong Braze Alloy(f)
			Local Strains(d)
			Mishandling(m)
			Bad Design(d)
			Inadequate Brazing(d)
			Thermal Distortion(n)
			Previous Repair(n)
	Broken Welds	Aft Manifold	Vib. & Thermal Loads(n)
		Drain Bracket	Vib. & Thermal Fatigue(d)
		DFI Bracket	Vibration(d)
		TPS Bracket	Added Loads(e)
		Steerhorn Bracket	Transient Loads(n)
		Fuel Supply Duct	Unspec. Routing(p)
		General Spot Welds	Random Failures(m)
		General Welds	Vib. & Incomplete Weld(m)
			OPEN
	Leaks	Hat Band	Stress Corrosion(n)
			Transient Loads(d)
			Inadeq. Expm. Hat Band(d)
			Strain at Braze(f)
		Joint F17	Seal Mt. Misposition(n)
	Cracks	Outer Jacket	Fabrication(f)
		Hat Band	Previous Repair(m)
	Blocked	Tubes	Contamination(m)
	Broken	TPS Bracket	Loads(d)
	Misaligned	Joints	Assy. Error(f)
			OPEN
	Damage	Foil	Fabr. Loads & Handling(d)
		Insulation	Loose Fit(m)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
A340 (cont.)	Defective Sensor	Temp. Sensor	Contamination(m)
		Radiometer	Contamination(m)
	Loose Fasteners	Bolts (Aft Manifold)	OPEN
A600	Erosion	Baffles	High Local Mix. Ratio(m)
			ASI Hot-gas Impinge.(n)
FUEL PREBURNER			Secondary Failure(n)
		LOX Posts	Temp. Spikes(n)
			Contamination(m)
		Face Plate	Hot-gas Flow(d)
			Lox Pin Missing(m)
			Slag(d)
			Fabrication Debris(n)
			Unknown/OPEN
			Secondary Failure
		Liner	Fuel Annulus Restric.(m)
			Unknown(n)
		Elliptical Plug	Direct Hot-gas Flow(p)
			Misinstalled Ring(m)
	Cracks	Baffles	High Mixture Ratio(m)
		Face Plate	Low-cycle Fatigue(d)
		Liner	Overheating(d)
		Moly-shield	Thermal Strains(n)
		Fuel Sleeve	OPEN
		Igniter	Hot-gas Recirculation(n)
		ASI Dome	Hot-gas Recirculation(n)
		Baffle Weld	Incomplete Penetration(f)
		Elliptical Washer	Residual Stress(m)
	Nonconcentric	LOX Posts	Thermal Distortion(s)
	Slag Deposits	Face Plate	Hot-gas Flow(d)
	Plugged	Coolant Holes	Weld Wire(m)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
A600 (cont.)			Cleaning(p)
	Contamination	Coolant Channels	External Source(n)
	Missing Parts	Support Pins	Misinstalled(p)
	Extra Parts	Support Pins	Misinstalled(i)
A700	Erosion	LOX Posts	Contam. in Fuel Annul.(n)
		Liner	Contam. in Fuel Annul.(n)
OXIDIZER	Cracks	LOX Posts	Hot-gas Recirculation(n)
PREBURNER	High Eddy Reading	LOX Posts	Work Hardening(f)
	Void	ASI Dome	Hot-gas(n)
	Crack	Weld #3	OPEN
B200	Erosion	Fishmouth Seal	ASI Temperature(f)
		Labyrinth Seal	Unknown(n)
HIGH PRESS.		Turbine Blades	Transient Temperature(d)
FUEL		Turbine Platform	ASI Temperature(d)
TURBOPUMP		1st Stage Vane	FPB Malfunctions(ref)
			High/Low-cycle Fatigue(f)
		G-5 Joint	Slag in Fuel Annulus(d)
		Nozzle	High Transient Temp.(d)
	Cracks	Labyrinth Seal	High-cycle Fatigue (f)
		Fishmouth Seal	Thermal Stress(d)
		Seals	Liquid Embrittlement(n)
		Seal Groove	Low-cycle Fatigue(n)
		Turb. Blade Shanks	Low-cycle Fatigue(n)
		Sheetmetal	Fitup & Weld Variation(i)
			Secondary Failure(n)
			Full-power Level(s)
			Insufficient Strength(d)
		Inlet Ducts	High-cycle Fatigue(i)
		Struts, Posts	Fitup, Weld Variations(i)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B200 (cont.)			High-cycle Fatigue(d)
			Oversized Electrode(m)
		Bolt Holes	Thermally Induced(d)
		Bellows Shield	Machining(n)
			High-cycle Fatigue(ref.)
			OPEN
		T/A Manifold	Thermal Gradients(m)
		Bearing Balls	Dry-lube Overheat(m)
		Turbine End Ring	Fitup, Weld Variations(m)
		Bearing Support	OPEN
		Inlet Cap Nut	ASI Temperature(d)
	Leak	Liftoff Seal	Contamination(i)
	Broken, Yield, Failure	Fishmouth Seal	Thermal Stress(ref.)
		Kel-f Seal	Secondary Failure(i)
		Seals	Undetermined(n)
		Turbine Blades	Contamination(d)
			Dislodged Damper(ref.)
			FPB Configuration(n)
		Vane	Unknown, Suspect Seal (n)
		Diffuser	Interference Fit(p)
			Overaging(m)
		Inlet	Cavitation(d)
	Burnt, Burn-thru	Vane	Secondary Failure(ref.)
		Turbine Blade	Secondary Failure(ref.)
	Wear, Pitting	Interstage Seals	Rubbing, High Torque(n)
		Seals (pitting)	Secondary Failure(ref.)
		Bearing Balls	Unknown(m)
		Shaft Insert	(ref. UCR A008411)
		Bearing Race	Contamination(n)
			Preload Spring Wear(ref.)
	Tolerances	Liftoff Seal	Supplier Problem(p)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B200 (cont.)			Not Reseating(ref.)
		Seal Grove	Thermal Gradients(m)
	Contamination, Debris	Spring (debris)	Vibration(n)
		Bearing (debris)	Unknown(n)
		General	Heat Shield Damage(ref.)
			Suspect Seal Wear(n) (ref. UCR A004585)
			Installation(n)
			Unknown Source(n)
	Gouge, Nick	Vane	Secondary Failure(ref.)
			Weld Operation(m)
			OPEN
	Damage	Nickel Insulation	Unknown(m)
		T/A Manifold	Weld Failed(p)
	Excess Shaft Travel	Shaft	Unknown(n)
			Wear-Balance Pistons(n) Orifice(n)
	Missing Parts	Locking Pins	ASI Temperature(d)
		Shield Nuts, Washers	Unknoen(d)
		Discharge Nut	OPEN
		Lugs	OPEN
		Damper (Damaged Blade)	OPEN
	Moisture	Bearing Support	Unknown(n)
		Pump	Unknown(n)
	High Vibration Levels	Turbopump	Low Suction, Wrong Labyrinth Seal(p)
			Unknown(n)
B400	Wear, Spalling, Surface Distress	Bearing Balls	Transient Axial Force(d)
			Bearing Loading(f)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B400 (cont.)			Vibration(ref.)
HIGH			OPEN
PRESSURE		Bearing Cartridge	Secondary Failure(ref.)
OXIDIZER			Loading Condition(ref.)
TURBOPUMP		Bearing Race	Loading Condition(ref.)
		Bearing Support	OPEN
		Preload Spring	Secondary Failure(ref.)
		Spring Lands	Secondary Failure(ref.)
		Isolator Dry-lube	Secondary Failure(n)
	Cracks	Nozzle Vane	OPEN
		Struts	?(Estimate Life Limits)
		Housing	?(Estimate Life Limits)
		Turbine Blades	High-cycle Fatigue(i)
			Fabrication Error(n)
			Main Injector Failed(n)
		Sheetmetal	?(Establish Life Limits)
		Jet Ring	Residual Weld Stress(n)
		Roll Pin	Unknown(i)
		Turbine Disk	Low-cycle Fatigue(n)
		Bolt Hole Flange	OPEN
		Welds	Unknown(i)
		Turbine Inlet	Fatigue (Est. Life Limits)
		Gold Plating	OPEN
	Erosion	Nozzle Vane	Mod. Start Sequence(p)
		Struts	Leaky OPOV(m)
		Turbine Blades	Unknown(n)
			Secondary Failure(ref.)
		Liner	OPEN
		Inlet	High Thrust Loads(n)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B400 (cont.)	Erosion (cont.)	Impeller	Cavitation(n)
	Contamination	Bearing Cage	Assembly Error(p)
		General	Unknown Source(n)
			Krytox Excess(t)
			Secondary Failure(n)
			Machining(t)
			Oil-Shuttle Transport(i)
			Filter Breakdown(ref.)
		Housing	Gold Rub, Thrust Load(n)
		Blades (Gold Splatter)	Bad Bonding(s)
	High Break Torque	Shaft	Rubbing Seals(n)
			Primary Seal Yield(d)
			Broken Dampers(f)
	Delamination, Fraying	Bearing Cage	Unknown(p)
			Fluid Environment (Est. Life Limits)
			Loading(ref.)
			Fluid Jet Impinging(d)
			OPEN
	Leak	Drain Line	(ref. UCR A011981)
	High Vibration Levels	Subsynchronous	Bearing Loading(ref.)
		Synchronous	Bearing Loading(ref.)
			Inadequate Balance(m)
	Rubbing	Turbine Disk	High Thrust Loads(s)
		Impeller	Secondary Failure(n)
	Excessive Travel	Shaft	Bearing Loading(ref.)
	Damage	Bellows Shield	Installation(n)
		Strut	Assembly(n)
		Jet Ring Flow Tubes	High-cycle Fatigue (est. life limits)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B400 (cont.)	Burnt	Sheetmetal	Main Injector Failed(n)
	Tolerances	Seal Groove	Too Deep(i)
B600	Gouge, Nick	Pump Inlet	OPEN
		Turbine Inlet	Temp. Sensor Debond(ref.)
LOW		Impeller	OPEN
PRESSURE	Broken	Liftoff Seal Nose	Unknown(n)
FUEL	Rupture, Cracks	Insulation	Mishandling(m)
TURBOMPUMP			Engine Generated (n)
			Moisture Entry(m)
		Housing Plating	Unknown(m)
		Omniplate	Previous Repair(m)
	Excessive Torque	Shaft	Excess Copper Plate(d)
			OPEN
	High Pressure Drop	Nozzle	Blockage(f)
			OPEN
	Low Pressure	Stator Shroud	Misbrazed(p)
	Leak	Turbopump	Not Determined(n)
	Loose	Insulator Boots	Installation Error(n)
	Contamination	General	Suspect Dust Cover(n)
			Inadequate Cleaning(t)
B800	High Break Torque	Bearing Balls	Wear(s)
		Bearing Cage	Friction(n)
LOW	Excessive Shaft Travel	Bearings	Wear(s)
PRESSURE			High Axial Loads(d)
OXIDIZER	Contamination	General	(ref. UCR A012678)
TURBOPUMP			Shop Debris(ref.)
			Unknown Source(n)
			Teflon-Tool Problem(n)
		Main Valve Assy.	Unknown(n)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
B800 (cont.)		Bearing Balls	Glove Fragments(t)
		Turbine Section	Silver Contamination(n)
		Rotor Arm	OPEN
		Nozzle Vane	OPEN
		General	Disch. Duct Failure(ref.)
	Raised Metal	Stator Silverplate	OPEN
		Flange	OPEN
	Chipped	Plating	Interference Fit(d)
	Discoloration	Shim	OPEN
	Pitting	Spline	OPEN
	Surface Undercut	Flange	Misalignment(n)
C100	Leak	FPB Check Valve	Dry-lube From Bolts(t)
		Oxid. Dome Purge V.	Contamination(n)
CHECK VALVES		FPB Check Valve	Sticky Poppet(i)
			Contamination(n)
			OPEN
		OPB ASI Check Val.	Poppet Bore Interfer.(i)
C200 PNEUMATIC	Leak	Vent Seat	DVS Test(ref.)
		Pneumatic Solenoid	Seal Impressions(m)
CONTROL ASSEMBLY	Contamination	Press. Act. Valve	Lube Oil, Unknown(m)
C210, C250			
C270, C300	Leak	Fuel Purge PAV	Transient Contam.(m)
Solen. Valve		HPOT Purge PAV	Inlet Seat Distorted(d)
PAV, PNEUM.		PAV	OPEN
FILTER, HEL.		Main Cham. Dome PAV	Transient Contam.(n)
PRE. VALVE			

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
D110	Leak	Main Fuel Valve	Suspect Contam.(n)
		Ball Seal	Contamination(i)
MAIN		Static Seal	Defective(m)
FUEL		Primary Seal	Dry-film Particles(n)
VALVE	Cracks	Housing	Thermal Stress(i)
		Bearing Race	Not Determined(n)
	Broken	Cam Follower Guide	Cryogenic Temperature(n)
	Contamination	Valve	Unknown Source(n)
	Damage	Bearing	Vibration(n)
D120	Leak	Bellows	Deformed(n)
		Ball Seal	Contamination(n)
MAIN	Contamination	Valve	Source Unknown(n)
OXIDIZER	Missing Part	Follower Guide	Assembly Error(t)
VALVE	Rust	Bearing	Unknown(n)
	Excessive Pressure	Valve	@ Hotfire(ref.)
D130	Leak	Ball Seal	Particle Contam.(n)
FUEL			Discrepant Bellows(n)
PREBURNER		Internal	Contamination(n)
OXIDIZER	Damage	Ball Seal	ASI Combust. Backflow(c)
VALVE	Contamination	Valve	Unknown(n)
	Low Flow Rate	Stretch Bolts	Assembly Error(t)
D140	Leak	Ball Seal	ASI Combus. Backflow(c)
OXIDIZER	Melting	Ball Seal	ASI Combus. Backflow(c)
PREBURNER	Contamination	General	Secondary Failure(ref.)
OXIDIZER	Overpressure	Valve	(ref. UCR A008305)
VALVE			

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
D150 CHAMBER COOLANT VALVE	Overtorqued	Studs	Improper Tool(t) Unknown(m)
	Contamination	Valve	Metal, Handling(m) Source Unknown(m)
D200 BLEED VALVE	Leak	Valve	Isolated Case(n)
D300 ANTIFLOOD VALVE	Position Signal Erratic	LVDT	Handling Damage(p) Broken Probe(n) Broken Wire(ref.) OPEN
	Crack	Poppet	Handling Damager(p) OPEN
	Remained Open	Poppet	Nut Lodged(i)
	Contamination	General	Tapping Debris(i) Source Unknown(t)
D500 GOX CONTROL VALVE	Leak	Valve	Source Unknown(i)
		Port 024.1	OPEN
	Low Supply Pressure	Valve	OEPN
D600 RECIRCULATION ISOLATION VALVE	Low Voltage	LVDT	Shim Install. Error(t)
	Contamination	Valve(metal)	Source Unknown(n)
		Valve	Source Unknown(n)
	Wear	Wedge Ring	OPEN
E001	Leak	Wireway	Epoxy did not Adhere(f) Bad Epoxy Coverage(f)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
E001 (cont.)			
MAIN		Static Seal	Burr Induced Scratch(i)
VALVE		Vent Port	Defective O-Ring-OPEN
ACTUATOR	Failure	Servoswitch	Thermal Damage(ref.)
	Drift	Hydraulic Lockup	Mfg. Error(n)
	Slew Rate Error	Actuator	Contamination(n)
E002	Leak	Wireway	Epoxy didn't Adhere(f)
			OPEN
PREBURNER		Servoswitch	O-Ring Omitted(t)
VALVE		Shaft Seal	Scratch, Handling(i)
ACTUATOR	Contamination	Shaft	Unknown Source(a)
	Pitting	Vent Port	Unknown Cause(a)
E110	Leak	Wireway	Epoxy didn't Adhere(f)
			Insufficient Coverage(p)
MAIN		Servovalve	Assembly, Dirt(t)
FUEL		Vent Port	Nibbled O-Ring(m)
VALVE			OPEN
ACTUATOR	Contamination	General	(ref. UCR A018556)
		Shaft Cavity	Unknown Source(n)
	Electrical	Servoswitch	Insulation Damager(t)
		Actuator	Short Circuit(p)
		Position Indicator	OPEN
	Test Failure	Failsafe Test	OPEN
		Pullon-dropout Test	OPEN
	Hydraulic Oil Wetting	Servovalve	Anomaly(a)
	Damage	Heater Blanket	Handling(a)
		Seal	Fabrication Error(t)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
E120	Leak	Actuator	Contamination(n)
			Hyd. Oil Contamin.(m)
MAIN			Contam. Induced Scratch(n)
			?(pending analysis)
OXIDIZER VALVE ACTUATOR	Broken	Wireway Nut	Undetermined(n)
E130	Wear	Dynamic Seal	Hyd. Oil Contamin.(m)
FUEL	Contamination	Actuator	(ref. UCR A018556)
PREBURNER	FID	Actuator	Suspect Contamination(n)
OXIDIZER	General Problem	O-Ring	Defective(a)
VALVE		Sequence Valve	OPEN
ACTUATOR			
E150	Leak	Wireway	Bad Epoxy Coverage(f)
	Contamination	Actuator	Source Unknown(n)
COOLANT	Early Purge Termination	Actuator	O-Ring Shift(d)
CHAMBER	RVDT Limit Exceeded	Actuator	Engine Flashback(n)
VALVE	Resistance Low	Insulation	Isolated Case(n)
ACTUATOR	FID	Actuator	Suspect Transient Con.(n)
	Malfunction	Servocoil	Open Circuit(n)
	Wear	Spring Guide	Mat'l Deficiency(d)
	Bad Pneum. Shutdown	Sleeve	Not per Specs(i)
F800	FID	Signal Cond. Module	Short Circuit(f)
		Accelerometer	Resonance(n)
FASCOS		FASCOS	Unknown(n)
	Chaffed	Wires	Poor Prep. & Routing(m)
	Power Supply Low	Resistor	Defective(n)
	Dents	Receptacle Threads	Unknown(p)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
G000	Erosion	Igniter Tip	Off-normal Combustion(m)
	Ceramic Flaking	Igniter	Off-normal Combustion(m)
IGNITER	Electrical Problems	Igniter	Bad Connection(n)
			Ground Strap Loose(m)
			Moisture on Tip(p)
	FID	Igniter	Moisture(n)
	Bad Output	Igniter Tip	Damager(m)
		Igniter	Unknown(n)
		Electrode	Off-normal Combustion(n)
	Quench Problem	Igniter	Off-normal Combustion(n)
	Erratic Operation	Igniter	Potting Void(p)
	Low Insulation Resis.	Igniter	Unknown(f)
H000, H001 H002	Birdcaged	Harness	Handling Damage(m)
	Broken	Ground Wire Lug	Handling Damage(f)
		Backshell	Bad Cleaning(t)
ELECTRICAL HARNESS		Wire	Handling Damage(t)
		Strain-relief Rope	Hardened by Epoxy(t)
		Retainer Ring	Stress Corrosion(n)
	Loose	Connector	OPEN
			Improper Torque(ref.)
			Unknown, FPL(d)
			Installation Error(p)
	Cracks	Retainer Ring	Stress Corrosion(d)
	Defective Part	Elastomer	Humid Environment(f)
		Connector	Pin Hole Misplaced(n)
			Particle Contamination(n)
		Elastomer	Moisture(p)
	Resistance Low	Harness	Supplier Oversight(p)
		Insulation	Moisture(n)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
H000, H001			
H002 (cont.)	Debonded	Torque Lock	Surface Contamination(n)
	Debonded	Torque Lock	Inadequate Torque(p)
			Bad Surface Prepar.(p)
	Open/Short Circuit	Harness	Handling(t)
			OPEN
J200	Output Failure	Gold Wire	Gold Wire Fatigue(d)
			Wire Break, Potting(i)
PRESSURE SENSORS		Sensor	Thermal Induced(s)
			Cold Environment(n)
			Unknown(d)
			Unknown(n)
		Shop Aid Plug	Not Removed(p)
		Sensor	Low Input Capacitance(m)
			Open Circuit(m)
	Bent	Pin	Handling Error(n)
	Noisy Signal	Sensor	Unknown(n)
	Cracks	Thermal Block	Installed Under Stress(p)
	Error Band Deviation	Overload Screws	Improper Adjustment(n)
		Sensor	Unknown(m)
	Output Drift	Sensor	Unknown(n)
	Calibration Failure	Sensor	Unknown(d)
	Output Resistance Low	Sensor	Supplier Data Mistake(p)
J300	Broken	Sensor Tip	Flow Debris Impact(d)
			Vibration Fatigue(d)
TEMPERATURE SENSORS			High-cycle Fatigue(i)
	Open/Short Circuit	Sensor	Debris Impact(n)
			Handling Damager(t)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
J300 (cont.)	Open/Short Circuit (cont.)		Overheat at Test(t)
			Fatigue(d)
		Sensor Wire	Handling Damage(t)
			OPEN
	Output Failure	Sensor	OPEN
		Pressure Seal	Cracks(d)
			Unknown Cause(n)
		Braze Joints	Defects(i)
		Element Wire	Handling Damage(f)
		Coax Cable	Fractured(f)
	Debonding	Sensor	Handling(m)
	Low Resistance	Insulation	Moisture(n)
			Overheating(n)
	Noisy Signal	Sensor	Moisture(n)
J600	Output Failure	Sensor	Unknown(n)
			Nut Variations(s)
FLOW/SPEED	Open Circuit	Sensor	Encapsulement Cracks(p)
PICKUP	Broken	Wire	Thermal Test Induced(p)
	Low Resistance	Sensor	Fabrication Damage(n)
J800	Noisy Signal	Accelerometer	Accel. & Mount Resonance
	Missing Part	Dielectric Insert	Unknown(n)
ACCLEROMETER	Output Failure	Accelerometer	Unknown(n)
K100	Leak	Seal	Defective(n)
		Joint F4.2	OPEN
FUEL		Duct	Cause Unknown(n)
LINE	Rust	LPFT Discharge Duct	OPEN
DUCT	Frost	Bellows	OPEN

