SSME 0523

TEST 902-772

FAILURE INVESTIGATION

FINAL REPORT

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1.0 Transmittal Letter

EP01 - TBD

TO:	NASA Headquarters Attn.: M/Associate Administrator for Space Flight
THRU:	Marshall Space Flight Center Attn.: DA01/Director
FROM:	Marshall Space Flight Center DA01/Chairman, Space Shuttle Main Engine (SSME) 0523 Major Incident Investigation Board
SUBJECT:	Final Report, SSME 0523 Incident Investigation

In accordance with NPG8621.1H, enclosed is the final report of the Board of Investigation for the subject mishap that occurred on June 16, 2000 at Stennis Space Center.

The report consists of four volumes: (1) the report, (2) appendices, (3) proposed corrective action implementation plan, and (4) a lessons-learned summary. The principal findings of the Board, along with recommended actions, were submitted to the SSME Project Manager on August 10, 2000. These findings and the SSME Project Office's response to them are provided in Volume I, Section 13, and in Volume III, respectively, of this report.

Robert L. Sackheim
MSFC, Assistant Director for
Space Propulsion

2.0 Signature Page

This report contains the activities, investigations, findings, and recommendations of the SSME 0523 Mishap Investigation Team.

________________________	________________________
R. L. Sackheim , Chairman	M. H. Kynard, Alternate Chairman
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R. Rosen, PhD	L. J. Maddux
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M. A. Neely	M. L. Talton
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T. D. Addlesperger	T. W. Hartline
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D. M. Ray	K. P. Van Hooser
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C. L. Kotila	K. J. Breisacher

3.0 List of Members, Consultants, Advisors, and Others

The following personnel were assigned to the SSME 0523 Major Mishap Investigation Team:

MISHAP BOARD MEMBERS

R. L. Sackheim	DA01	Chairman; MSFC, Asst. Director for Space Propulsion
M. H. Kynard	MP21	Alternate Chairman; MSFC, SSME Project Office
R. Rosen, PhD	ARC	ARC, Associate Director (added 6/21/2000)
L. J. Maddux	TD31	MSFC, Engine Systems
M. L. Talton	ED33	MSFC, Materials and Processes
T. D. Addlesperger	SSC	SSC, Test Operations
D. M. Ray	TD61	MSFC, Combustion Devices
K. P. Van Hooser	TD61	MSFC, Turbomachinery
K. J. Breisacher	GRC	GRC, Propulsion (added 6/21/2000)
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H. V. McConnaughey	TD50	MSFC, Manager, Vehicle & Systems Development
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4.0 Executive Summary

Space Shuttle Main Engine (SSME) 0523 was assembled as a unique development engine for a specific series of tests. The plan for the test series was to demonstrate safe operation of the Pratt & Whitney High Pressure Fuel Turbopump (HPFTP/AT) at the High Pressure Fuel Turbine discharge temperature (HPFT DS T) redline values. The engine was in a hybrid Block I/II configuration with a standard throat Main Combustion Chamber (MCC) and a HPFTP/AT. The major objective of the first test in the series was to characterize the effects of Coolant Control Valve (CCV) position on HPFT DS T.

During the assembly of SSME 0523, Permacel P-670 (LOX) tape was introduced into the fuel system during some "hands on" process (temporary closure, contamination barrier, unintentional introduction, etc.). A list of the probable locations of introduction is discussed in Section 7.6. Despite normal processing inspections, the tape contamination went unnoticed and was left in the fuel system during the remainder of assembly and pre-test activities.

On June 16, 2000, test number 902-772 of SSME 0523 was conducted on test stand A2 at Stennis Space Center (SSC). The test was scheduled for a total duration of 200 seconds. A thrust profile of the planned test is provided in Figure 6.0-1.

At engine start, the tape contamination was forced downstream in the fuel system, eventually coming to rest as debris in both the Fuel Preburner (FPB) injector and Oxidizer Preburner (OPB) injector. The amount of debris in the FPB was sufficient to block multiple fuel inlet holes of several FPB injector elements in localized areas. This blockage caused a localized high mixture ratio area in the preburner without affecting overall engine system performance. Data analysis indicates a localized temperature increase occurred in the vicinity of HPFT DS T Channel A (flight instrumentation location) and the HPFT DS T KG2dT (ground test instrumentation location) beginning at approximately 2.7 seconds. The HPFT DS T Channel B measurement and the HPFT DS T measurement at KG2cT remained at nominal values. All other performance parameters indicated normal engine operation at this time.