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
K100 (cont.)	Stiff Joint	Duct	Excessive Epoxy(n)
	Tear	Joint Boot	Unknown(m)
	Cracks	Nickel Insulation	Unknown(n)
			OPEN
		Seal	Machining Error(n)
		Weld	Improper Technique(t)
	Tolerance	Seal Groove	Undersize(f)
		Joint	Tolerance Stackup(p)
	Contamination	Duct	Unknown Source(m)
			Shop Debris(t)
	Broken	Burst Diaphragm	Vibration, Handling(n)
		Screw	Impact-Unknown(n)
	Debonded	Joint Overmold	Improper Adhesive(f)
	Yielded	Nuts	Increased Stresses(n)
	Pitting	Seal	Humidity(m)
	Damage	Seal Groove	Installation(t)
K200	Test Failure	Duct	Seamweld Crack(n)
	Cracks	Duct	OPEN
OXIDIZER LINE DUCT		Weld	OPEN
		Support Link	Flex Jt. Backwards(m)
	Wear	Duct	Handling(n)
	Contamination	Duct	Unknown(m)
		Joint	Bolts Stripped(m)
		Seal Groove	Measurement Error(t)
	Impression Marks	Ring	Installation(t)
	Tolerances	Duct	Unknown(i)

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
K300	Damage	Drain Manifold	Repeated Removal(m)
	Misaligned	Joint	Unknown(i)
DRAIN LINE	Contamination	Joint	Unknown(n)
K500	Kink	Hose	Handling(p)
	Compressed	Hose	Installation Error(t)
PNEUMATIC	Misaligned	Joint	Unknown(i)
HOSE/LINE	Contamination	Joint & Seal	Source Unknown(n)
K600	Cracks	Duct	Installation(t)
CONTROLLER		Side Panel	OPEN
COOLING DUCT			
L100	Delamination	Seal	Unknown(n)
	Chatter Marks	Seal & Housing	Housing Moved Radially(n)
STATIC	Tolerances	Seal	Unknown(n)
SEAL			Improper ID(f)
			Incorrect Calculation(p)
	Protrusion	Seal	Unknown(n)
	Damage	Seal	Came Loose(ref.)
L200	Broken	Bolt	Excessive Torque(t)
	Loose	Bolt	Installation Overload(n)
STRETCH	Missing Part	Key	Installation Error(t)
BOLTS	Protruding Part	Keys	Installation Error(t)
L300	Leak	Joints	Scratches(t)
JOINT			Unknown Cause(a)
LEAKAGE			

UCR REVIEW SUMMARY (CONTINUED)

COMPONENT	FAILURE TYPE	PARTS	CAUSE
M000	Fretting	Block & Body	Vibration(n)
	Wear/Galling	Gimbal	Interference(f)
GIMBAL	Crack	Bushing	Mat'l Ductility(f)
N200 THERMAL PROTECTION	Separation	Insulation	Application Technique(m)
N400 POGO ACCUMULATOR	Cracks	Slotted Wall	OPEN
N600	Deformed	Orifice	Unknown(n)
	Tolerances	Orifice	Wrong Rework(t)
LEE JET		Lee Jet Pin	Installation Error(t)
ORIFICE	Low Torque	Lee Jet	Installation Error(t)

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APPENDIX F

SUMMARIES OF SSME ACCIDENT/INCIDENT REPORTS

SSME ACCIDENT/INCIDENT REPORT SUMMARIES

(I) TEST MPT SF6-003 STEERHORN FAILURE (February 25, 1980)

During a main propulsion test on the NSTL test stand, the HPOTP secondary seal cavity pressure exceeded the 100 psi maximum redline value. During the shutdown, Steerhorn No. 3 ruptured. According to strain gage data and analysis, the loads were not sufficient to fail a steerhorn for about 48 tests and this test was only the eighth for the failed steerhorn. Investigation showed inadequate welds and revealed Inconel 62 weld wire was used instead of Inconel 718. The resulting joint strength was approximately half of the design strength. The recommendations to prevent recurrence follow:

(1) Eliminate all 0.049 inch thick steerhorns
(2) Continue steerhorn redesign
(3) Reinforce all tee welds
(4) Investigate nozzle aerodynamic shock loading
(5) Continue strain gage and accelerometer monitoring
(6) Conduct survey to determine critical welds and weld wire utilization
(7) Determine the need for additional controls on filler wire certification

(II) ENGINE 0010 TEST 901-284 HIGH PRESSURE OXIDIZER TURBOPUMP FIRE (January 15, 1981)

During a test at NSTL test stand A-1, the Redline Acceleration Safety Cutoff System (RASCOS) initiated the shutdown. The low-pressure oxidizer discharge duct ruptured during shutdown, causing extensive engine damage. Failure of the duct was caused by a fire originating in the main oxidizer pump.

Two unrelated failures caused abnormal operation of the engine. The first failure was the loss of the channel B pressure measurement (chamber) due to controller channel B shutdown induced by a facility power surge. The other failure was the dislodging of a purge Lee Jet device introducing a large pressure bias. Deep throttling to 60 percent RPL and an engine mxiture ratio of 3.5 (6.0-normal) resulted.

The conditions caused a thrust balance towards the pump and a gradual ice buildup in the turbine, which finally caused the thrust balance capability to be exceeded. Rubbing caused metal ignition in an oxygen environment and fire propagated throughout the pump causing the low-pressure oxidizer discharge duct to rupture.

Had similar conditions been encountered during launch, an engine shutdown would have been initiated prior to launch commit for loss of redundancy. The corrective actions recommended were:

(1) Implement shutdown on test stands for major component failures before SRB

(2) Incorporate additional main chamber pressure reasonableness checks in the software during start transients to ensure redundancy
(3) Delete the low main chamber pressure redline and add lower HPOTP turbine discharge temperature redline to check for possible icing
(4) Modify Lee Jet orifice retention method
(5) Perform a pull test on all Lee Jet body installations
(6) Study to assess engine control and redline logic for vulnerability
(7) Study to assess all other Lee Jet installations in SSME
(8) Study of HPOTP turbine end clearances
(9) Inspect all facility Invertron units
(10) Replace all facility Invertron unit power transistors

(III) ENGINE 0009, TEST 901-307: ENGINE 0204, TEST 902-244 FUEL PREBURNER FAILURES (December 22, 1981)

Failures were in the LOX post injection elements caused by high-cycle fatigue. The mechanism for high alternating stress is the combined mainstage mechanical vibration and the element hydrogen flow induced vibration. Also, in engine 0204, the injector face plate was eroded and slag buildup was found on forty posts.

The design fix was to increase the moment of inertia and damping in the cantilevered LOX posts. This would reduce peak alternating stresses below the endurance limit. The fix incorporated three pin supports between the LOX posts and the fuel sleeve to restrict the motion.

(IV) POWERED UNIT 2015 PROOF TEST FAILURE: FUEL PREBURNER-FUEL SUPPLY DUCT

The fuel preburner fuel supply duct ruptured during the powerhead proof pressure test. A hardness test performed on the duct found it to be low of the designed hardness. The supplier failed to heat treat the elbow because of a misunderstanding of Rocketdyne drawing requirements. Also, Rocketdyne receiving inspection failed to detect the omission of heat treatment. Recurrence control consisted of:

(1) The planning at the supplier incorporates heat treatment
(2) Future supplier planning for small suppliers will be reviewed by Rocketdyne personnel
(3) Receiving inspection plans have been revised to incorporate physical verification of heat treatment for all appropriate parts
(4) Previously accepted parts requiring heat treatment that were accepted by the same individual at prescreening have been checked for compliance
(5) Personnel responsible for prescreening have been advised of the requirements at a workshop

(V) ENGINE 2013 NSTL TEST 901-364 HIGH-PRESSURE FUEL TURBOPUMP KAISER HAT FAILURE (July 14, 1982)

A scheduled 500 second full power level mission simulation test was terminated at 392.16 seconds due to the preburner pump radial accelerometer redline. Major portions of the engine were severed from the test stand attachments. Using various data, analyses, motion pictures, test fire simulations, and model simulations, it was concluded that the recently redesigned HPFTP Kaiser hat provided a hot-gas leak path of hot gas into the bearing coolant. Turbine bearing failure was followed by rotor displacement, turbine blade failure, rotor seizure, rupture of the HPFTP inlet, and an oxidizer rich shutdown. This was the first test of the latest redesign of the Kaiser hat assembly. Recommendations were:

(1) Return to the old Kaiser hat assembly configuration
(2) Periodic inspection of the Coolie hat nut for retention

Additional actions to prevent other recognized potential failures:

(1) Reduce turbine operating temperature
(2) Improve HPFTP Liftoff seal dimensional control
(3) Improve Kaiser hat inlet design with a seal
(4) Improve fuel preburner propellant distribution by cooling ASI core

(VI) ENGINE 0107, SSFL TEST 750-168 OXIDIZER PREBURNER OXIDIZER VALVE BALL SEAL FAILURE (January 27, 1983)

A scheduled 300 second test was terminated normally, but subsequent data analyses showed the HPOTP discharge temperature rising significantly beginning two seconds after shutdown command until the temperature sensors failed. No external damage ws apparent, but significant high-mixture erosion was found in the HPOTP turbine area and hot-gas manifold. A leaking oxidizer preburner valve was found to be the source of the high-mixture ratio. The ball seal had circumferential erosion and a radial seal crack was found. The cause was a fuel-rich ASI hot-gas backflow into the valve seal cavity during shutdown.

Corrective action was recommended to preclude hot-gas backflow during shutdown. Until an adequate solution is established, the OPOV seal test life should be limited to ensure seal damage does not approach proportions experienced in this incident.

(VII) HEAT EXCHANGER COIL ARC BURN (July 25, 1983)

During the tungsten inert gas (TIG) weld operation that joins a transfer tube to the heat exchanger liner the welder made inadvertent contact to the heat exchanger coil producing an arc burn. This incident was the result of the welder being unable to see the weld joint for about 1.5 inches of arc length. The welder removed the protective closure around the heat exchanger coil to weld past the point of visual obstruction. At this point the welder mis-positioned his torch too close to the coil. Corrective actions were implemented:

(1) Manufacturing operations record (MOR) books were revised to add caution notes at potentially hazardous operations to prevent operators from removing protective covers. Caution notes will appear as follows:
   (a) At the beginning of each operation - "Do not remove coil protection without manager's concurrence"
   (b) At the end of each operation - "Replace covers if removed"

(2) Department 518 has met with welders to reinforce the need for discipline in adhering to procedures.

(3) Improved heat exchanger coil shields which cannot be removed unless a sealed safety wire is cut, were designed and installed.

(4) Long term corrective action involves design of covers from a more durable heat and chemical resistant materials. This will eliminate the need to remove covers for clean and oven dry operations.

(5) Rocketdyne is developing special welding goggles with a face shield that protects the welder from heat and radiation. The new goggles will improve visibility over the entire weld area.

(VIII) SSFL TEST 750-175, ENGINE 2208 HIGH PRESSURE OXIDIZER DUCT FAILURE (December 15, 1983)

A test at the SSFL Laboratory was terminated prematurely by the preburner pump redline accelerometers sixteen seconds after the engine had been throttled from FPL (109 percent) to 111 percent of rated power level and the high-pressure oxidizer discharge duct failed.

The investigation concluded the failure resulted from a high-cycle fatigue crack in the duct wall at the edge of one of the ultrasonic flow transducer blocks mounted on the duct wall. The failure was cuased by the combination of thinning the duct wall to install the transducer blocks, the added block masses, and the increased local stresses caused by brazing the blocks to the wall of the duct.

It was recommended that to rely on braze fillets to reduce stress concentration not be done in the future. Any such applications would necessitate extensive analysis and testing to ensure integrity of the parts involved.

APPENDIX G

SSME FAULT TREE DIAGRAMS BY COMPONENT

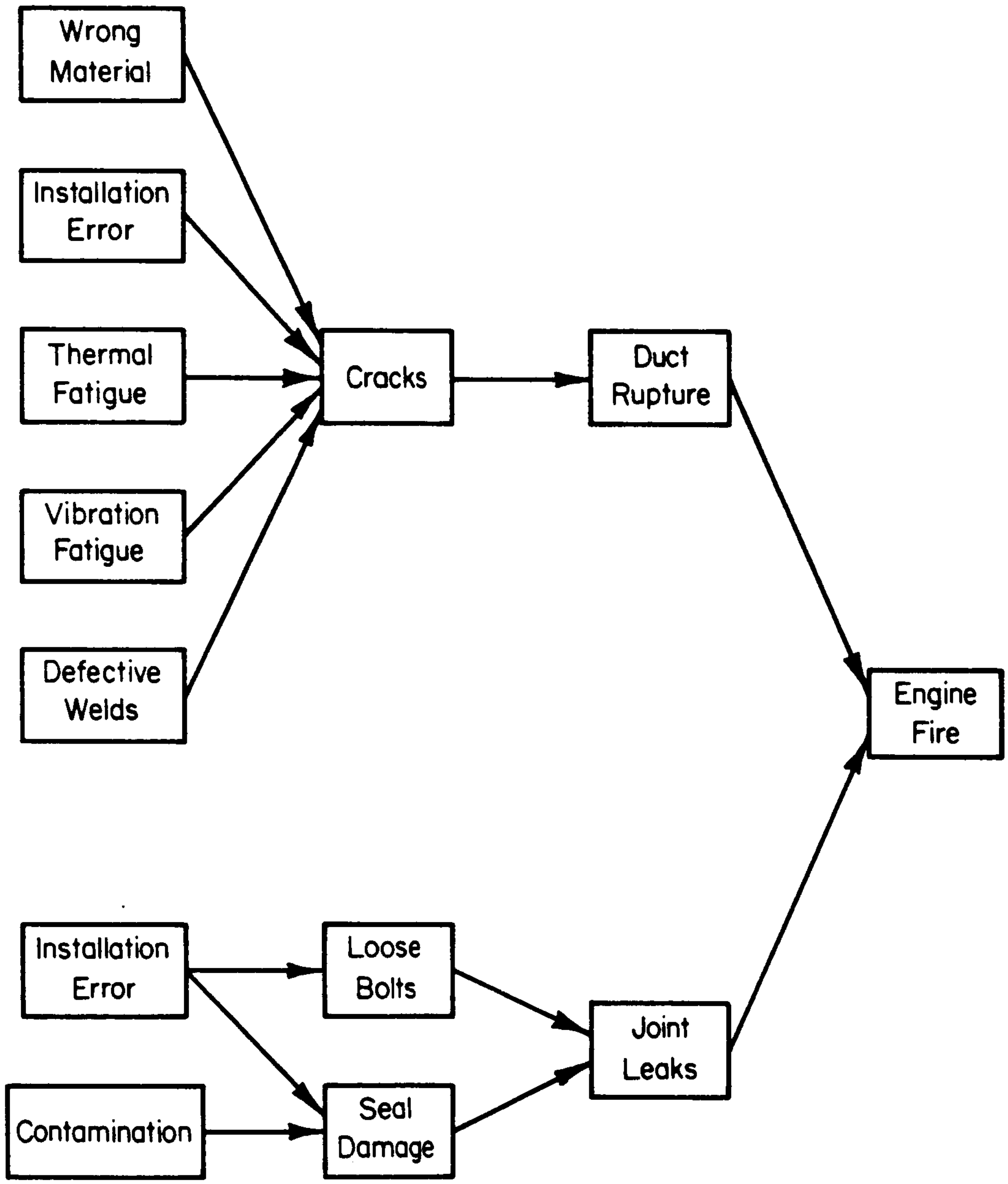

FIGURE G-1. HOT-GAS MANIFOLD (A100) FAULT TREE

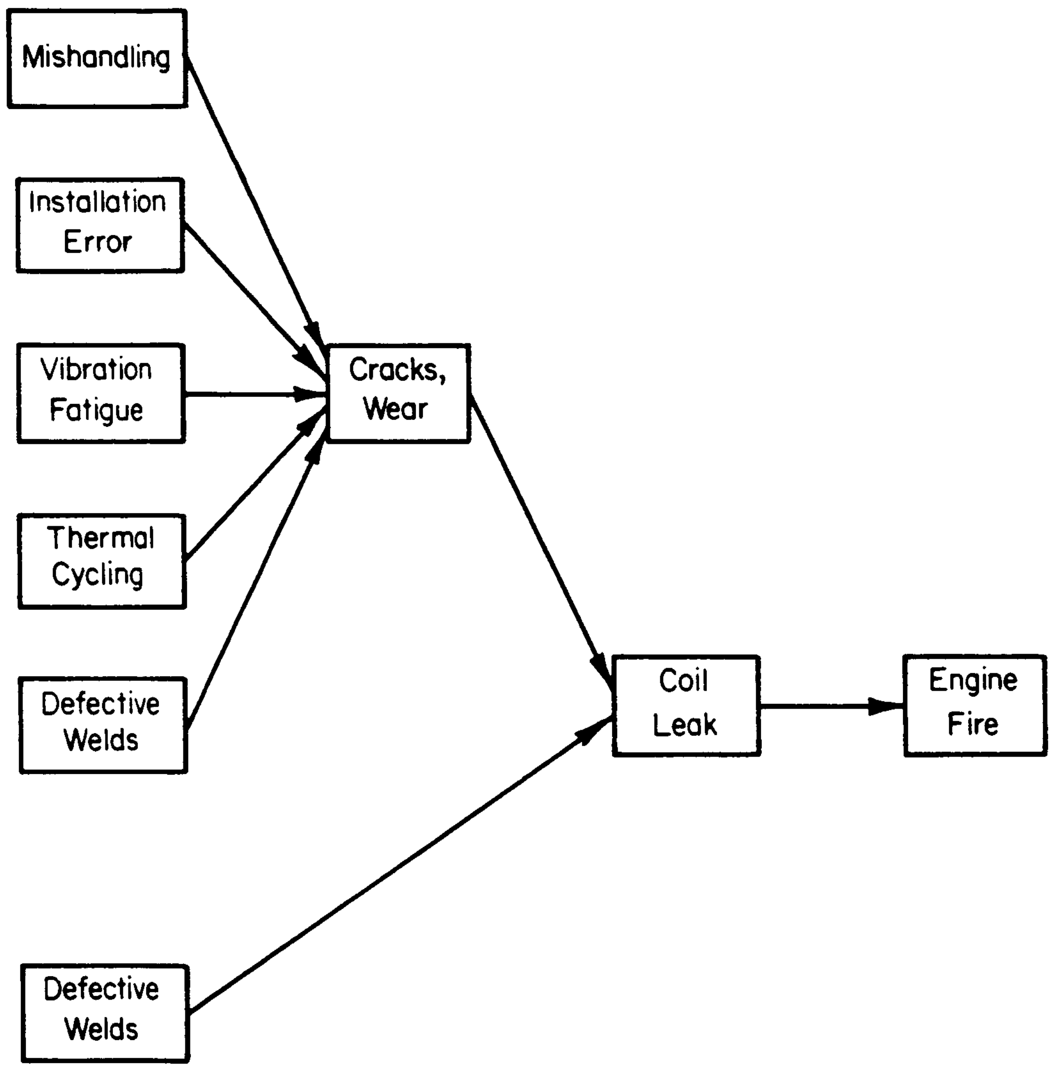

FIGURE G-2. HEAT EXCHANGER (A150) FAULT TREE

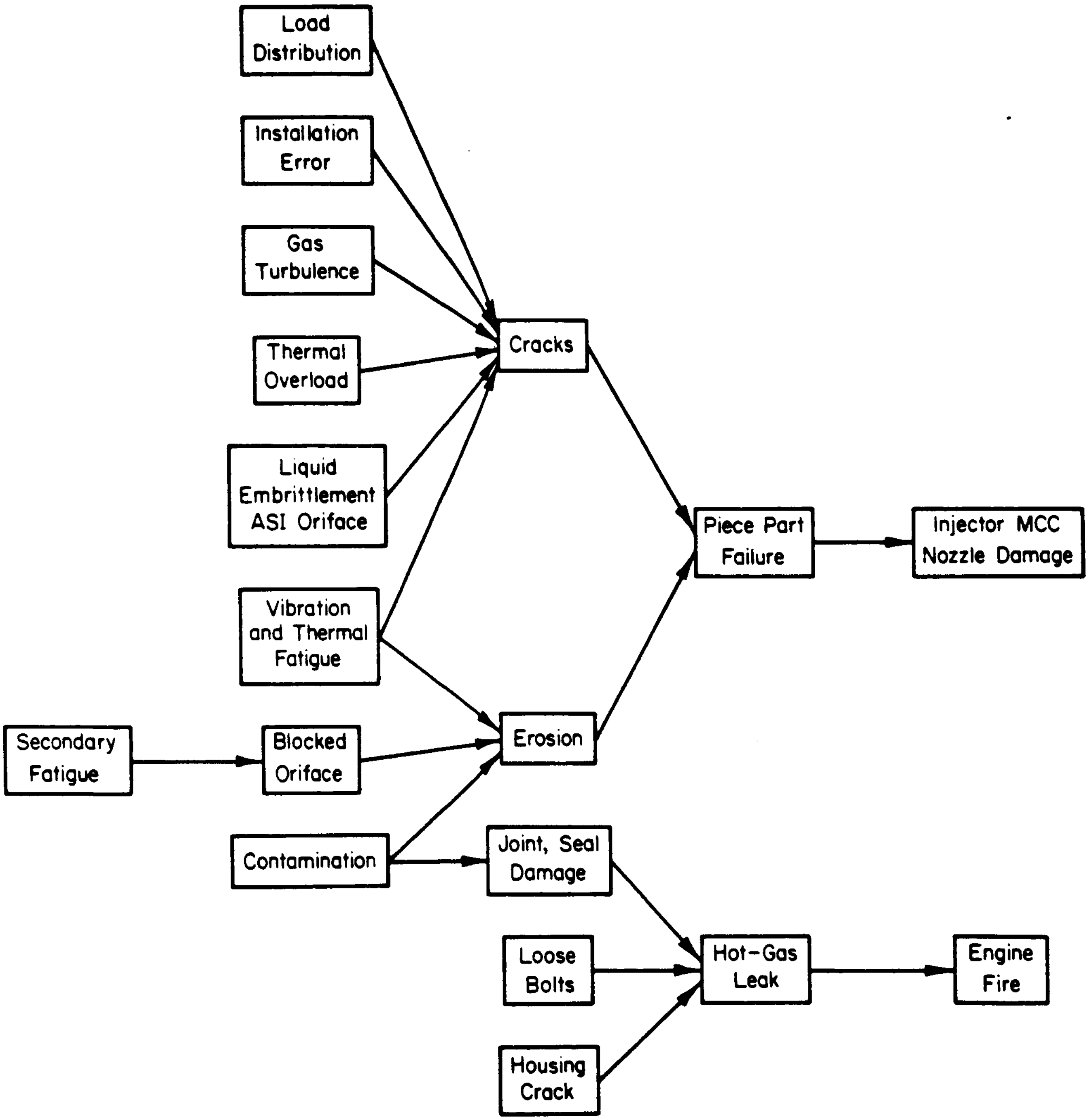

FIGURE G-3. MAIN INJECTOR (A200) FAULT TREE

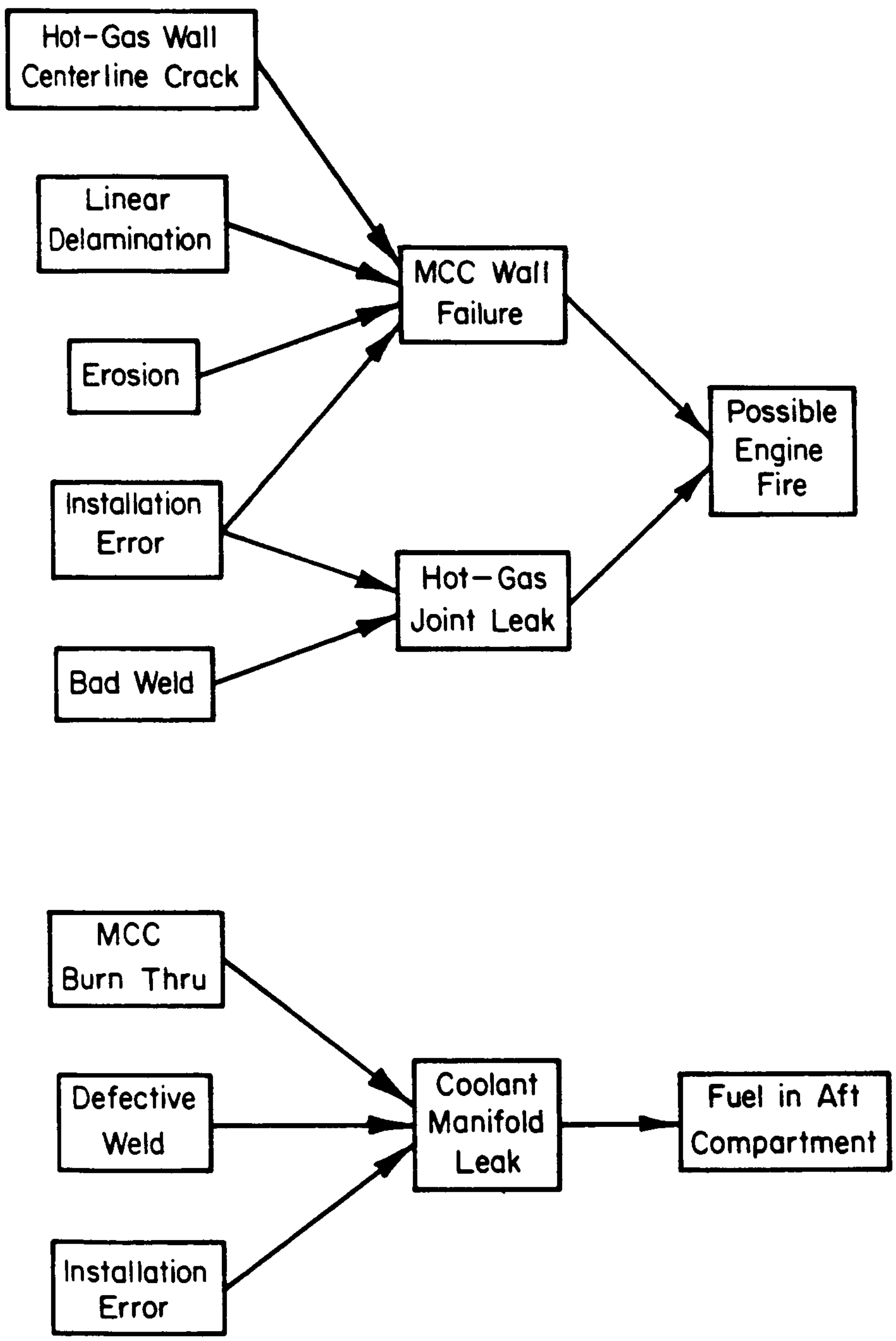

FIGURE G-4. MAIN COMBUSTION CHAMBER (A330) FAULT TREE

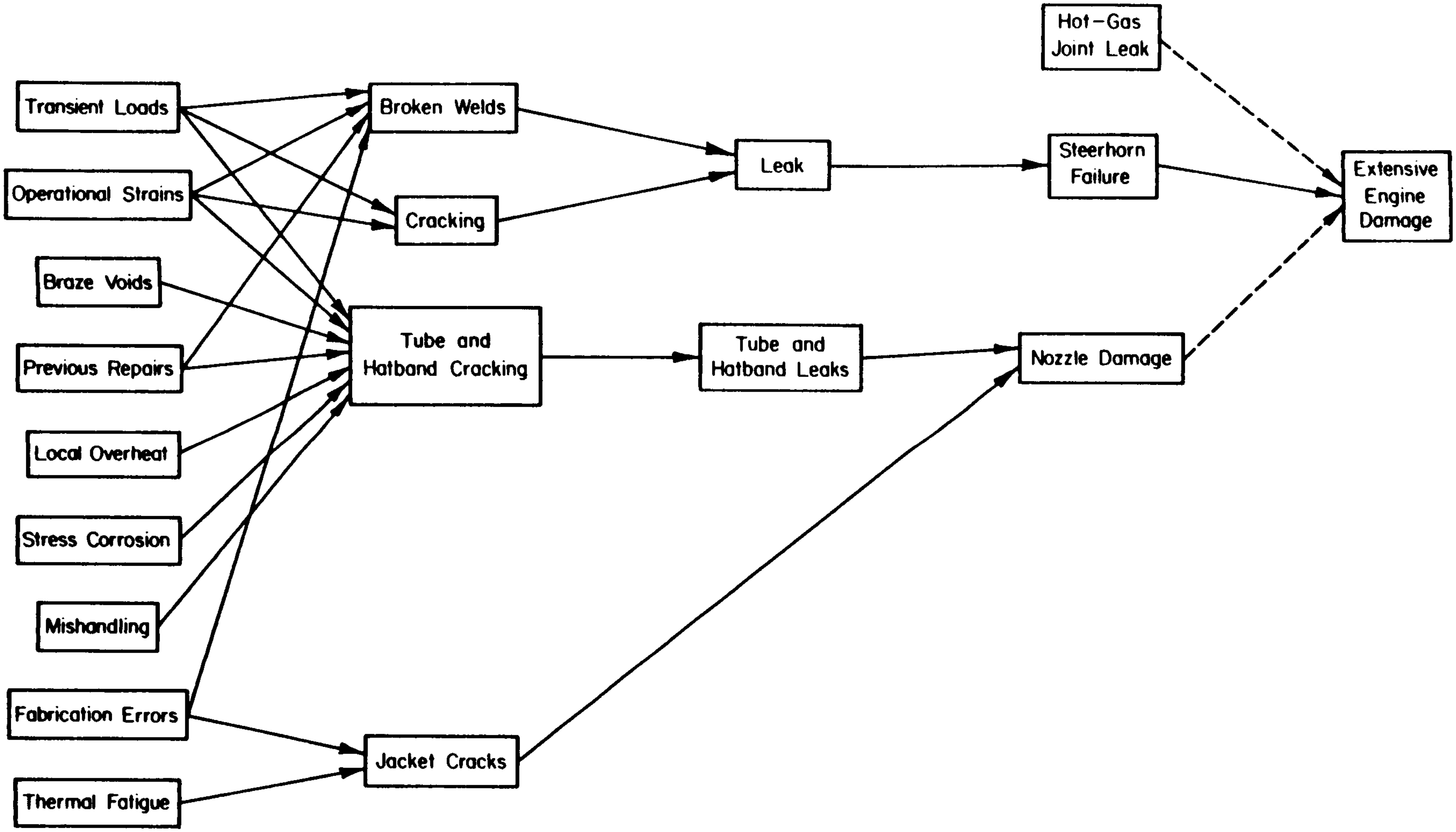

FIGURE G-5. NOZZLE ASSEMBLY (A340) FAULT TREE

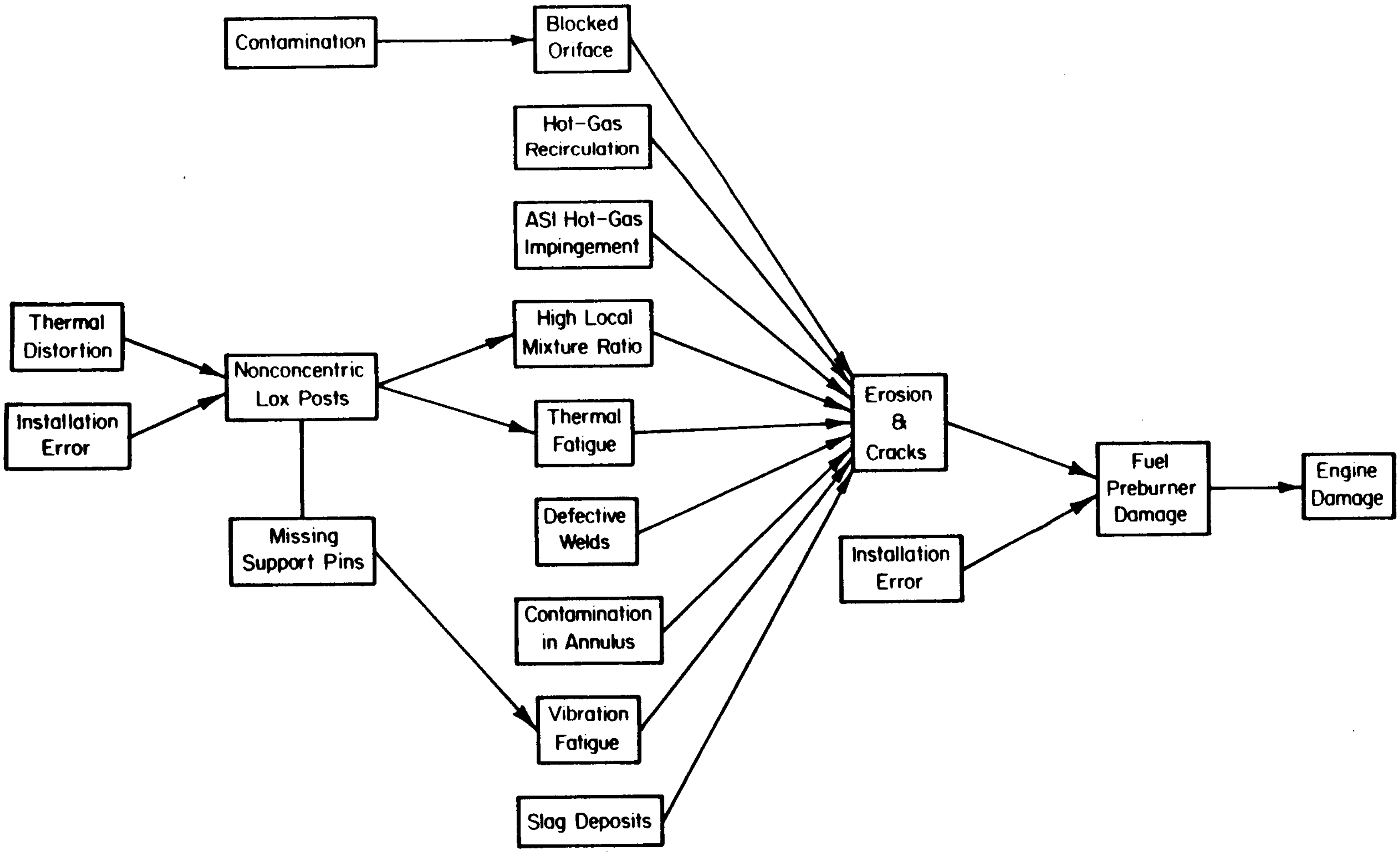

FIGURE G-6. OXIDIZER AND FUEL PREBURNER (A600 & A700) FAULT TREE

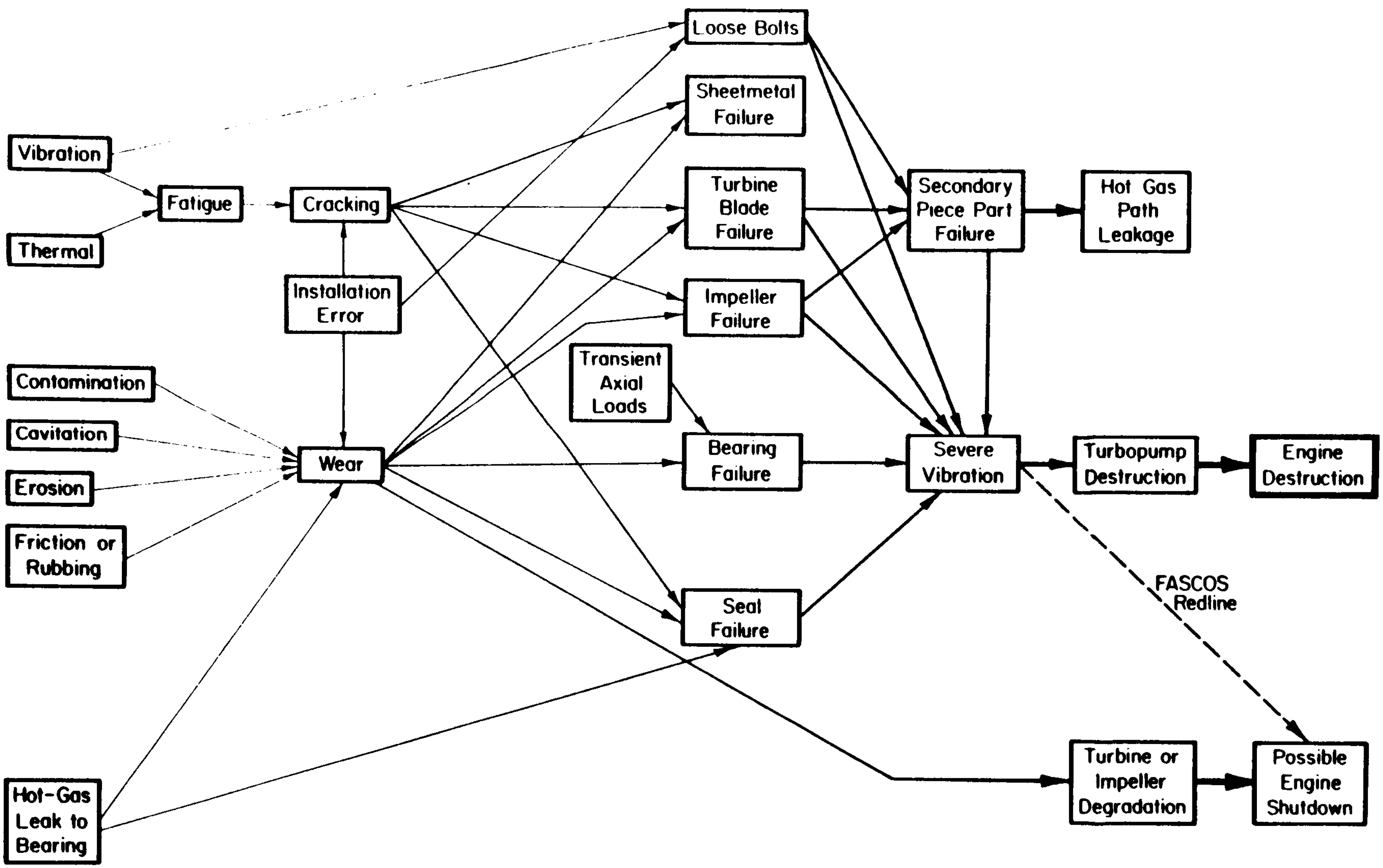

FIGURE G-7. TURBOPUMP (B200, B400, B600, & B800) FAULT TREE

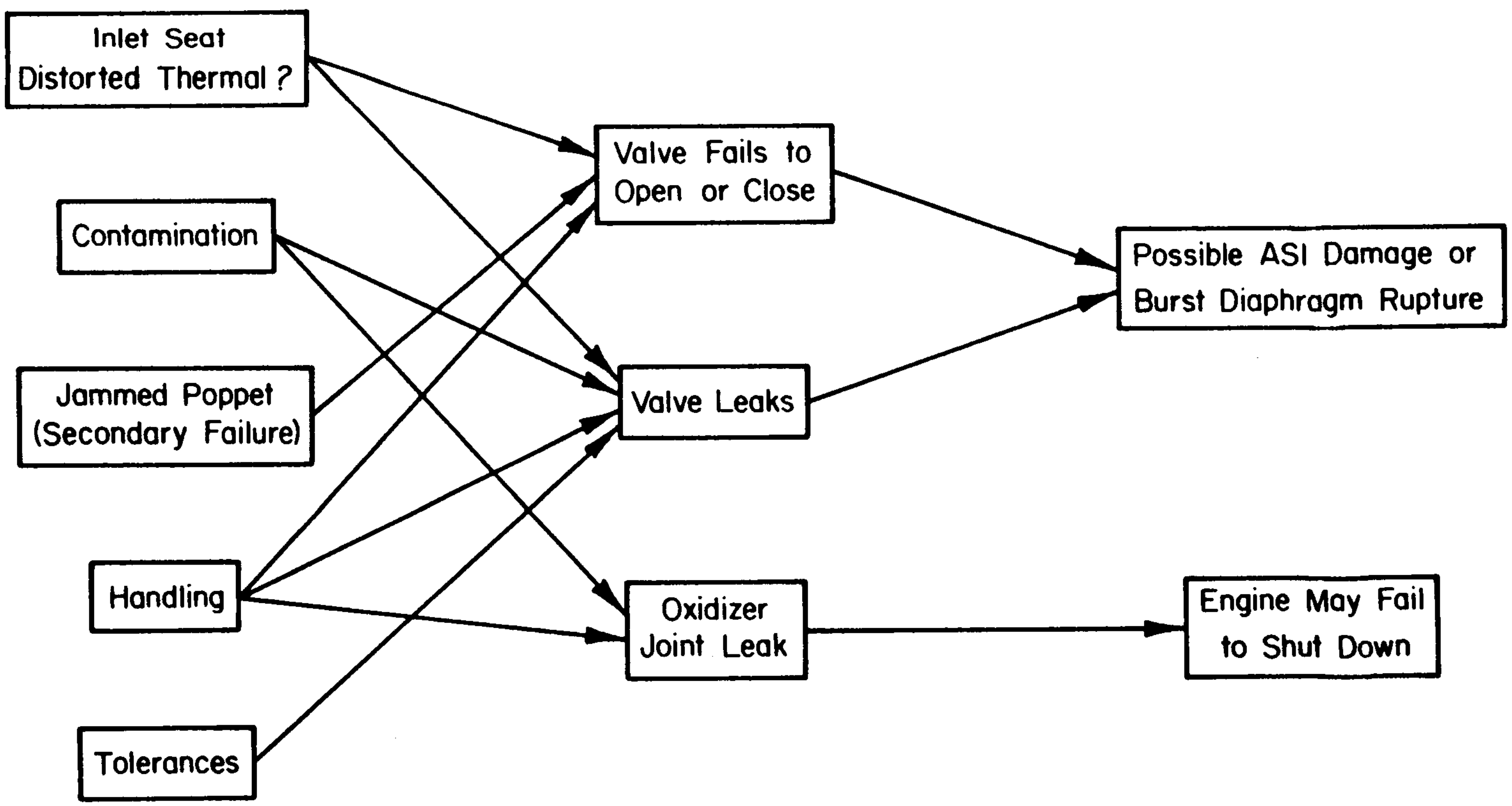

FIGURE G-8. CHECK & PRESSURE ACTIVATED VALVE (C100 - C270) FAULT TREE

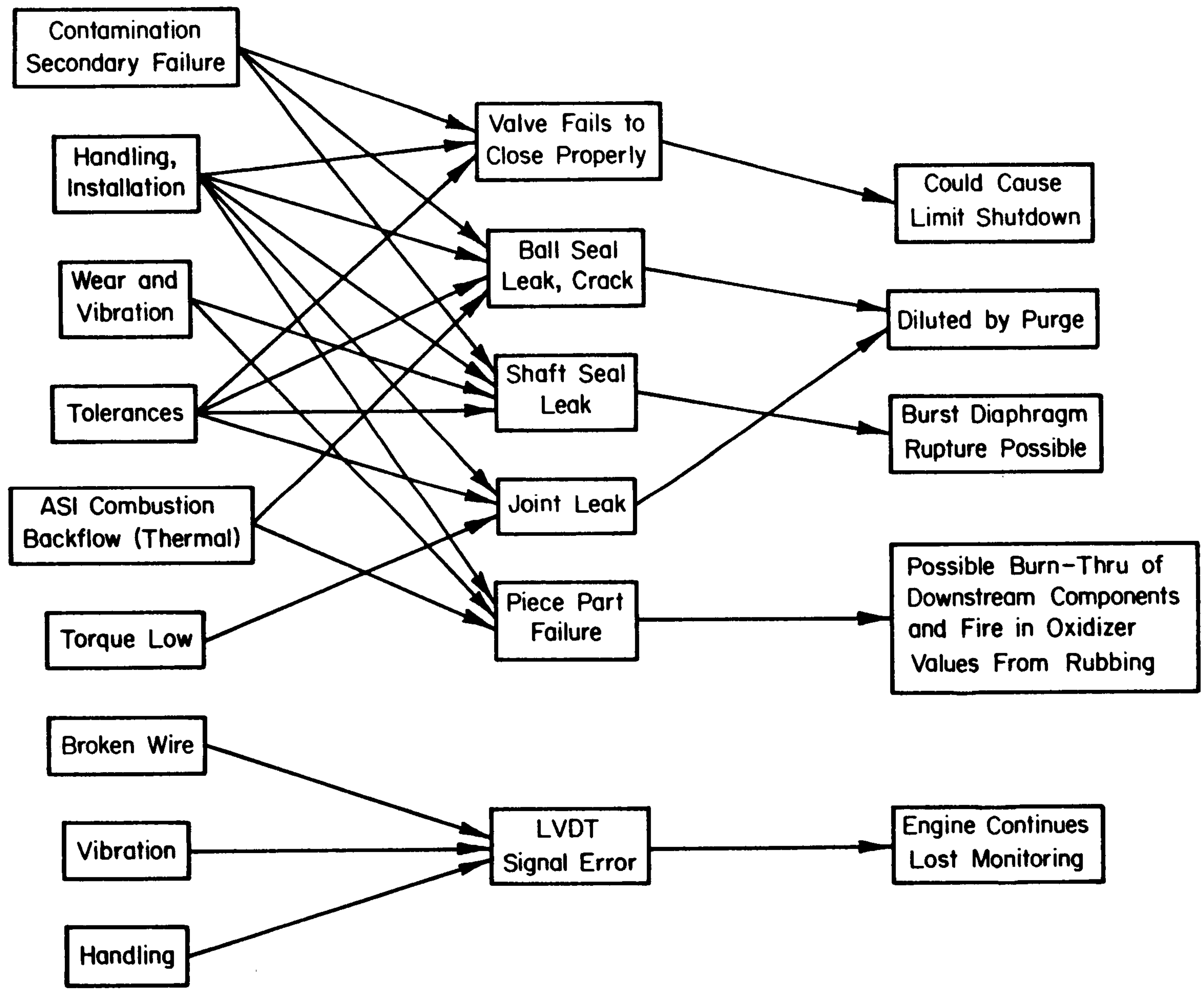

FIGURE G-9. VALUE (D110 - D600) FAULT TREE

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APPENDIX H

SUMMARY OF SSME TEST FIRING CUTOFF DATA

SSME ENGINE FIRING CUTOFF TABLES

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPOT RPM Speed	1									1		1		NSTL	Facility recorder ground bad - repair
	1									1		1		NSTL	Circuit noise - filter added
			2	1						3		3		NSTL	RPM sensor failed from vibration fatigue - redesign
				1						1		1		NSTL	Signal conditioning shorted - not flight hardware
				2						2		2		NSTL	Open circuit from vibration fatigue- redesign
				1						1		1		NSTL	Reasonableness limits too narrow - change limits
					1					1				NSTL	Limit set wrong, software mistake - change software
Totals	2	—	2	5	1	—	—	—	—	10		10			
HPOT Turbine Discharge Temperature			2									2		NSTL	Incomplete OPB combustion - change valve sequence
			1							1		1		NSTL	Improper redline assigned - change redline setting
			1									1		NSTL	New configuration OPOV temperature spike - change valve sequence
			1							1		1		NSTL	Software error - change software
			1	1	1					3		3		NSTL	Open circuit from vibration fatigue - redesign
				1								1		NSTL	Damage to HPOT from MOV that was installed wrong - repair
				1								1		NSTL	High mixture ratio at start - change valve sequence
				1						1		1		NSTL	Sensor fatigue failure - install new sensor
					1					1		1		SSME A-3	Initial calibration wrong - rebalance engine
						1						1		NSTL	Primary faceplate erosion in preburner from fatigue - repair
							2					2		NSTL	Main injector failure - old configuration
							1			1		1		NSTL	Low temperature, wrong constant - change constant
Totals	—	—	6	4	2	1	3	—	—	8		16			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPOT Radial Accelerometers			1									1		NSTL	Tip seal wear, damage from previous test - damage from previous test
			1									1		NSTL	Inadequate balancing - improve balancing procedure
			1									1		NSTL	Cross-vibrations from HPFT severe turbine blade erosion, high alternating stresses - redesign
				1						1		1		NSTL	Faulty connecting cable - redline deleted
				1						1		1		NSTL	Cross-vibration from HPFT seal rubbing - change seal clearances
				1								1		NSTL	Long dwell time at HPOT first critical resonance - slew rate changed
				1								1		NSTL	Intermediate seal damage caused by subsynchronous vibration - redesign
				1							1			NSTL	HPOT fire caused by failure of special instrumentation device - none
				1						1		1		NSTL	Intermittent signetic chip - get higher reliability chip
				1						1		1		NSTL	Cross-vibration in start and shutdown, HPFT turbine blade platform cracks - redesign
						1				1		1		NSTL	PC lee jet and channel B power failure - software change
								2			2			NSTL	Subsynchronous vibration from bearing loading - pending design change
								1				1		NSTL	Inadequate balancing - rebalance
									1			1		NSTL	Low temperature, wrong constant - change constant
Totals	—	—	3	7	—	1	—	3	1	5	3	12			
HPOT Primary Seal Drain Temperature			2									2		NSTL	Liftoff seal rubbing - design change, replace with labyrinth seal
			1							1		1		NSTL	No failure - redline deleted
			1							1		1		NSTL	Redline constant not predicted well - change redline
Totals	—	—	4	—	—	—	—	—	—	2		4			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPOT Primary Seal Drain Pressure			1							1		1		NSTL	Moisture in connector - relocate
			3							3		3		NSTL	Inaccurate redline - change
			5									5		NSTL	Rubbing of liftoff primary LOX seal - change to labyrinth seal
			2							2		2		NSTL	Faulty transducer - nonflight hardware
			1							1		1		NSTL	New configuration, redline inadequate - change redline
Totals			12							7		12			
HPOT Primary Seal Cavity Pressure		1										1		NSTL	Secondary turbine wave spring failure - eliminate spring in design
Totals		1										1			
HPOT Intermediate Seal Purge		1										1		NSTL	Solenoid deactivated (dual coil) - change to single coil
Totals		1										1			
HPOT Intermediate Seal Cavity Pressure			1							1		1		NSTL	Pressure buildup slower than expected - change redline
			1									1		NSTL	Turbine seal rubbing - reduced coolant flow to open tolerances
			1							1		1		NSTL	Tube did not reach seal cavity - refitted
			1							1		1		NSTL	No failure - raise redline
			1							1		1		NSTL	Special seal clearances - modify redline
						1				1		1		NSTL	Tight clearance - not a failure, ok
Totals			5			1				5		6			
HPOT Preburner Pump Discharge Pressure		2								2		2		NSTL	Exploratory test - N/A
Totals		2								2		2			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPOT Axial Acceleratometers				1						1		1		NSTL	Bad facility cable and accelerometer - change cable and transducer
				1						1		1		NSTL	Cross-vibration from HPFT - increase redline
				1						1		1		NSTL	Accelerometer not honded properly - add screws
Totals				3						3		3			
HPFT Radial Accelerometers			2							2		2		NSTL	Bad accelerometers and slight cavitation - change accelerometers
		16										16		NSTL	Dynamic instability, whirl - redesign
		1										1		NSTL	Bearing failure, inadequate cooling - design change
		1								1		1		NSTL	Unknown
		1	1							2		2		NSTL	Test instrumentation failure - voting circuit added
				2								2		NSTL	HPFT cavitation - sequence change
				1								1		NSTL	LPFT turbine seal leak into discharge duct - repair
				1								1		NSTL	Turbine erosion from temp. spikes during start transients - change sequence
				1								1		NSTL	Turbine blade coating spalled, temp. spikes - add blade inspection
				1						1		1		NSTL	Broken pin in cable - new cable design
				1								1		NSTL	Turbine blades cracked - inspection
					1							1		NSTL	Rotor inbalance - rebalance
								1				1		NSTL	HPFT cavitation - test plan
								1			1			NSTL	Bearing and nut fatigue cause severe damage - FPB modification to reduce temperature
Totals		19	3	7	1			2		6	1	31			
HPFT RPM Speed		1								1		1		NSTL	Sensor failed - modify installation
				1						1		1		NSTL	Installed improperly - change installation
Totals		1		1						2		2			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPFT Turbine Inlet Temperature		3										3		NSTL	Valve sequencing problem - change sequence