The localized temperature increase caused melting of the turbine inlet housing struts and first stage vanes in the HPFTP/AT. At 4.97 seconds, all three airfoils on a first stage vane segment were melted through the chord, causing local structural failure of that segment of vanes. The inner platform of the vane segment fell into the hot gas flow stream impacting the first stage blades. This caused the first stage blades to fail creating significant HPFTP/AT rotor imbalance. Data analysis indicates that the HPFTP/AT synchronous vibration amplitudes increased sharply to levels significantly higher than nominal operation. The sharp increase in vibration levels were followed by a drop in HPFTP/AT performance and a corresponding response by the engine control system attempting to recover performance.

At 5.04 seconds, the HPFT DS T Launch Commit Criteria (LCC) was activated. At 5.08 seconds, two Failure Identifications (FID's) were issued indicating that HPFT DS T Channel A2 and HPFT DS T Channel A3 had exceeded the 1860R redline. These FID's were accompanied by a Major Component Failure (MCF) indication. The facility Command and Data Simulator (CADS) was set to respond to any MCF indication before 6.6 seconds with a command to perform engine shutdown. The CADS unit issued a shutdown command and the engine entered shutdown phase at 5.18 seconds.

The facility responded to the vibration redline violation by sending a shutdown command to the controller just after the CADS initiated shutdown. The turbine temperature and vibration levels continued to increase after shutdown.

The engine powered down nominally with the exception of the HPFTP/AT. During the shutdown transient, severe imbalance and excessive loading of the roller bearing caused it to fail. The HPFTP/AT spindown was much faster than nominal due to internal damage.

Post incident inspection of the engine revealed significant hardware damage to the HPFTP/AT with less significant damage to the powerhead and MCC. There was no facility damage and no personnel were injured. (Damaged hardware is listed and discussed in Section 7.3 and Appendices E and F.)

It was determined that there was sufficient engine damage to classify the incident as a Type A Mishap. NASA Headquarters was notified once the Type A determination was made, with a follow up message sent by SSC using the Mishap Report Form 1627 in accordance with NPG 8621.1, NASA Procedures and Guidelines for Mishap Reporting, Investigating and Recordkeeping.

The MSFC SSME Contingency Team was activated as an interim investigation board to ensure proper initial mishap actions were conducted. Both Rocketdyne and Pratt & Whitney were directed to impound all engine and facility hardware associated with the test as well as all processing paperwork. Post-test actions and inspections were restricted to minimize the possibility of disturbing evidence.

Mr. Robert Sackheim was appointed as the Mishap Investigation Board Chairman on June 21, 2000. In addition, the other Board members were appointed in accordance with NPG 8621.1 (See Volume II, Appendix B, "Directives Appointing Board").

Members of the Investigation Board traveled to SSC and inspected the engine, damaged components, and test documentation. Records of the damage and disassembly procedures were obtained. In addition, members of the investigation team traveled to Rocketdyne, Canoga Park, CA and Pratt & Whitney, West Palm Beach, FL to observe disassembly, analysis, and testing of the engine hardware. Materials analyses of contamination found in the engine were conducted and verified at the MSFC Materials Laboratory; at Rocketdyne, Canoga Park, CA; and at Pratt & Whitney, West Palm Beach, FL and East Hartford, CT.

In summary, the investigation team concluded that during the processing and assembly of SSME 0523, Permacel P-670 tape contamination was introduced into the fuel system. The tape came to rest as debris in the fuel manifold of the FPB, causing a localized high mixture ratio in the FPB. The resulting hot streak impinged on the turbine inlet housing struts and first stage vanes. A vane segment burned through and the inner section fell into the first stage blades. This caused rotor imbalance and significant turbine and pump damage.

The investigation team has the following recommendations (see Section 9.0 for a complete list of Findings, Observations, and Recommendations):

1. Verify that all systems are free of foreign object debris prior to hotfire. Limit the opportunity for contamination introduction by minimizing the use of potential contaminants and using permanent closures on joints where applicable. Keep joints closed at all times when access is not required to perform work.
2. Implement an improved method of dealing with loose, non-serialized materials to ensure full accounting. Additional inspections and checkouts should be considered to verify that the engine is contamination free prior to any hotfire.
3. The use of reusable barriers, which can be controlled and accounted for, should be investigated.
4. Provide clear instructions in processing paperwork and discrepancy paperwork. Use positive identification of engine hardware to ensure that the work is being done on the correct part.
5. Correct electronic paperwork systems to either prevent changes or provide a clear tracking of change activities. Further, ensure that all SSME documentation changes can be tracked.
6. Review both the HPFT DS T LCC and the Real Time Vibration Monitoring System (RTVMS) to determine if the current activation time and limit value are appropriate. Further, a review of all post engine start LCC's and ignition confirm limits should be performed to ensure consistency with current flight safety philosophy.
7. Although there was no finding or observation directly linking the FPB contamination issue (LOX tape) to schedule pressures, the Board recommends that the SSME program and contractor team examine SSME assembly activity scheduling to ensure a work environment exists that does not contribute to future issues and problems. In general the agency and its contractor teams need to avoid schedule practices that create undue risk.