		1								1		1		NSTL	Erroneous reading - change monitor
		1										1		NSTL	Tip seal erosion caused degraded performance - redesign
		4	1							5		5		NSTL	Erroneous reading - redline deleted for turbine discharge temperature
Totals		9	1							6		10			
HPFT Turbine Discharge Temp.			1							1		1		NSTL	Transducer misidentification - redo
			1							1		1		NSTL	Facility amp overload - redesign circuit
			1									1		NSTL	Degraded performance, tip seal erosion - redesign
			1							1		1		NSTL	Preburner high temp. at start - redline delay added at start
			1									1		NSTL	Valve sequencing problem - change sequencing
			1									1		NSTL	OPB injector faceplate erosion caused low fuel flow - repair
			1							1		1		NSTL	Faulty MCC PC flight transducer, burst diaphragm cracked, fuel temp. raised - nonflight
			1							1		1		NSTL	Sensor thermocouple failed - not applicable to engine
			3									3		NSTL	Nozzle tube splits - improved drying procedure
			1							1		1		NSTL	Thermocouple tip damage caused by contamination - repair
				2								2		NSTL	HPFT Cavitation - sequence changed
				1						1		1		NSTL	Facility leads reversed - change
				1								1		NSTL	Turnaround manifold bulge, overtemp at shutdown - redesign
				1							1			NSTL	MOV Fire, flow induced vibrations - redesign
					1							1		NSTL	Exterior MFV Leakage, valve cap to body bolts broken - redesign
					1					1		1		NSTL	Open circuit - repair
					1							1		NSTL	Start sequence problem - change sequence
						1						1		NSTL	Turbine coolant liners bulging, overpressure - new liners

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SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPFT Turbine Discharge Temp. (Continued)				1		1						2		NSTL	Main injector primary face plate and LOX post erosion by fatigue - material change
					3							2	1	NSTL	Nozzle tube ruptures, inadequate brazing - improve brazing
					1							1		NSTL	Nozzle assembly problem - repair
							1			1		1		NSTL	Turnaround manifold weld failure - planning and drawing change
							1				1			NSTL	Turbine blade failure - none, unique configuration
				1								1		NSTL	FPOV seal leakage caused by wear - prehot-fire flow test added
				1								1		NSTL	Mechanical rubbing caused by inadequate assembly techniques - assembly procedures improved
				1								1		NSTL	Rotor assembly balance caused failure - inhouse balancing after assembly
								1			1			SSFL	Water in engine caused by EDM problem - change EDM procedure
								1		1		1		NSTL	T/C's failed - replace T/C's with flight RTB systems
								1				1		NSTL	LPFT low performance, rotor labyrinth seal leak - refer to UCR A008357
								1				1		NSTL	Low HPFT performance - revise software and change to 1.5 MCC orifice
								1				1		NSTL	Low pump efficiency - remove pump
Totals			12	9	7	2	2	5		10	3	33	1		
HPFT Miscellaneous Cutoffs					1							1		NSTL	HPFT overtemp? from steerhorn failure - redesign
Unsure of What R/L Used					—				1			1		SSFL	Pump cavitation from inlet failure - suction requirement lower
Totals					1				1			2			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HPFT Axial Accelerometer R/L	2	5										7		NSTL	Dyanmic instability (whirl) - redesign
	1	1								2		2		NSTL	Facility device design limit - modify device
		1								1		1		NSTL	Axial thrust bearing welded - design changes
Totals	3	7								3		10			
HPFT Thrust Bearing Speed		2								2		2		NSTL	Erratic transducer output - add filter
Totals		2								2		2			
Fuel Preburner Temperature		1								1		1		NSTL	Facility malfunction - correct problem
		1										1		NSTL	Degraded performance of HPFT from tip seal erosion - redesign
Totals		2								1		2			
Oxidizer Preburner Temperature	1	6										7		NSTL	Valve Sequencing - change sequence
		1								1		1		NSTL	Erroneous reading - change to HPOT turbine discharge temperature
		1										1		NSTL	CCV Position error - change schedule
		2										2		NSTL	Degraded performance of HPFT from tip seal erosion - redesign
Totals	1	10								1		11			
HE Coil Delta Pressure		1										1		NSTL	Increased pressure buildup delay due to facility orifice - change
HE Discharge Pressure				1								1		NSTL	High HPOT break torque, unknown cause - none
				1							1			NSTL	Rework weld damage - change weld procedures
HE Purge Pressure			1							1		1		NSTL	Facility solenoid failure - repair
Totals		1	1	2						1	1	3			
LPDT Discharge Pressure				1						1		1		NSTL	Sensor short circuit - metal contamination
Totals				1						1		1			

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SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
LPFT Discharge Pressure							2					2		NSTL	Orifice size requirement omitted - change drawings
									1			1		SSFL	Stator shroud misbrazed - change drawing
			1							1		1		NSTL	Sensor failed - replace
									1	1		1		NSTL	Incorrect constant in software - change constant
Totals			1				2		2	2		5			
LPFT Discharge Flow								1		1		1		NSTL	Constant is wrong - change constant
Totals								1		1		1			
LPFT Radial Accelerometers				1						1		1		NSTL	Bad facility cable - replace cable
				1						1		1		NSTL	Unknown cause - none
				1						1		1		NSTL	Some vibration caused by suction pressure, ok - redline too low
Totals				3						3		3			
Oxidizer Flowmeter				1						1		1		NSTL	Output noisy, vibration fatigue - redesign
				2						2		2		NSTL	Calibration error - delete flowmeter
Totals				3						3		3			
OPOV Position	1												1	NSTL	Ball Seal Leakage, high pressure forced ball against D/S seal - design change
			1									1		NSTL	Shutdown sequence wrong - change sequence
							1	1		2		2		SSFL	Command limit error - change limit
Totals	1		1				1	1		2		3	1		
MOV Position				1						1		1		NSTL	Installed improperly - change installation procedure
Totals				1						1		1			
MOV Accelerometers					2							2		NSTL	Vibration induced stress - redesign
Totals					2							2			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
HGM Liner Delta Pressure		1										1		NSTL	Low mixture ratio - change valve positioning
		1										1		NSTL	High injector resistance - design change
Totals		2										2			
MCC PC Pressure			1							1		1		NSTL	Thrust overshoot at start, ok - change redline
			3									3		NSTL	Start sequence marginal - change sequence
			1							1		1		NSTL	Sensor failure, frozen part - replace
			1									1		NSTL	Valves misindexed caused pump deterioration - change valves
			1									1		NSTL	Low PC, slow oxidizer buildup - change oxidizer valve position
				1						1		1		NSTL	Transducer plumbed to wrong port - drawing revised
				1						1		1		NSTL	Low pressure because of wrong redline in software - change redline
Totals			7	2						4		9			
MCC Burst Diaphragm						1						1		NSTL	MCC leak caused burst diaphragm rupture - repair
Totals						1						1			
Engine Exit Plane Pressure									1			1		NSTL	OPEN
Totals									1			1			
MCC Hot-Gas Temperature				1						1		1		NSTL	Faulty thermocouple, tip burned off from debris - not flight hardware
Totals				1						1		1			

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
FIRE - Observer Cutoff or Unspecified			1								1			NSTL	Primary LOX seal rubbing - replaced by labyrinth seal
					1						1			NSTL	Steerhorn failure, filler wire material mistake - weld wire audit
			1									1		NSTL	Hole burnt through FPB body, inadequate cooling - redesign
			1									1		NSTL	HPOT bearing inadequate coolant flow - redesign
					1							1		NSTL	Gas leak, improperly torqued plug - assembly procedure change
						1					1			NSTL	Slag in annulus, LOX post nonconcentric, caused faceplate erosion - concentricity awareness
Totals			3		2	1					3	3			
Controller and Facility Problems	1									1		1		NSTL	Bad calculation of limit - change limit in software
	1									1		1		NSTL	Test limit switch cut by vibration at start - delete redline
		1										1		NSTL	Cutoff system failed due to failed diode - redesign
				1						1		1		NSTL	Unknown - ?
			1							1		1		NSTL	Software error - change
			1							1		1		NSTL	Reference supply oscillation - change circuit
			1							1		1		NSTL	Loose facility diffuser water pressure coupling - tighten
			1							1		1		NSTL	Structural failure of facility diffuser welds - not an engine problem
				1						1		1		NSTL	Facility instrumentation leak - repair
				1						1		1		NSTL	Facility malfunction causing freezing GN2 - repair
				1						1		1		NSTL	Erroneous signal - not an engine problem
				1						1		1		NSTL	Electrical harness connector disengaged - repair
				2	1					3		3		NSTL	Bad facility thermocouple - replace
				1						1		1		NSTL	Fuel inlet pressure too low - lower redline
				1	2	1		1		5		5		NSTL	Circuit breaker tripped - not a flight item
					1					1		1		NSTL	Facility timer improperly set - precaution
					3					3		3		NSTL	Facility accelerometer failed - replace

SSME ENGINE FIRING CUTOFF TABLES (Continued)

Cutoff Measurement	Date 75	76	77	78	79	80	81	82	83	Improper Cutoff	Criticality 1	2	3	Place	Causes-Action
Controller and Facility Problems (Continued)					1					1		1		NSTL	Voting logic c/o - software change
					2					2		2		NSTL	Failed to issue start command - facility ready logic changed
					1					1		1		NSTL	Software ran out of time - change software
					1					1		1		NSTL	Facility connector broke - repair
					1					1		1		SSME A-3	Facility transducer problem - removed transducer
					2					2		2		SSFL	Facility computer cutoff - tests planned to eliminate recurrence
							1			1		1		NSTL	Pin separation - closer on stand work monitoring
							1			1		1		SSFL	Accelerometer cable malfunction - replace
							1			1		1		SSFL	Channel B power interrupt, cause unknown - none
							1			1		1		NSTL	Accelerometer failures - nonflight hardware
								1		1		1		SSFL	Bad connector - repair
								1		1		1		NSTL	Channel A failure on Channel B power interrupt - software change
									1	1		1		NSTL	Circuit broken, pumps started together - change circuit
									1	1		1		SSFL	Wiring short circuit - repair
									1	1		1		NSTL	F/M calibration wrong - software change
Totals	2	1	4	9	15	1	4	3	3	41		42			

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APPENDIX I

FAILURE MODE RANKING

Description of Procedure and Summary of Results

C-4

SSME FAILURE MODE RANKING PROCEDURE

I. Three Line UCR Review

A. Considered all UCR's of criticality 1, 2, and 3
B. Deleted UCR's that did not affect engine performance
C. Deletec UCR's that were minor and did not recur after corrective action was taken by Rocketdyne

II. Full Page UCR Review

A. Deleted minor problems that did not affect engine performance and safety
B. Deleted some minor problems that present quality assurance steps would catch

III. Ranking of Failures

A. Risk Factor
Determine, from the criticality factor, the full page UCR description, and the FMEA report

RISK FACTOR VALUES

1.000	Loss of vehicle
0.500	Probable loss of vehicle
0.333	Loss of engine
0.250	Probable loss of engine
0.200	Extensive engine damage
0.167	Local engine damage
0.143	Minor local engine damage
0.125	Very minor damage
0.111	Piece part damage
0.100	Part still OK

B. Time Factor
The estimated least amount of time from occurrence of failure mode to engine loss or limit shutdown with reference to the FMEA report

TIME FACTOR VALUES

1.000	Instantaneous
0.500	Milliseconds
0.333	One to ten seconds
0.250	Ten to sixty seconds
0.167	Hour to never

C. Frequency of Failure Factor
The square root of the number of UCR's written for each failure mode divided by one-hundred, which ranged from 0.1 to 1.02

D. Cost Factor
The square root of the estimated cost per annum in millions of dollars subtracting costs that detection would not eliminate.

1. Ground rules for cost estimates
   a. Estimate the probability per flight and test stand firing of possible failure occurrences. Probabilities and costs will be broken down into the different levels of risk factor. Probabilities are based on the number of UCR's and their information content along with the FMEA report and the Probabilities in the Space Shuttle Range Safety Hazards Analysis Report.
   b. Divide the probability by three if only applicable to flight. This assumes there are on average two test firings for every engine flight firing.
   c. Multiply the probability of occurrence times the cost.
   d. Add each subtotal and multiply by 150. The assumption is that there are 150 firings total per year including test and flight firings.
   e. Cost structure in dollars

Vehicle loss	2 Billion
Mission loss	200 Million
Engine loss	33 Million
Major engine damage	20 Million
Local engine damage	Varies

IV. Ranking Algorithm

A. 10,000 x RF x TF x FFF x CF = Total

B. Ranking divisions

Total	Rank
>400	1
200-400	2
100-200	3
50-100	4
30-50	5
20-30	6
12-20	7
7.5-12	8
3.5-7.5	9
<3.5	10

Ranking of Failure Modes

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
A100	Cracks, rupture in duct	0.176	0.334	0.592	0.641	223.0	2	No	--
	Loose stud fasteners	0.125	0.25	0.265	0.256	21.2	6	Yes	Yes
	Leaks, G-5 seals	0.143	0.2	0.265	0.363	22.0	6	Yes	Yes
	Contamination	0.111	0.2	0.283	0.114	7.16	9	--	--
	Leak in MCC ignition jt.	1.0	0.5	0.100	0.574	287.0	2	Yes	No
	Stud keys missing or broken	0.125	0.25	0.300	0.226	21.2	6	Yes	Yes
A150	Cracks, leaks on coil	0.444	0.5	0.245	0.917	498.8	1	Yes	Yes
	Clearance problems	0.125	0.25	0.300	0.260	21.2	6	Yes	Yes
A200	Heat shield retainer cracks	0.125	0.2	0.435	0.406	44.2	5	Yes	No
	LOX post cracks	0.111	0.2	0.245	0.277	15.1	7	Yes	No
	ASI supply line cracks	1.0	0.2	0.224	0.694	310.9	2	Yes	No
	Reinforcement ring cracks	0.143	0.2	0.200	0.250	14.3	7	Yes	No
	Face and interprop. plate cracks	0.1154	0.2	0.300	0.259	17.9	7	Yes	No
	LOX post erosion	0.125	0.2	0.200	0.239	12.0	7	Yes	No
	Face plate erosion	0.125	0.2	0.173	0.237	10.3	8	Yes	No
	Loose T-bolts	0.125	0.25	0.224	0.351	24.6	6	Yes	No
	Metal contamination	0.111	0.167	0.424	0.257	20.2	6	--	--
A330	Hot-gas wall centerline cracks	0.143	0.2	0.173	0.198	9.8	8	Yes	Yes
	Burst diaphragm leaks	0.1667	0.1667	0.316	0.182	16.0	7	Yes	No
	Turbine drive manifold leak	0.5	0.5	0.1	0.424	106.0	3	--	--
	Liner delamination	0.125	0.2	0.173	0.226	9.8	8	Yes	No
	Hot-gas wall erosion	0.111	0.1667	0.141	0.550	1.4	10	Yes	Yes
	Wear on strut clevis	0.111	0.1667	0.1	0.071	1.3	10	--	--
	Contamination	0.111	0.1667	0.265	0.122	5.0	9	Yes	Yes
	Coolant inlet welds mismatch	0.125	0.2	0.2	0.190	9.5	8	Yes	Yes
A340	Tube leaks	0.125	0.2	1.02	0.095	24.2	6	Yes	Yes
	Tube cracks	0.1228	0.2	0.911	0.057	12.8	7	Yes	Yes
	Hat band leaks	0.111	0.25	0.332	0.078	7.2	9	Yes	Yes
	Steerhorn rupture	0.5	0.333	0.1	0.458	76.3	4	Yes	No
	Outer jacket cracks	0.143	0.25	0.173	0.134	8.3	8	Yes	Yes

Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
A340 (Cont.)	Broken welds	0.11087	0.1667	0.55	0.122	12.2	7	Yes	Yes
	Misaligned fuel joints	0.111	0.1667	0.2	0.189	7.0	9	Yes	Yes
	Defective temp. and radiometer srs	0.1	0.1667	0.173	*	*	10	--	--
A600	Baffle and LOX post erosion	0.125	0.2	0.490	0.399	48.9	5	Yes	Yes
	Face plate erosion	0.1538	0.2	0.447	0.399	54.9	4	Yes	Yes
	Cracks-baffles, moly shield, liner	0.111	0.2	0.583	0.348	45.0	5	Yes	Yes
	Nonconcentric LOX posts	0.111	0.2	0.332	0.319	23.5	6	Yes	Yes
	Missing or extra support pins	0.111	0.2	0.469	0.355	36.6	5	Yes	No
	Contamination	0.111	0.167	0.224	0.710	2.9	10	--	--
A700	LOX posts and liner erosion	0.125	0.2	0.1731	0.225	9.73	8	Yes	No
	LOX post cracks	0.125	0.2	0.1411	0.232	8.18	8	Yes	No
B200	1st stage vane erosion	0.125	0.2	0.30	0.339	25.4	6	--	--
	Turb. blade and platform erosion	0.125	0.2	0.412	0.457	47.1	5	Yes	Yes
	G-5 joint erosion	1.0	0.333	0.1	0.423	140.9	3	Yes	No
	Seal cracks	0.143	0.2	0.387	0.326	36.1	5	Yes	No
	Turbine blade shank cracks	0.125	0.2	0.141	0.182	6.4	9	Yes	No
	Sheetmetal cracks	0.1111	0.1667	0.346	0.126	8.1	8	Yes	Yes
	Struts and post cracks	0.1154	0.1667	0.794	0.191	29.1	6	Yes	Yes
	Inlet duct cracks	0.143	0.2	0.141	0.166	6.7	9	Yes	Yes
	Bellows shield cracks	0.15	0.2	0.3	0.322	29.0	6	Yes	No
	T/A manifold cracks	0.143	0.2	0.173	0.173	8.5	8	Yes	Yes
	Bearing ball dry-lube cracks	0.111	0.2	0.2	0.139	6.2	9	No	--
	Turbine end ring cracks	0.111	0.2	0.1414	0.144	4.5	9	No	--
	Bearing support cracks	0.111	0.1667	0.1414	0.122	3.2	10	No	--
	Coolie cap nut cracks	0.1667	0.2	0.36	0.282	33.8	5	Yes	No
	Liftoff seal leak	0.1667	0.25	0.224	0.295	27.5	6	Yes	No
	Broken seals	0.1333	0.25	0.316	0.279	29.3	6	Yes	No
	Broken turbine blades	0.143	0.25	0.283	0.324	32.8	5	Yes	No
	Vane failure	0.125	0.25	0.224	0.212	14.8	7	No	--
	Diffuser failure	0.333	0.333	0.173	0.346	66.4	4	No	--
	Inlet failure	0.5	0.333	0.1	0.355	59.1	4	No	--

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Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
B200 (Cont.)	Burnt vane	0.125	0.2	0.173	0.155	6.7	9	No	--
	Nickel insulation damage	0.111	0.167	0.3	0.088	4.9	9	Yes	Yes
	T/A manifold damage	0.333	0.333	0.1	0.245	27.2	6	Yes	Yes
	Excess shaft travel*	0.111	0.25	0.3	*	*	7	Yes	Yes
	Missing locking pins	0.143	0.25	0.283	0.274	27.7	6	?	?
	Missing shield nuts	0.5	0.333	0.1414	0.387	91.1	4	?	?
	Missing discharge nuts and lugs	0.125	0.25	0.1732	0.190	10.3	8	?	?
	Vibration levels (cavitation)*	0.333	0.333	0.1414	*	*	5	Yes	No
	Bearing ball wear	0.143	0.25	0.1	0.160	5.7	9	No	--
	Contamination	0.111	0.25	0.6324	0.157	27.6	6	Yes	No
	Gouges in vane	0.111	0.1667	0.2	0.095	3.5	9	No	--
B400	Bearing ball and race wear	0.208	0.2727	0.6	0.744	253.2	2	Yes	Yes
	Bearing support wear	0.125	0.25	0.141	0.235	10.35	8	No	--
	Spring lands wear	0.1667	0.25	0.1	0.235	9.8	8	No	--
	Nozzle vane cracks	0.143	0.2	0.173	0.220	10.9	8	Yes	No
	Strut cracks	0.111	0.1667	0.245	0.090	4.1	9	Yes	No
	Housing cracks	0.1667	0.2	0.316	0.204	21.5	6	Yes	No
	Turbine blade cracks	0.125	0.25	0.424	0.245	32.5	5	Yes	No
	Sheetmetal cracks	0.111	0.1667	0.224	0.095	3.9	9	Yes	No
	Strut erosion	0.125	0.2	0.1	0.110	2.8	10	Yes	No
	Liner erosion	0.1667	0.25	0.1	0.155	6.5	9	Yes	No
	Contamination	0.11765	0.222	0.616	0.155	24.5	6	Yes	Yes
	Turb. blade contamination	0.143	0.2	0.265	0.105	8.0	8	No	--
	Shaft torque* - rubbing, damper	0.125	0.25	0.469	*	*	6	Yes	Yes
	Bearing cage delamination	0.125	0.25	0.412	0.295	40.0	5	Yes	Yes
	Vibration* bearing loading	0.5	0.333	0.36	*	*	1	Yes	No
	Turbine disk rubbing	0.143	0.2	0.1	0.189	5.4	9	Yes	No
	Shaft travel* - bearing loading	0.1667	0.25	0.1	*	*	9	Yes	No
	Strut damage	0.143	0.25	0.173	0.155	9.6	8	Yes	No
B600	Insulation rupture, cracks	0.1176	0.2	0.265	0.128	8.0	8	Yes	Yes
	Excessive torque	0.125	0.2	0.283	0.155	11.0	8	Yes	No
	Contamination	0.125	0.2	0.141	0.105	3.7	9	No	--

Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
B800	Bearing ball wear	0.1667	0.25	0.245	0.194	19.8	7	Yes	Yes
	Shaft torque* - Brg. cage friction	0.1	0.2	0.412	0.078	6.4	9	Yes	Yes
	Contamination	0.1143	0.2	0.447	0.105	10.7	8	Yes	No
	Stator ding	0.143	0.2	0.1	0.075	2.1	10	No	--
	Flange surface undercut	0.125	0.2	0.141	0.1	3.5	9	No	--
C100	Check valve leaks	0.143	0.333	0.224	0.290	31.0	5	Yes	No?
C270	HPOT purge PAV leak	0.143	0.25	0.20	0.35	25.0	6	Yes	No?
D110	Ball seal leak	0.143	0.25	0.141	0.219	11.0	8	Yes	No
	Contamination	0.143	0.2	0.1	0.067	1.9	10	No	--
D120	Ball seal leak	0.143	0.25	0.173	0.282	17.4	7	Yes	No
	Excessive pressure*	0.125	0.25	0.1	*	*	9		
D130	Ball seal leak	0.143	0.25	0.1	0.160	5.7	9	Yes	Yes
	Internal leak	0.143	0.25	0.1	0.120	4.3	9	No	--
	Contamination	0.111	0.2	0.1	0.067	1.5	10	No	--
	Low flow rate; bolt assembly	0.143	0.25	0.141	0.197	9.9	8	No	--
D140	Ball seal leak and melting	0.143	0.25	0.458	0.463	75.8	4	Yes	No
	Excessive pressure*	0.143	0.25	0.1	*	*	9	No	--
D150	Studs overtorqued	0.143	0.25	0.1	0.134	4.8	9	--	--
D300	LVDT signal erratic	0.111	0.25	0.245	0.077	5.2	9	Yes	No
	Cracked poppet	0.5	0.333	0.141	0.410	96.2	4	No	--
	Poppet remained open	0.2	0.333	0.1	0.116	11.1	8	No	--
	Contamination	0.1	0.2	0.141	0.096	2.7	10	No	--
D500	Valve leak	0.143	0.25	0.1	0.109	3.9	9	Yes	No
	Port 024.1 leak	0.143	0.2	0.1	0.058	1.7	10	Yes	No

Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
D600	LVDT voltage low	0.111	0.25	0.1	0.077	2.1	10	Yes	No
	Contamination	0.111	0.2	0.141	0.077	2.4	10	No	--
E001-150	Wireway leak	0.103	0.2	0.424	0.096	8.3	8	--	--
	Seal leak	0.117	0.2	0.265	0.096	6.0	9	Yes	No
	Vent port leak	0.111	0.2	0.141	0.069	2.2	10	--	--
	Servoswitch failure	0.2	0.2	0.1	0.077	3.1	10	--	--
	Vent port pitting	0.143	0.2	0.1	0.089	2.5	10	--	--
	Broken wireway nut	0.125	0.2	0.1	0.096	2.4	10	No	--
	Early purged end - O-ring	0.25	0.2	0.2	0.155	15.5	7	Yes	Yes
	RVDT limit* - engine flashback	0.143	0.2	0.1	*	*	10	--	--
	Defective O-ring	0.143	0.2	0.1	0.077	2.2	10	--	--
	Sequence valve anomaly	0.143	0.2	0.1	0.077	2.2	10	--	--
	Contamination	0.1176	0.2	0.2	0.071	3.3	10	--	--
	Hydraulic oil wetting	0.111	0.2	0.1	0.048	1.1	10	Yes	Yes
	FID?	0.182	0.2	0.141	0.129	6.6	9	--	--
	Electrical problems	0.133	0.2	0.141	0.096	3.6	9	--	--
F800	FID?	0.12	0.25	0.387	0.079	9.2	8	Yes	Yes
	Chaffed wires	0.111	0.25	0.1	0.041	1.1	10	Yes	Yes
G000	Igniter tip erosion	0.143	0.25	0.374	0.263	35.2	5	Yes	Yes
	Bad output	0.143	0.2	0.346	0.191	18.9	7	Yes	Yes
	Low insulation resistance	0.125	0.2	0.245	0.122	7.5	8	Yes	Yes
H000-002	Birdcaged harness	0.125	0.25	0.412	0.263	33.8	5	Yes	Yes
	Broken wire, backshell	0.1154	0.25	0.33	0.226	21.5	6	Yes	Yes
	Loose or defective connector	0.143	0.25	0.436	0.319	49.7	5	Yes	Yes
	Insulation resistance low	0.111	0.25	0.1	0.056	1.6	10	Yes	Yes
	Debonded torque lock	0.143	0.25	0.316	0.268	30.3	5	Yes	Yes
	Open or short circuit	0.143	0.25	0.173	0.190	11.8	8	Yes	Yes
J200	Output failure	0.1277	0.33	0.49	*	*	4	Yes	Yes
	Bent pin	0.125	0.33	0.141	*	*	8	Yes	Yes

Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
J200 (Cont.)	Output drift	0.125	0.25	0.141	*	*	9	Yes	Yes
	Low output resistance	0.125	0.25	0.1	*	*	9	Yes	Yes
J300	Output failure	0.125	0.333	0.49	*	*	4	Yes	Yes
	Sensor debonding	0.125	0.333	0.608	*	*	4	Yes	Yes
	Broken sensor tip	0.125	0.333	0.224	*	*	7	Yes	Yes
	Low insulation resistance	0.125	0.25	0.283	*	*	7	Yes	Yes
J600	Output failure	0.111	0.25	0.2	*	*	8	Yes	Yes
J800	Output failure	0.125	0.25	0.173	*	*	8	Yes	Yes
	Missing dielectric insert	0.125	0.25	0.1	*	*	9	--	--
K100	Leak	0.143	0.333	0.173	0.232	19.1	7	Yes	Yes
	Joint overmold debonded	0.125	0.25	0.173	0.114	6.2	9	Yes	Yes
	Broken burst diaphragm	0.111	0.25	0.316	0.173	15.1	7	Yes	No
	Joint boot tear	0.125	0.25	0.1	0.056	1.8	10	Yes	Yes
	Nickel insulation cracks	0.125	0.25	0.1	0.056	1.8	10	Yes	Yes
	Seal cracks	0.125	0.25	0.1	0.073	2.3	10	--	--
	Weld cracks	0.1667	0.333	0.141	0.16	12.5	7	--	--
	Tolerances	0.133	0.25	0.173	0.095	5.5	9	--	--
	Frost on bellows	0.1111	0.2	0.1	0.067	1.5	10	--	--
K200	Cracks on ducts	0.222	0.25	0.141	0.155	12.2	7	--	--
	Support link cracks	0.1667	0.25	0.1	0.079	3.3	10	--	--
	Duct wear	0.143	0.2	0.1	0.067	1.9	10	--	--
	Contamination	0.1176	0.2	0.361	0.131	11.1	8	Yes	No
	Impressions on ring	0.143	0.25	0.1	0.077	2.8	10	--	--
K300	Misaligned joint	0.125	0.2	0.1	0.032	0.8	10	Yes	Yes
	Contamination	0.111	0.2	0.1	0.071	1.6	10	--	--
K500	Kink, twist, or compressed	0.143	0.2	0.2	0.130	7.4	8	Yes	No
	Contamination in joint	0.111	0.2	0.173	0.067	2.6	10	--	--

Ranking of Failure Modes (Continued)

Comp.	Failure	Risk Factor	Response Time Factor	Failure Frequency Factor	Failure Cost Factor	Total	Rank	Inspect at KSC	Found at KSC
K600	Controller cooling duct cracks	0.143	0.2	0.173	0.054	2.7	10	--	--
L000	Seal damage	0.143	0.333	0.224	0.333	35.5	5	--	--
	Protrusion on seal	0.143	0.25	0.141	0.203	10.2	8	--	--
L200	Loose stretch bolts	0.125	0.25	0.1	*	*	9	Yes	Yes
M000	Wear, fretting on gimbal	0.143	0.25	0.245	0.32	28.0	6	No	--
	Crack in bushing	0.1667	0.25	0.173	0.33	24.0	6	--	--
N600	Deformed orifice	0.1667	0.25	0.173	0.219	15.8	7	--	--
	Tolerances	0.111	0.25	0.141	0.096	3.8	9	--	--
	Low torque	0.11	0.25	0.1	0.069	1.9	10	--	--

Final Ranking of Failure Modes

Rank	Comp.	Failure	Possible Cost Savings ($ Million) per Annum
1	B400	Vibration - bearing loading*	--
	A150	Cracks, leak on coil	0.840
2	A100	Cracks, rupture in duct	0.410
	A100	Leak in MCC ignition jt.	0.330
	A200	ASI supply line cracks	0.480
	B400	Bearing ball and race wear	0.550
3	A330	Turbine drive manifold leak	0.180
	B200	G-5 joint erection	0.180
4	J200, J300	Output failure*	--
	A340	Steerhorn rupture	0.200
	A600	Faceplate erosion	0.240
	B200	Diffuser failure	0.120
	B200	Inlet failure	0.120
	B200	Missing shield nuts	0.150
	D140	Ball seal leak and melting	0.214
	D300	Cracked poppet	0.168
	J300	Sensor debonding*	--
5	A200	Heat sheild retained cracks	0.165
	A600	Baffle & LOX post erosion	0.160
	A600	Baffle, molyshields & liner cracks	0.120
	A600	Missing or extra support pins	0.126
	B200	Turbine blade & platform erosion	0.210
	B200	Seal cracks	0.106
	B200	Coolie cup nut cracks	0.080
	B200	Broken turbine blades	0.105
	B400	Turbine blade cracks	0.060
	B400	Bearing cage delamination	0.087
	C100	Check valve leaks	0.084
	G000	Igniter tips erosion	0.069
	H000-002	Birdcaged harness	0.069
	H000-002	Loose, defective connector	0.102
	H000-002	Debonded torque lock	0.072
	L000	Seal damage	0.110
	B200	Vibration levels (cavitation)*	--
6	A100	Loose stud fasterners	0.065
	A100	Leaks G-5 seals	0.133
	A100	Stud keys missing, broken	0.051
	A150	Tube clearance problems	0.063
	A200	Loose T-bolts	0.123

Final Ranking of Failure Modes (Continued)

Rank	Comp.	Failure	Possible Cost Savings ($ Million) per Annum
6	A200	Metal contamination	0.066
	A340	Tube leaks	0.009
	A600	Nonconcentric lox posts	0.102
	B200	Struts & post cracks	0.036
	B200	1st stage vane erosion	0.115
	B200	Bellows shield cracks	0.104
	B200	Liftoff seal leak	0.087
	B200	Broken seals	0.078
	B200	T/A manifold damage	0.060
	B200	Missing locking pins	0.075
	B200	Contamination	0.025
	B400	Housing cracks	0.042
	B400	Contamination	0.024
	B400	Shaft torque--rubbing dampers	--
	C270	HPOTP purge PAV leak	0.123
	H000-002	Broken wire, backshell	0.051
	M000	Wear, fretting on gimbal	0.102
	M000	Crack in bushing	0.109
7	A200	LOX post cracks	0.077
	A200	Face & Interprop. plate carcks	0.067
	A330	Burst diaphragm leaks	0.033
	B200	Excess shaft travel*	--
	B800	Bearing ball wear	0.038
	D120	Ball seal leak	0.080
	E001-150	Early purge O-ring shaft	0.024
	G000	Bad output	0.036
	J300	Broken sensor tip	--
	J300	Low insulation resistance	--
	K100	Leak	0.054
	K100	Broken burst diaphragm	0.030
	N600	Deformed orifice	0.048
	A200	Reinforcement ring cracks	0.063
	B200	Vane failure	0.045
	A200	LOX post erosion	0.057
	A340	Tube cracks	0.003
	A340	Broken welds	0.015
	K100	Weld cracks	0.026
	K200	Cracks on ducts	0.023
8	D130	Low flow rate - bolt assy.	0.039
	A200	Face plate erosion	0.056
	A330	Hot-gas wall centerline cracks	0.039
	A330	Liner delamination	0.051

Final Ranking of Failure Modes (Continued)

Rank	Comp.	Failure	Possible Cost Savings ($ Million) per Annum
8	A330	Coolant inlet welds mismatch	0.036
	A340	Outer jacket cracks	0.018
	A700	LOX post & liner erosion	0.051
	A700	LOX post cracks	0.102
	B200	Sheetmetal cracks	0.016
	B200	T/A manifold cracks	0.030
	B200	Missing discharge nuts and lugs	0.036
	B400	Bearing support wear	0.055
	B400	Spring lands wear	0.055
	B400	Nozzle vane cracks	0.048
	B400	Turbine blade contamination	0.011
	B400	Strut damage	0.024
	B600	Insulation rupture, cracks	0.016
	B600	Excessive torque	0.024
	B800	Contamination	0.011
	D120	Ball seal leak	0.030
	D300	Poppet remained open	0.013
	E001-150	Wireway leak	0.009
	F800	FID?	0.006
	G000	Low insulation resistance	0.015
	H000-002	Open or short circuit	0.036
	J200	Bent pin*	--
	J600	Output failure	0.040
	J800	Output failure	0.030
	K200	Contamination	0.017
	K500	Kink, twist, or compressed	0.017
	L000	Protrusion on seals	0.041
9	A100	Contamination	0.013
	A330	Contamination	0.014
	A340	Hat band leaks	0.006
	A340	Misaligned fuel joints	0.036
	B200	Turbine blade shank cracks	0.033
	B200	Inlet duct cracks	0.028
	B200	Bearing ball dry-lube cracks	0.019
	B200	Turbine end ring cracks	0.021
	B200	Burnt vane	0.024
	B200	Nickel insulation damage	0.008
	B200	Bearing ball wear	0.026
	B200	Gouges in vane	0.009
	B400	Strut cracks	0.008
	B400	Sheetmetal cracks	0.009
	B400	Liner erosion	0.024
	B400	Turbine disk rubbing	0.036
	B400	Shaft travel* - bearing loading	--
	B600	Contamination	0.011

Final Ranking of Failure Modes (Continued)

Rank	Comp.	Failure	Possible Cost Savings ($ Million) per Annum
9	B800	Shaft torque* - bearing cage friction	0.006
	B800	Flange surface undercut	0.010
	D120	Excessive pressure*	--
	D130	Ball seal leak	0.026
	D130	Internal leak	0.014
	D140	Excessive pressure*	--
	D150	Studs overtorqued	0.018
	D300	LVDT signal erratic	0.006
	D500	Valve leak	0.012
	E001-150	Seal leak	0.009
	E001-150	FID?	0.017
	E001-150	Electrical problems	0.009
	J200	Output drift*	--
	J200	Low output resistance*	--
	J800	Missing dielectric insert	--
	K100	Joint overmold debonded	0.013
	K100	Tolerances	0.009
	L200	Loose stretch bolts*	--
	N600	Tolerances	0.009
10	A330	Hot-gas wall erosion	0.303
	A330	Wear on strut clevis	0.005
	A340	Defective temp., & radiometer sensors	--
	A600	Contamination	0.504
	B200	Bearing support cracks	0.015
	B400	Strut erosion	0.012
	B800	Stator ding	0.006
	D110	Contamination	0.004
	D130	Contamination	0.004
	D300	Contamination	0.009
	D500	Port 0240.1 leak	0.003
	D600	LVDT voltage low	0.006
	D600	Contamination	0.006
	E001-150	Vent port leak	0.005
	E001-150	Servoswitch failure	0.006
	E001-150	Vent port pitting	0.008
	E001-150	Broken wireway nut	0.009
	E001-150	RVDT limit* - engine flashback	--
	E001-140	Defective O-ring	0.006
	E001-005	Sequence valve anomaly	0.006
	E001-150	Contamination	0.005
	E001-150	Hydraulic oil wetting	0.002

Final Ranking of Failure Modes (Continued)

Rank	Comp.	Failure	Possible Cost Savings ($ Million) per Annum
10	F800	Chaffed wires	0.002
	H000-002	Insulation resistance low	0.003
	K100	Joint boot tear	0.003
	K100	Nickel insulation cracks	0.003
	K100	Seal cracks	0.005
	K100	Frost on bellows	0.004
	K200	Support link cracks	0.006
	K200	Duct wear	0.004
	K200	Impressions on ring	0.006
	K300	Misaligned joint	0.001
	K300	Contamination	0.005
	K500	Contamination in joint	0.004
	K600	Controller cooling duct cracks	0.003
	N600	Low torque	0.005

APPENDIX J

LISTING OF SSME MEASUREMENT PARAMETERS BY COMPONENT

MEASUREMENT PARAMETER TABLES KEY

F -- Inflight Measurement

G -- Between Flight Measurement

B -- Both Inflight and Between Flight Measurement

D -- Detection of Failure

T -- Trending Information

COMPONENT A100--HOT-GAS MANIFOLD

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Cracks, Ruptured Duct -vibration- -thermal- -no heat treatment- -defective welds-	3	Engine Fire	Vibration (F)(T) Temperature (F)(T)(D) Acoustic (B)(D) Loads (F)(T) Optical (B)(D) Performance (F)(D) Leak Detection (G)(D) Pressure (F)(D)	Accelerometer Thermocouple, RTD Acoustic Emission Strain Gages Holography (leak) Various (MCC) Pressure Sensor	Ultrasonic (leak) NDT, Visual Various	AE is a possibility for crack detection, but may be difficult to implement. Present instrument information may be helpful in detecting leakage, but may not be sensitive enough to stop the engine before catastrophic failure. Trending with vibration and temperature sensors could be helpful in tracking life limits.
Loose Stud Fasteners -wrong torque- -stretching- -soft keys-	7	Hot-gas Leak Engine Fire	Vibration (F)(D) Torque (G)(D) Optical (B)(D) Load (F)(T)	Accelerometer ? Strain Gages	Torquemeter Visual	Using some sort of alignment marks with an optical system for detection may be possible on flight or at least as ground check. Vibration data may indicate a loose fastener also.
G-5 Seal and MCC Ignition Joint Leaks -installation problems-	7,1	Engine Fire	Optical (B)(D) Leak Detection (G)(D) Temperature (F)(D) Acoustic (B)(D) Performance (F)(D)	Holography (leak) Thermocouple, RTD Acoustic Emission Various	Various Ultrasonic (leak)	Same as duct leaks.
Contamination -unknown-	8	Performance Degradation	Performance (F)(D) Optical (G)(D)	Various	Borescope, Visual	Not much can be done except some sort of monitoring of performance degradation.

COMPONENT A150--HEAT EXCHANGER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Coil Tube Cracks and Leaks -mishandling- -wrong material- -wear, thermal fatigue- -bad weld-	1	Turbopump Destruction Engine Destruction	Temperature (F)(T) Acoustic (B)(D) Optical (G)(D) Leak Test (G)(D)	Thermocouple, RTD, Pyrometer Acoustic Emission	Ultrasonic Leak Detection Borescope, NDT (eddy current) Various	This failure is very hard if not impossible to monitor inflight. Trending normal fatigue failure may be possible. Ground inspection may be improved by a new eddy current device that measures wall thickness. Any new design should attempt to eliminate the heat exchanger coil.
Clearance Problems -thermal cycling- -fabrication errors-	7	Coil Wear, Leaks Turbopump Destruction Engine Destruction	Temperature (F)(T) Optical (G)(D)	Thermocouple, RTD, Pyrometer	Borescope	Same as above.

COMPONENT A200--MAIN INJECTOR

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
LOX Post, Heat Shield Retainer, Reinforcement Ring, & Interpropellant Plate Cracks -gas turbulence at fpl- -thermal overload- -secondary failure-	6,8	Piece Part Failure MCC Damage	Temperature (F)(T)(D) Vibration (F)(T) Optical (G)(D) Acoustic (F)(D)	Thermocouple, RTD, Pyrometer Accelerometer Acoustic Emission	NDT, Visible	An ability to trend both vibration and thermal fatigue could be very helpful. AE would be very hard to implement in this such a harsh, noisy environment. Detecting temperature imbalances or hot spots in the MCC could determine main injector LOX post problems.
ASI Supply Line Cracks -liquid embrittlement-	2		Temperature (F)(T) Optical (G)(D) Acoustic (F)(D)	Thermocouple, RTD, Pyrometer Acoustic Emission	NDT, Visible	Monitoring temperature for trending liquid embrittlement may be the only way to detect or trend this failure mode. AE might be feasible for crack detection.
LOX Post and Face Plate Erosion -high-cycle fatigue- -blocked orifice-	9	Piece Part Failure MCC Damage	Temperature (F)(T)(D) Vibration (F)(T) Optical (G)(D)	Thermocouple, RTD, Pyrometer Accelerometer	NDT, Visual	Trending temperature and vibration may be the most valuable information for inflight sensing. This may be a long-term degradation which would facilitate an efficient ground inspection technique like some sort of automated optical method.
Loose T-Bolts -installation- -operation-	8	Hot-Gas Leak	Vibration (F)(D) Optical (B)(D) Torque (G)(D)	Accelerometer ?	Visual Torquemeter	Some method of optically detecting alignment marks to tell if the bolts are loose, either ground or flight would be helpful. Vibration data might help detect loose bolts.

COMPONENT A200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Metal Contamination -unknown-	8	Blocked Orifice	Optical (G)(D)		Visual	This failure mode could only be detected inflight if the block caused some sort of large temperature imbalance.

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COMPONENT A330--MAIN COMBUSTION CHAMBER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Hot-Gas Wall Cracking -hot-gas impingement-	9	MCC Damage	Temperature (F)(T) Optical (B)(D) Acoustic (F)(D)	Thermocouple, RTD, Pyrometer Temperature? Acoustic Emission	NDT, Visual	An optical method to determine hot spots in the MCC chamber wall from outside the engine might be a good way to monitor the health of the chamber. An efficient ground inspection method is probably adequate for this failure.
Burst Diaphragm Leak -temperature rise-	7	Possible Engine Shutdown	Temperature (F)(T) Acoustic (B)(D) Pressure (F)(D) Leak Detection (G)(D) Optical (G)(D)	Thermocouple, RTD Acoustic Emission Pressure Sensor	Ultrasonic Detection Various Visual	This failure mode should be easily detectable with basic sensors. Trending of temperature can help in determining maintenance needs of the burst diaphragm.
Turbine Drive Manifold Leak -weld repair-	4	Fuel Leak	Pressure (F)(D) Acoustic (B)(D) Optical (B)(D) Leak Detection (G)(D)	Pressure Sensor Acoustic Emission Global Leak Detection	Ultrasonic Leak Visual, NDT Various	This is the most critical failure mode on the MCC and may warrant special attention for inflight diagnostics. A laser global leak detection for any leakage may be helpful for this failure and other SSME leakage problems.
Liner Delamination -unknown-	9	MCC Leak Engine Fire	Acoustic (F)(D) Optical (B)(D)	Acoustic Emission Temperature?	Visual, NDT	Delamination would be very hard to detect inflight until some leakage occurred. AE might be able to pick up the cracking or delamination signal. An optical system that measures MCC wall hot spots might help.

COMPONENT A330--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Hot-Gas Wall Erosion -contamination-	10	MCC Damage	Optical (B)(D)	Temperature?	Visual, NDT	Same as linear delamination.
Strut Clevis Wear -OPEN-	10	Minor Piece Part Damage	Optical (G)(D)		Visual	Not a major problem warranting any special attention.
Contamination -fabrication- -unknown-	9	MCC Erosion	Optical (G)(D)		Visual, NDT	Contamination is not a major problem unless it causes gross erosion of the MCC wall. This can easily be checked between flights.

COMPONENT A340--NOZZLE ASSEMBLY

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Tube Leaks and Cracks -repairs- -overheated- -brazing errors- -operational strains- -corrosion- -thermal distortion-	4	Low Rate Fuel Leakage	Optical (B)(D) Vibration (F)(T) Temperature (F)(T) Leak Detection (G)(D) Acoustic (B)(D)	Global Leak Detection Accelerometer Thermocouple, Optical? Acoustic Emission	Visual, NDT Various Ultrasonic Detection	This failure mode is a very common, routine maintenance-type problem. Inflight leak location would be very difficult, so the most likely cost reduction would come with an automated ground inspection technique to locate small leaks. There is a small ultrasonic device that is used to quickly locate condenser leaks for the electric power industry that might be useful.
Hat Band Leaks -stress corrosion- -transient loads- -braze strains-	7	Low Rate Fuel Leakage	Optical (B)(D) Vibration (F)(T) Temperature (F)(T) Leak Detection (G)(D) Acoustic (B)(D)	Global Leak Detection Accelerometer Thermocouple, Optical? Acoustic Emission	Visual, NDT Various Ultrasonic Detection	Same as above.
Steerhorn Rupture -wrong weld wire-	5	Engine Destruction	Vibration (F)(T)(D) Acoustic (B)(D) Pressure (F)(D) Optical (G)(D)	Accelerometer Acoustic Emission Pressure Sensor	Ultrasonic Detection NDT	If this or a similar failure were to occur, there is little means of detection that will enable safe shut-down. The failure progresses so quickly that any detection method would have to detect the cracking before rupture. AE may be possible, but not likely. Better QC and inspection methods are a necessary part of the process.

COMPONENT A340--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Outer Jacket Cracks -fabrication errors- -thermal cycling-	8	Local Nozzle Damage	Temperature (F)(T) Acoustic (F)(D) Optical (B)(D)	Thermocouple, RTD Acoustic Emission Temperature?	Visual, NDT	This failure mode is very hard to detect inflight. Envision some sort of optical scanning to determine temperature gradients and thus calculate thermal cycling characteristics. An automated ground NDT inspection might save time and costs.
Broken Welds -transient loads- -random failures- -poor routing-	9	Local Nozzle Damage	Vibration (F)(T) Loads (F)(T) Optical (G)(D) Acoustic (F)(D)	Accelerometer Strain Gage Acoustic Emission	Visual, NDT	Trending loads or vibration data may be helpful but will not take care of the random fabrication caused failures. This requires better QC. AE is possible, but not likely.
Misaligned Joints -assembly error- -OPEN-	9	Gas Leak	Optical (G)(D)		Visual	This failure mode should require better QC at the assembly and checkout areas.
Defective Sensors -contamination-	10	No Flight Data	Signal Output (F)(D)	Transducer Signal		The reliability of the sensor set is extremely important in any diagnostic scheme. Continued improvement in the ruggedness of basic sensors is a must. Also, self checking and calibration would be helpful in determining the validity of the data and improve confidence in the sensors' output.

COMPONENT A600--FUEL PREBURNER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Baffle and LOX Post Erosion -high local mixture ratio- -hot-gas impingement-	6	Preburner and HPFTP Damage	Temperature (F)(T) Optical (G)(D) Worn Particles (G)(D)	Thermocouple, RTD, Pyrometer	Borescope ?	Most of the failure modes in this preburner are interrelated and temperature monitoring for overall component health may be warranted. The health of this component is important to the downstream components.
Face Plate Erosion -hot-gas flow- -missing lox pin- -slag deposit- -unknown-	6	Piece Part Failure	Temperature (F)(T) Optical (G)(D) Loads (F)(T)	Thermocouple, RTD, Pyrometer Strain Gages	Borescope	Same as above.
Baffle, Molyshield, Liner and Baffle Weld Cracks -high local mixture ratio- -thermal strain-	6	Piece Part Failure Secondary Turbine Damage	Temperature (F)(T) Optical (G)(D) Loads (F)(T)	Thermocouple, RTD, Pyrometer Strain Gages	Borescope	Same as above.
Nonconcentric LOX Posts -thermal distortion-	7	High Local Mixture Ratio	Temperature (F)(T) Optical (G)(D)	Thermocouple, RTD, Pyrometer	?	Some sort of quick optical method to check concentricity should be possible.
Missing or Extra Support Pin -installation-	6	Nonconcentric LOX Posts	Optical (G)(D) Weight (G)(D)		Borescope	Better QC is necessary because this failure could be the major cause of the above failure modes.
Contamination -unknown-	9	Erosion or Plugged Posts	Optical (G)(D) Temperature (F)(T)	Thermocouple, RTD, Pyrometer	Borescope	This is another cause of temperature imbalance types of failures. There is not much that can be done to directly measure inflight.

COMPONENT A700--OXIDIZER PREBURNER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
LOX Post and Liner Erosion -fuel annulus contamination-	9	Preburner and HPOTP Damage	Temperature (F)(T) Optical (G)(D) Worn Particles (?)(D)	Thermocouple, RTD, Pyrometer	Borescope ?	Problems in the oxidizer preburner are very infrequent, probably due to lower temperature than the fuel preburner. May not require inflight attention, although temperature health monitoring might be helpful since the chances of any failure damaging the heat exchanger coil is great.
LOX Post Cracking -hot-gas recirculation-	9	Piece Part Failure Secondary HE or Turbine Damage	Temperature (F)(T) Optical (G)(D)	Thermocouple, RTD, Pyrometer	Borescope	Same as above.

COMPONENT B200--HIGH PRESSURE FUEL TURBOPUMP

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Turbine Blade & Platform Erosion -transient temperatures- -asi temperature-	6	Performance Degradation Turbine Blade Failure Secondary Failure	Temperature (F)(T) Optical (G)(D) Performance (F)(D) Worn Particles (G)(D)	Thermocouple, RTD, Pyrometer Various Isotope Wear	 Borescope Isotope Tracer	Present instruments may be sensitive to this failure mode with the correct processing to extract the correct performance criteria. The possibility exists of using the isotope wear method to detect erosion. ID: 21b, 22b
First Stage Vane Erosion -fpb malfunction- -high, low cycle fatigue-	7	Performance Degradation Pump Damage	Vibration (F)(T) Temperature (F)(T) Optical (G)(D) Worn Particles (G)(D)	Accelerometer Thermocouple, RTD Isotope Wear	 Borescope Isotope Tracer	The same measuring criteria apply to this failure mode as to the turbine erosion failure mode. Also, vibration and temperature trending may be applicable. ID: 3b
G-5 Joint Erosion -slag in fuel annulus-	6	Bellows Joint Leak Engine Fire	Temperature (F)(T) Performance (F)(D)(T) Optical (G)(D) Leak Tests (G)(D) Worn Particles (G)(D)	Thermocouple, RTD, Pyrometer Various Isotope Wear	 Borescope, NDT Various Isotope Tracer	Using performance measurement parameters to trend this type of failure is possible. Waiting to detect a leak may be too late. Various NDT ground inspection techniques are possible including a new eddy current device that can measure the wall thickness. ID: 29a
Cracked Seals -high-cycle fatigue-	6	Turbopump Vibration High Break Torque	Vibration (F)(D)(T) Acoustic (B)(D) Performance (F)(D)	Accelerometer, Ultrasonic Doppler AE, Ultrasonic Doppler Various		Ultrasonic Doppler transducer may be more sensitive to shaft vibration than the conventional housing accelerometers. This might provide earlier and more reliable

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Cracked Seals (continued)			Break Torque (G)(D)		Torquemeter	engine cutoff while possibly distinguishing failure modes. AE would be hard to apply, but a combination of performance criteria may help. ID: 10a,11a,12a,13a,14a,15a, 16a,17a,18a,26a
Turbine Blade Shank Cracks -low-cycle fatigue-	9	Blade Failure Secondary Failure	Acoustic (F)(D) Vibration (F)(T) Temperature (F)(T) Optical (G)(D)	Acoustic Emission Accelerometer Pyrometer	Borescope	Blade cracking is hard to detect in service. This is where R&D is needed. Presently, two methods are being tried, pyrometer and AE. AE needs to be telemetried off the shaft and the pyrometer attempts to correlate an increase in blade temperature with cracking. ID: 21a,22a
Sheetmetal Cracks -fitup & weld variations- -secondary failures- -full power levels- -strength problems-	8	Hot-Gas Leak	Vibration (F)(T) Acoustic (F)(D) Optical (G)(D) Loads (F)(T)	Accelerometer Acoustic Emissions Strain Gages, Accelerometer	Borescope	AE might be possible for crack detection, but probably not a cost-effective method. A method using trending of vibration levels might give enough information to set inspection periods based on need. Strain gages might be useful to determine the load history and fatigue life. ID: 28a
Strut & Post Cracks -high-cycle fatigue- -fitup & weld	6	Sheetmetal, Bellows Failure	Vibration (F)(T) Acoustic (F)(D) Optical (G)(D)	Accelerometer Acoustic Emission	Borescope	Same as sheetmetal cracks. ID: 28a

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
variations-			Loads (F)(T)	Strain Gages, Accelerometer		
Inlet Duct Cracks -high-cycle fatigue-	9	Fuel Leak	Vibration (F)(T) Acoustic (F)(D) Optical (G)(D) Loads (F)(T)	Accelerometer Acoustic Emission Strain Gages, Accelerometer	Borescope	This may also be a good candidate for trending the vibration levels. Strain gages for trending stresses would be helpful. AE crack detection probably is not warranted for such an infrequent failure. ID: 2b
Bellows Shield Cracks -high-cycle fatigue- -machining- -OPEN-	7	Hot-Gas Leak	Vibration (F)(T) Acoustic (F)(D) Optical (G)(D) Loads (F)(T)	Accelerometer Acoustic Emission Strain gages, Accelerometer	Visual, NDT	Same as the inlet duct and the sheetmetal cracking. ID: 28a
T/A Manifold Cracks -thermal gradients-	9	Fuel Leak	Temperature (F)(T) Acoustic (F)(D) Optical (G)(D)	Thermocouple, RTD Acoustic Emission	Visual, NDT	Temperature information for trending may be possible, and as in the previous cases the use of AE crack detection may not be warranted. ID: 9b
Bearing Bail Dry Lube Cracks -overheat-	9	Bearing Wear	Temperature (F)(T) Optical (G)(D) Acoustic (B)(D)	Thermocouple, RTD Acoustic Emission	Borescope Acoustic Pickup	A method for monitoring bearing coolant temperature would be a good indicator of of bearing health. ID: 35b, 38b,44b,47b
Turbine End Ring Cracks -fitup & weld variations	9	Hot-Gas Leak	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Borescope	Another cracking problem that would not warrant use of AE. ID: 28a

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Bearing Support Cracks -joint strength-	10	Turbopump Vibrations	Vibrations (F)(T) Acoustic (F)(D) Optical (G)(D)	Accelerometer, Deflectometer AE, Ultrasonic Doppler	Borescope	The ultrasonic Doppler Transducer might be sensitive enough to detect structural weakening of the supports. This transducer may be sensitive to several types of failures which would be better than using several failure specific devices. ID: 54b
Coolie Cap Nut Cracks -asi temperature-	6	Hot-Gas Leak into Pump Turbopump Destruction	Temperature (F)(T) Optical (G)(D)	Thermocouple, RTD, Pyrometer	Borescope	With ASI temperature monitoring or temperature upstream of the Coolie nut, the failure mode can be trended. ID: 28a
Liftoff Seal Leaks -contamination-	7	Pre- or Post-Flight Fuel Leak into Hot-Gas Manifold	Leak Test (G)(D) Temperature (F)(D)	Thermocouple, RTD	Various	A temperature sensor on the turbine side of the liftoff seal could probably detect the leakage. ID: 18a
Broken Seals -thermal stress- -unknown-	6	Engine Damage Possible Engine Destruction	Vibration (F)(D)(T) Temperature (F)(T) RPM Falloff (F)(D) Acoustic (F)(D) Torque (G)(D) Worn Particles (B)(D) Leak Test (G)(D)	Accelerometer Thermocouple, RTD Noncontact Displacement Probe AE, Ultrasonic Doppler Isotope Wear	Torquemeter Isotope Tracer Various	A combination of vibration and temperature measurements along with RPM measurement, the failure may be trended and detected. ID: 10a,11a, 12a,13a,14a,15a,16a,17a,18a 26a
Broken Turbine Blades -contamination-	5	Secondary Failure High	Vibration (F)(D) Acoustic (F)(D)	Accelerometer AE, Ultrasonic		Same as turbine blade shank cracks. ID: 21a,22a

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
		Turbopump Vibrations	Performance (F)(D) Optical (G)(D)	Doppler Various	Borescope	If the failure was a secondary impact failure, then a transient impact vibration signal could be picked up, upstream temperature could be used for trending temperature related stresses. AE might pick up a crack propagating at a high rate. ID: 3c
Vane Failure -unknown-	7	Secondary Failure	Vibration (F)(D) Temperature (F)(T) Acoustic (F)(D) Optical (G)(D)	Accelerometer Thermocouple, RTD Acoustic Emission	Borescope	
Diffuser Failure -interference fit-	5	Secondary Failure High Turbopump Vibrations Engine Destruction	Vibration (F)(D) Acoustic (F)(D) Optical (G)(D)	Accelerometer AE, Ultrasonic Doppler	Borescope	Ultrasonic doppler transducer should be very sensitive to rubbing vibration signatures. Other vibration detecting techniques are applicable for this failure mode. ID: 5b,7b
Inlet Failure -cavitation-	5	Secondary Failure Fuel Leak	Vibration (F)(D)(T) Acoustic (F)(D) Performance (F)(D) Optical (G)(D)	Accelerometer AE, Ultrasonic Doppler Various	Visual, NDT	Vibration measurements might distinguish and trend cavitation, especially the ultrasonic doppler transducer. ID: 3a
Burnt Vane -Secondary Failure	9	Local Turbopump Damage	Optical (G)(D) Temperature (F)(D) Performance (F)(T) Worn Particles (G)(D)	Thermocouple, RTD Various Isotope Wear	Borescope Isotope Tracer	Detection of temperature transients may be the only valid trending or detection measurement. ID: 3c

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Bearing Ball Wear -unknown-	9	Bearing Failure Engine Destruction	Vibration (F)(D)(T) Acoustic (B)(D) Optical (G)(D) Shaft Travel (G)(D) Worn Particles (B)(D) RPM (F)(T)	Accelerometer, AE, Ultrasonic Doppler Isotope Wear Noncontact Displacement Probe	Acoustic Pickup Borescope Deflection Isotope Tracer	High frequency, local measurements may be necessary for acceptable detection lead time to catastrophic failure. Not as important as on oxidizer pump. Isotope wear method excellent for wear but not for cracking or pitting. Ultrasonic Doppler may or may not give the high frequency information needed for detection. ID: 35a,38a,44a,47a
Contamination -installation error- -unknown-	5	Piece Part Failure Performance Degradation	Vibration (F)(D) Optical (G)(D) Performance (F)(D)	Accelerometer Various	Borescope	Unless some performance parameter is affected, inflight detection of general contamination would be very difficult.
Vane Gouged -secondary failure- -OPEN	9	Broken Vane Impeller Failure	Vibration (F)(D) Optical (G)(D)	Accelerometer	Borescope	Detection of the transient impact by vibration sensor would be the best indicator. ID: 3c
Nickel Insulation Damage -unknown-	3	Leak Possible Fire	Temperature (F)(D) Acoustic (F)(D) Optical (G)(D)	Thermocouple, RTD Acoustic Emission	Visual	Measurement of cracking with AE sensor may be difficult. Local thermal measurements might be the only inflight measurements possible. May require ground inspection.
T/A Manifold Damage -weld failure-	6	Fuel Leak	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Visual, NDT	Structural integrity monitoring and factory

COMPONENT B200--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
			Performance (F)(D)	Various		inspections may need to be improved. AE sensing in flight would be very difficult, but waiting to detect when leaking might be too late. ID: 9b
Missing Locking Pins -asi temperature	6	Loose Bolts	Temperature (F)(T) Optical (G)(D) Vibration (F)(D)	Thermocouple, RTD Accelerometer	Borescope	Detecting the transient asi temperature rise might be the only way to trend this type of failure. Detection of loose fasteners by measuring vibration might be possible. ID: 54b
Missing Shield Nuts & Washers -unknown-	4	Loose Bolts	Vibration (F)(D) Torque (G)(T) Optical (G)(D)	Accelerometer, Ultrasonic Doppler	Torquemeter Visual	Vibration measurement methods might be possible. ID: 54b
Missing Discharge Nut & Lug -OPEN	8	Fuel Leak	Optical (G)(D) Torque (G)(T) Vibration (F)(D)	Accelerometer	Visual Torquemeter	Same as above. ID: 53b
High Vibration Levels -low suction, cavitation-	5	Turbopump Damage	Vibration (F)(D) Performance (F)(D) Flow (F)(D)	Accelerometer, Ultrasonic Doppler Various		Ultrasonic Doppler transducer may be very sensitive to a cavitation induced signal. ID: 1a
Excessive Shaft Travel -balance piston wear- -unknown-	7	Turbopump Damage	Axial Force (F)(T) Displacement (B)(D) Vibration (F)(D) Worn Particles (B)(D)	Strain Gage, Force Transducer Non-contact Displacement Probe Accelerometer Isotope Wear	Displacement Isotope Tracer	A method that measures and stores the maximum axial excursion during flight would be good. Isotope wear could detect balance piston wear. ID: 55a

COMPONENT B400--HIGH OXIDIZER TURBOPUMP

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Bearing Ball and Race -transient axial loads- -bearing loading- -vibration- -OPEN-	2	Bearing Failure Engine Destruction	Vibration (F)(T)(D) Acoustic (F)(G)(D) Optical (G)(D) Loads (F)(T) Shaft Travel (G)(D) Worn Particles (G)(F)(D) RPM (F)(D) Magnetic (B)(T)(D)	Accelerometer, Deflectometer AE, Ultrasonic Doppler Strain Gages, Accelerometer Isotope Wear Noncontact Displacement Probe Ball-Pass Indicator	Same Acoustic Probe Borescope Deflection Isotope Tracer Ball-Pass Indicator	High frequency, local measurements may be necessary to discriminate signal from background inflight, especially for trend information. Imminent failure may not be detected in time by a gross acceleration measurement. Using a magnetic flux pickup to determine the ball speed around the race could easily detect wear. Isotope wear detection will trend wear, but not pitting or cracks. Important to monitor inflight for engine safety. ID: 7-18a,b
Bearing Support Wear and Spring Lands Wear -bearing loading-	8	Bearing Wear Bearing Failure Engine Destruction	Vibration (F)(T)(D) Acoustic (F)(G)(D) Optical (G)(D) Loads (F)(T) Shaft Travel (G)(D) Worn Particles (G)(D)	Accelerometer, Deflectometer Acoustic Emission Strain Gages, Accelerometer	Same Acoustic Probe Borescope Deflection Isotope Tracer	This failure mode may be discriminated from bearing wear and pitting by its frequency content using the same transducer. This failure mode is much less of problem than bearing wear. A single sensor might be used for several failure modes based on their individual frequency content or a combination of measurements might be used for one failure mode (expert system). ID: 19a

COMPONENT B400--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Nozzle Vane Cracks -Casting defects-	8	Broken Vane Secondary Failure	Acoustic (F)(D) Optical (G)(D) Loads (F)(T)	Acoustic Emission Strain Gage, Accelerometer	Borescope	This type of failure mode may be very difficult to monitor directly with AE. Preliminary NDT inspection quality insurance is important since direct monitoring is so difficult. ID: 3c
Strut Cracks -unknown-	9	Sheetmetal, Bellows Failure (unlikely)	Acoustic (F)(D) Optical (G)(D) Loads (F)(T)	Acoustic Emission Strain Gage, Accelerometer	Borescope	This type of failure mode may not be worth monitoring directly, but use stress-time analysis to trend the fatigue. AE might detect a reasonable size leak. ID: 39a
Turbine Blade Cracks -high-cycle fatigue-	5	Blade Failure Secondary Failure	Acoustic (F)(D) Vibration (F)(T) Temperature (F)(T) Optical (G)(D)	Acoustic Emissions Accelerometer Pyrometer, Thermocouple	Borescope	AE crack detection is possible if transducer is in shaft or rotor hub necessitating a telemetry system. Stress-time analysis for for trending could reduce frequency of tear-downs and inspections. ID: 29,30a
Housing Cracks -high-cycle fatigue-	6	Turbopump Failure Engine Destruction	Vibration (F)(T) Acoustic (F)(D) Optical (G)(D)	Accelerometer Acoustic Emission	Visual, Various NDT	A good candidate for stress-time analysis using vibration data to determine life of the pump housing. Presently using design criteria and service time to establish limits. ID: 45a
Sheetmetal Cracks -unknown-	9	Hot-gas Leak	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Borescope	Similar situation to strut cracks. Probably just stress

COMPONENT B400--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
			Loads (F)(T)	Strain Gage, Accelerometer		relief cracks. ID: 39a
Strut Erosion -leaky opov-	10	Sheetmetal Failure	Temperature (F)(T) Worn Particles (G)(D)	Pyrometer, Thermo-couple	Isotope Tracer	Minor problem that probably should be dealt with using upstream and downstream system parameters to indicate likely strut, turbine or sheetmetal erosion. ID: 39b
Liner Erosion -OPEN-	9	Piece Part Failure (unlikely)	Temperature (F)(T) Worn Particles (G)(D)	Pyrometer, Thermo-couple	Isotope Tracer	Same as strut erosion. ID: 31,32b
Contamination -in bearing cage- -unknown- -assembly error-	6	Performance Degraded Bearing Problems Blocked Coolant & Lubrication Passages	Optical (G)(D) Vibrations (F)(D) Performance (F)(T)	Accelerometer Various	Borescope	Keeping various performance criteria within safe limits is important (ie., temp, vib, flow, press). Problem in in determining failure from upstream component piece part failures, maybe some vibration impact detection.
Turbine Blade -bad gold plating-	8	Performance Degraded Blade cracks	Optical (G)(D) Performance (F)(T)	Various	Borescope	Monitor turbine performance criteria. ID: 29,30b
Bearing Cage Delamination -fluid environment- -bearing loading- -OPEN-	5	Bearing wear, pitting	Vibration (F)(T) Optical (G)(D) Acoustic (F)(G)(D) Worn Particles (G)(D)	Accelerometer, Deflectometer Acoustic Emission	Borescope Acoustic Probe Isotope Tracer	Check for same basic signals as in bearing wear. ID: 7-18,b
Turbine Disk Rubbing -high thrust loads-	9	Turbine Failure (unlikely)	Vibration (F)(D) Loads (F)(T)	Accelerometer Strain Gage,		General accelerometer measurements in a particular

COMPONENT B400--(Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
			Acoustic (G)(D) Optical (G)(D)	Accelerometer	Acoustic Probe Borescope	frequency range might detect various parts and seals rubbing. High thrust loads can be detected by any axial acceleration measurement. ID: 27a
Strut Damage -assembly-	8	Sheetmetal or Bellows Failure, Leak	Acoustic (F)(D) Vibration (F)(D) Optical (G)(D) Performance (F)(T)	Acoustic Emission Accelerometer Various	Borescope	AE could detect a leak and vibration measurement might detect a structural defect. Performance parameters might help in trending a more serious failure. ID: 39a
Shaft Travel* -bearing loading-	9	Bearing Wear	Shaft Travel (G)(D)		Deflection	Accurate shaft travel and torque measurements can indicate a lot about condition of bearings and support. ID: 7-18a,b
Subsynchronous and Synchronous Vibration Levels* -bearing loading-	1	Bearing Failure Engine Destruction	Vibration (F)(D)	Accelerometer Ultrasonic Doppler		It is important that the pump is balanced and not running near the second critical. The pump may or may not be shut down in time when detected. ID: 1b
High Shaft Break Torque	6	Broken Seals, Parts	Torque (G)(D)		Torquemeter	Other parameters (ie. vib) could indicate rubbing problems to reduce between flight inspections. ID: 2b,21a,27a,29c,30c, 35a,40-43a

COMPONENT B600--LOW PRESSURE FUEL TURBOPUMP

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Insulation Cracks, Rupture -moisture entry- -engine generated-	8	Turbopump Damage	Moisture (G)(D) Optical (G)(D) Acoustic (F)(D)	Acoustic Emission	Visual, NDT	This failure mode is fairly straight forward to detect on ground, but very difficult inflight unless some performance parameter becomes affected.
Contamination -inadequate cleaning-	9	Performance Degradation Piece Part Failure	Optical (G)(D)		Borescope	Unless the performance is affected, there is not much that can be done inflight.
Excessive Torque* -excess copper plate-	7	Performance Degradation Vibration	Torque (G)(D) Vibration (F)(D) Performance (F)(D)	Accelerometer, Ultrasonic Doppler Various	Torquemeter	Vibration data with the right signal processing should detect rubbing.

COMPONENT B800--LOW PRESSURE FUEL TURBOPUMP

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Bearing Ball Wear -high axial load-	6	Turbopump Vibration	Vibration (F)(T)(D) Optical (G)(D) Loads (F)(T) Magnetic(B)(T)(D) Shaft Travel (G)(D) Worn Particle (B)(D) RPM(F)(T)	Accelerometer, Deflectometer Strain Gages, Accelerometer Ball-Pass Indicator Isotope Wear Noncontact Displacement Probe	Borescope Ball-Pass Indicator Deflection Isotope Tracer	High frequency, local measurements may be neccessary to discriminate signal from a background inflight. Using a magnetic pickup to determine the ball speed around the race could be an easy way of detecting wear. A gross accelerometer measurement may not detect the imminent catastrophic failure in time. Isotope wear is a good measurement technique for trending wear but will not detect cracks or pitting.
Stator Ding -OPEN-	10	Turbine Blade or Sheetmetal Damage	Optical (G)(D) Vibration (F)(D)	Accelerometer	Borescope	Impact signals from secondary failures could be picked up by an accelerometer to alert maintenance of possible damage.
Flange Surface Undercut -misalignment-	9	Hot-Gas Leak	Optical (G)(D)		Visual	This should be addressed as a quality control, assembly problems.
Contamination -shop debris- -unknown- -glove fragments in bearings-	6	Piece Part Damage Bearing Failure	Vibration (F)(D) Optical (G)(D) Torque (G)(D)	Accelerometer, Deflectometer	Borescope Torquemeter	Shop debris, etc. should not get into the pump, needs better QC.

COMPONENT B800--LOW PRESSURE FUEL TURBOPUMP (Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
High Break Torque* -bearing cage friction-	7	Bearing Ball Wear	Vibration (F)(D) Torque (G)(D) Acoustic (G)(D)	Accelerometer, Deflectometer	Torquemeter Acoustic Probe	The vibration spectrum might be distinguishable for this failure mode.

COMPONENT C100, C270--CHECK VALVES, PRESSURE ACTIVATED VALVES

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Check Valve Leaks -dry lube for bolts- -contamination- -sticky poppet- -poppet bore -interference-	5	Burst Diaphragm Rupture Engine Fails to Shutdown	Pressure (F)(D) Leak Test (G)(D) Acoustic (F)(D) Performance (F)(D)	Pressure Sensor Acoustic Emission Various	Various	Leakage may be detected by an AE transducer on the valve. Other parameters affected by the leak could also detect leakage inflight.
HPOT Purge PAV Leak -inlet seat distorted-	6	?	Pressure (F)(D) Leak Test (G)(D) Acoustic (F)(D) Performance (F)(D)	Pressure Sensor Acoustic Emission Various	Various	Same as above.

COMPONENT D100 - D150--MFV, MOV, FPOV, OPOV, CCV

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Ball Seal Leaks -contamination- -deformed bellows- -asi combustion	5-9	Burst Diaphragm Rupture Engine Fails To Shut-down Possible Engine Fire	Temperature (F)(T) Leak Test (G)(D) Acoustic (F)(D) Pressure (F)(D) Performance (F)(D)	Thermocouple, RTD Acoustic Emission Pressure Sensor Various	Various	Detecting leakage using an acoustic emission sensor may be possible. Basic performance parameters sensitive to leakage may be monitored.
Excessive Pressure -?-	9	Valve Damage	Pressure (F)(D)	Pressure Sensor		A pressure sensor which may be good for any other failure modes could a good choice if it is necessary to monitor this failure mode.
Internal Leak -contamination-	9	Burst Diaphragm Rupture	Leak Test (G)(T) Acoustic (F)(D) Performance (F)(D)	Acoustic Emission Various	Various	Same as ball seal leakage.
Contamination -unknown-	10	Valve Leakage	Optical (G)(D) Flow (F)(D) Pressure (F)(D)	Flowmeter Pressure Sensor	Disassembly	Cannot directly monitor, but detect valve problems caused by the contaminant.
Low Flow Rate -stretch bolt assembly error-	8	Performance Degradation	Flow (F)(D) Torque (G)(D) Pressure (F)(D)	Flowmeter Pressure Sensor	Torquemeter	A flow or pressure measurement ought to pick up this failure mode. An optical method of determining bolt torque would be helpful for maintenance efficiency.
Studs Overtorqued -improper tool-	9	Low Flow Rate	Torque (G)(D) Flow (F)(D) Pressure (F)(D)	Flowmeter Pressure Sensor	Torquemeter	Same as above for bolt torque.

COMPONENT D300, D500, D600--ANTIFLOOD, GOX CONTROL AND RECIRCULATION ISOLATION VALVES

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
LVDT Signal Erratic -broken wire- -vibration induced- -installation error- -OPEN-	8-10	Engine Ready Inhibit Possible Engine Shutdown	Vibration (F)(T) Self-test (F)(D)	Accelerometer		More reliable transducers and cabling might be necessary. Also, self-test and calibrating transducers are possible that are possible that would give more confidence in the signal.
Cracked Poppet -handling- -OPEN-	4	Engine Shutdown or Delay Possible Engine Fire or Explosion	Acoustic (F)(T) Optical (G)(D)	Acoustic Emission	Disassembly, NDT	This failure mode could be very dangerous so early detection is a must. Acoustic emission for crack detection inflight might be possible. Some sort of nonintrusive NDT technique might be possible.
Poppet Remained Open -?-	8	Engine Start Delay	LVDT Signal (F)(D) Performance (F)(D)	LVDT Output Pressure, Flow, Temp.		This failure should be detectable.
Contamination -tapping debris- -unknown-	10	Stuck Valve Valve Leakage	Performance (F)(D)	Pressure, Flow Temp.		Contamination is hard to detect unless it causes a more detectable failure mode to occur.
Leak is 60X Valve -unknown-	10	Oxidizer in Aft Compartment	Acoustic (F)(D) Performance (F)(D) Leak Test (G)(D)	Acoustic Emission Pressure, Flow, Temp.	Various	May be possible to detect inflight with the correct downstream performance information or possibly with AE.
Leak is Port 024.1 -defective seal-	9	?	Acoustic (F)(D) Performance (F)(D) Leak Test (G)(D)	Acoustic Emission Pressure, Flow, Temp.	Various	Same as above.

COMPONENT F800--FASCOS HEATER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
FID? -signal conditioning module short- -accelerometer resonance- -unknown-	5	Possible Controller Circuit Damage	Signal (F)(D) Vibrations (F)(T)	Signal output Accelerometer		The most frequent cause was an accelerometer mount which should be corrected.
Chaffed Wires -poor routing-	10	Electrical Problems	Optical (G)(D) Signal (F)(D)	Signal output	Visual	Better wire handling and routing at installation for this failure mode.

COMPONENT G000--IGNITER

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Igniter Tip Erosion Ceramic Flaking -off-normal combustion-	6	Low MCC Pressure Limit Shutdown Possible Hardware Damage	Temperature (F)(T) Optical (G)(D) Signal (F)(D) Pressure (F)(D)	Thermocouple, RTD Spark Monitor Signal Pressure Sensor	Borescope, Disassembly	This failure mode is somewhat protected from causing major damage by MCC pressure caused shutdown. A spark strength monitor should show igniter tip degradation.
Electrical Problems, Bad Output -moisture on tip- -damage- -unknown- -off-normal combustion -potting void-	7	Bad Spark Low MCC Pressure Limit Shutdown Possible Hardware Damage	Temperature (F)(T) Optical (G)(D) Pressure (F)(D) Signal (F)(D)	Thermocouple, RTD Pressure Sensor Spark Monitor Signal	Borescope, Disassembly	This is not a slowly progressive failure mode and can be an intermittent type of failure, which is hard to trace.
Low Insulation Resistance -unknown-	8	Electrical Problems	Electrical (G)(D)		Resistance Check	This is not important to check inflight.

COMPONENT H000 - H002--ELECTRICAL HARNESSES

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Birdcaged Harness -handling damage-	6	Possible Engine Firing Delay Possible Engine Shutdown	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	The electrical wiring failures can be difficult to pin down since they can be intermittent. Continuity checks may not find failures so great care has to be taken installation.
Broken Groundwire Lug Backshell, Wire -handling- -bad cleaning-	6	Possible Engine Firing Delay Possible Engine Shutdown	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	Same as above.
Loose Connector -improper torque- -installation error- -unknown- -OPEN-	8	Possible Engine Firing Delay Possible Engine Shutdown	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	Same as above.
Defective Connector -pinhole misplaced- -contamination-	8	Possible Engine Firing Delay Possible Engine Shutdown	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	Same as above.
Insulation Resistance Low -moisture-	10	Wire Short, Open Circuit	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	Same as above.
Debonded Torque Lack -contamination- -inadequate cleaning- -surface preparation-	4	Loose Connector	Torque (G)(D) Optical (G)(D)		Torquemeter Visual	Inspection of the torque lacks between flights may be necessary.
Open or Short Circuit -handling- -OPEN-	8	Possible Engine Firing Delay Possible Engine Shutdown	Electrical (B)(D) Optical (G)(D)	Continuity	Continuity Visual	Same as broken wire, etc.

COMPONENT J200, J300, J600, J800--SENSORS

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Output Failure and Drift (all) -wire and sensor- -thermal- -cold- -input capacitance- -unknown- -coax cable fracture-	4-8	Loss of Measurement	Temperature (F)(T) Electrical (B)(D)	Thermocouple, RTD Continuity, Self-calibration	Continuity	Self-calibration and or self-checking ability in the sensors should be achievable. A "third wire" could be used for the calibration signal and low amp circuitry could be used. Transducers and associated wiring must be made more rugged if they are to be counted on for diagnostics and be the cause of reliability problems.
Sensor Debonding (Temp.) -handling damage-	4	Secondary Damage	Electrical (B)(D) Optical (G)(D) Acoustic (F)(D)	Noise level, Continuity Acoustic Emission	Noise Level, Continuity Visual	More care needed in mounting transducers.
Bent Pin (Pressure) -handling-	8	Bad Electrical Connection	Optical (G)(D)		Visual	Same as above.
Output Resistance Low -supplier data mistake-	7-9	Noisy Signal	Electrical (B)(D)	Noise level	Resistance	Check out transducers when when received.
Broken Sensor Tip (Temp.) -vibration fatigue-	7	Bad Reading Secondary	Electrical (B)(D) Optical (G)(D)	Self-calibration Visual	Calibration	More rugged transducer or better mounting scheme.
Missing Dielectric Insert -unknown-	9	Faulty Transducer	Electrical (B)(D) Optical (G)(D)	Noise Level	Noise Level Visual	Check Transducer carefully when received.

COMPONENT K100--FUEL LINE DUCT

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Leak in Duct -defective seal- -OPEN (joint leak)- -unknown-	7	Fuel Leak Possible Engine Damage	Acoustic (F)(D) Pressure (F)(D) Leak Test (G)(D) Flow (F)(D) Performance (F)(D)	Acoustic Emission Pressure Sensor Flowmeter Various (HPFTP)	Various	Many system parameters that may already be measured may pinpoint this failure, especially just downstream of the duct. Leak detection by acoustic emission may be possible, but not highly probable.
Joint Overmold Debonded or Joint Boot Tear -improper adhesive- -unknown-	8 9	Joint Damage Fuel Leak	Optical (G)(D) Acoustic (F)(D)	Acoustic Emission	Visual	These failure modes may only need a quick visual ground inspection.
Broken Burst Diaphragm -vibration- -handling-	7	Fuel Leak	Pressure (F)(D) Vibration (F)(T) Flow (F)(D) Leak Test (G)(D)	Pressure Sensor Accelerometer Flowmeter	Various	This failure should be easily detectable inflight by pressure reading or some combination system parameters.
Nickel Insulation Cracks -unknown-	9	Liquid Air Drips	Temperature (F)(D) Acoustic (F)(D) Optical (G)(D)	Thermocouple, Pyrometer Acoustic Emission	Visual, NDT	This failure mode should only need a quick ground inspection.
Seal Cracks -machining-	9	Joint Leak	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	NDT	This failure mode will probably not be detectable inflight until a leak occurs unless acoustic emission can detect the crack signal.
Weld Cracks -improper weld techniques-	7	Bellows Rupture Aft Compartment Overpressure	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Dye Penetrant, NDT	Same as above.

COMPONENT K100--FUEL LINE DUCT (Continued)

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Tolerance Problems -seal groove undersized- -joint tolerance stackup-	8	Joint Leak	Optical (G)(D)		Dimension Measurement	Can only be detected on ground at assembly.
Frost on Bellows -OPEN-	10	?	Temperature (F)(D)	Thermocouple, Pyrometer		Temperature measurement should detect this failure.

COMPONENT K200--OXIDIZER LINE DUCTS

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Cracks in Duct -seamweld cracking- -OPEN-	7	Duct Leak Oxidizer in Aft Compartment Engine Fails to Shutdown	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Visual, NDT	This failure mode will be probably be undetectable until a leak develop unless acoustic emission could detect the cracking.
Support Link Crack -flex joint backwards-	9	Joint Leak	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Visual, NDT	Same as above.
Duct Wear -handling-	10	Duct Leak	Optical (G)(D)		Visual	This failure should never get to a test cell or launching pad.
Contamination -unknown- -bolts stripped-	7	Possible Leak or Fire	Optical (G)(D)		Disassembly	Contamination is hard to detect unless it causes a more detectable failure like leaks.
Impression Marks on Ring -installation-	9	Possible Leak	Optical (G)(D)		Visual, NDT	Another failure mode difficult to detect inflight.

COMPONENT K300--OXIDIZER LINE DUCTS

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Misaligned Joint -unknown-	10	Leakage	Optical (G)(D)		Visual	The effect of any leakage is minimal, this failure mode is fairly unimportant and requires infrequent ground inspection.
Contamination -unknown-	10	Leakage Blockage-High Pressure	Optical (G)(D) Pressure (F)(D)	Pressure Sensor	Disassembly	Same as above.

COMPONENT K200--PNEUMATIC HOSE/LINE

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Kink, Twisted or Compressed -unknown-	8	Reduced Helium	Pressure (F)(D) Flow (F)(D) Optical (G)(D)	Pressure Sensor Flowmeter	Visual	If helium flow is reduced to HPOTP shaft seal it will be detected and there is no need for additional diagnostics, maybe a better design to reduce the problem.
Joint and Seal Contamination- -unknown-	9	Helium Leak Reduced Helium Flow	Optical (G)(D) Pressure (F)(D) Flow (F)(D)	Pressure Sensor Flowmeter	Disassembly	Same as above for the helium flow.

COMPONENT LOOO--STATIC SEAL

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Delamination, Chatter Marks and Other Damage -came loose- -unknown- -housing moved radially-	6	Joint Leak Engine Start Delay Possible Fire Fluid in Aft Compartment	Acoustic (F)(D) Vibration (F)(T) Optical (G)(D)	Acoustic Emission Accelerometer	Disassembly	Acoustic emission for leak detection may be possible, but more than likely a optimized ground inspection routine is necessary including the checking of bolt torque.
Seal Protrusion -unknown-	8	Possible Joint Leak	Optical (G)(D)		Disassembly	This would only be picked up in ground inspection.

COMPONENT L200--STRETCH BOLTS

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Loose Bolts -installation overload-	9	Leaks or Vibration	Vibration (F)(D) Optical (B)(D) Torque (G)(D)	Accelerometer ?	Visual Torquemeter	Some method of optically detecting alignment marks to tell if the bolt are loose, either ground or flight would be helpful. Vibration data might help detect loose bolts.

COMPONENT MOOO--GIMBAL

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Block and Body Wear, Fretting -interference- -vibration-	7	Gimbal Failure Loss of Engine	Vibration (F)(T) Actuator Force (F)(T) Optical (G)(D)	Accelerometer Load Cell, Actuator Pressure	Visual, NDT	Actuator force monitoring would be an easy way to detect either a sticky gimbal or a loose one.
Crack in Bushing -material ductility-	7	Gimbal Failure Loss of Engine	Acoustic (F)(D) Optical (G)(D)	Acoustic Emission	Visual, NDT	AE might detect cracking, but ground inspection is probably necessary.

COMPONENT N600--LEE JET ORIFICE

Failure Mode -Causes-	Rank	Effect	Measurable Parameters	Inflight Measurements	Between Flight Measurements	Comments
Deformed Orifice -hydrogen and oxygen ignition-	7	?	Temperature (F)(T) Optical (G)(D) Performance (F)(D)	Thermocouple, RTD Various	 Visual	Monitoring the temperature would be the easiest inflight measurement.
Tolerances -installation-	9	?	Optical (G)(D)		Dimensions	
Low Torque -installation-	10	?	Torque (G)(D) Optical (B)(D)	?	Torquemeter Visual	A method of optically determ-ining bolt alignment for correct torque would be helpful.

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