8. SSME Project Office should understand the mechanism causing the roller bearing failure and ensure that the conditions experienced were outside the designed capability of the roller bearing.
9. SSME Project Office should investigate evidence to ensure that SSME 0523 powerhead structural properties were adequate relative to the possible existence of residual stresses. Ensure that an unacceptable condition does not exist in the flight fleet.

5.0 Method of Investigation

On Friday, June 16, 2000, a Space Shuttle Main Engine premature cutoff was reported at Stennis Space Center. Test 902-772 was terminated at approximately 5.0 seconds when a Major Component Failure (MCF) was issued because of high HPFTP/AT turbine discharge temperatures. It was determined after performing post-test inspections that there was sufficient engine damage to classify the incident as a Type A Mishap. NASA Headquarters was notified by telephone once the Type A determination was made, with a follow up message sent by SSC using the Mishap Report Form 1627 in accordance with NPG 8621.1, NASA Procedures and Guidelines for Mishap Reporting, Investigating and Recordkeeping.

The MSFC SSME Contingency Team was activated to act as an interim investigation board and ensure proper initial mishap actions were carried out. Both Rocketdyne and Pratt & Whitney were directed to impound all engine and facility hardware associated with the test as well as all processing paperwork. Post-test actions and inspections were restricted to minimize the possibility of disturbing evidence.

The MSFC Center director recommended Mr. Robert Sackheim, as the Mishap Investigation Board Chairman. On June 21, 2000, he was approved as the Chairman by Headquarters Code M. In addition, the other Board members were appointed in accordance with NPG 8621.1 (See Volume II, Appendix B, "Directives Appointing Board"). Board membership consisted of technical members from MSFC and included representatives from Ames Research Center, Glenn Research Center, Johnson Space Center, and Stennis Space Center. Headquarters Code Q appointed a Safety and Mission Assurance representative from MSFC to act as the Ex-Officio member of the Board.

The hardware was placed under the control of the Investigation Board. All actions taken against the incident hardware required approval of the Board members or their appointed representatives. Members of the Investigation Board traveled to SSC and inspected the engine, damaged components and test documentation. Photographic and videographic records of the damage and disassembly procedures were obtained. In addition, members of the investigation team traveled to Rocketdyne, Canoga Park, CA and Pratt & Whitney, West Palm Beach, FL to observe disassembly, analysis, and testing of the engine hardware. Materials analyses of contamination found in the engine were conducted and verified at the MSFC Materials Laboratory; at Rocketdyne, Canoga Park, CA, and at Pratt & Whitney, West Palm Beach, FL and East Hartford, CT.

The Board also used the following methods during the investigation:

a. Coordinated investigation activities between NASA, Rocketdyne, and Pratt & Whitney.

b. Reviewed and analyzed test and hardware data to aid in establishing the timeline of events and the failure scenario jointly between NASA, Rocketdyne, and Pratt & Whitney.

c. Created an action item list in which every item was tracked to completion to ensure investigation requirements were accomplished.

d. Conducted a Fault Tree Analysis (FTA) to ensure all possible mishap scenarios were investigated and to identify the primary cause of the failure.

e. Utilized all available analysis, including data simulation, materials analysis, thermal analysis, and dynamics analysis to aid in formulating and understanding the failure scenario.

f. Reviewed the history of other related failures and assessed the potential impact of this mishap to flight and developmental hardware.

g. Conducted team meetings to plan, status, and direct the investigation and to complete the final report.

h. Discussed the summary of findings and recommendations with the SSME Project Office and the MSFC Center Director.

6.0 Narrative Description of Mishap

On June 16, 2000, test number 902-772 was being conducted on Space Shuttle Main Engine (SSME) 0523, installed in test stand A2 at Stennis Space Center (SSC). The engine was a hybrid Block I/II configuration with a standard throat Main Combustion Chamber (MCC) and a Pratt & Whitney High Pressure Fuel Turbopump (HPFTP/AT). The major objective of the test was to characterize the effects of Coolant Control Valve (CCV) position on High Pressure Fuel Turbine discharge temperature (HPFT DS T). The test was scheduled for a total duration of 200 seconds. Nominal operation was planned for the first 90 seconds of the test, followed by CCV excursions to determine the effects on turbine temperature. A thrust profile of the planned test is provided in Figure 6.0-1.

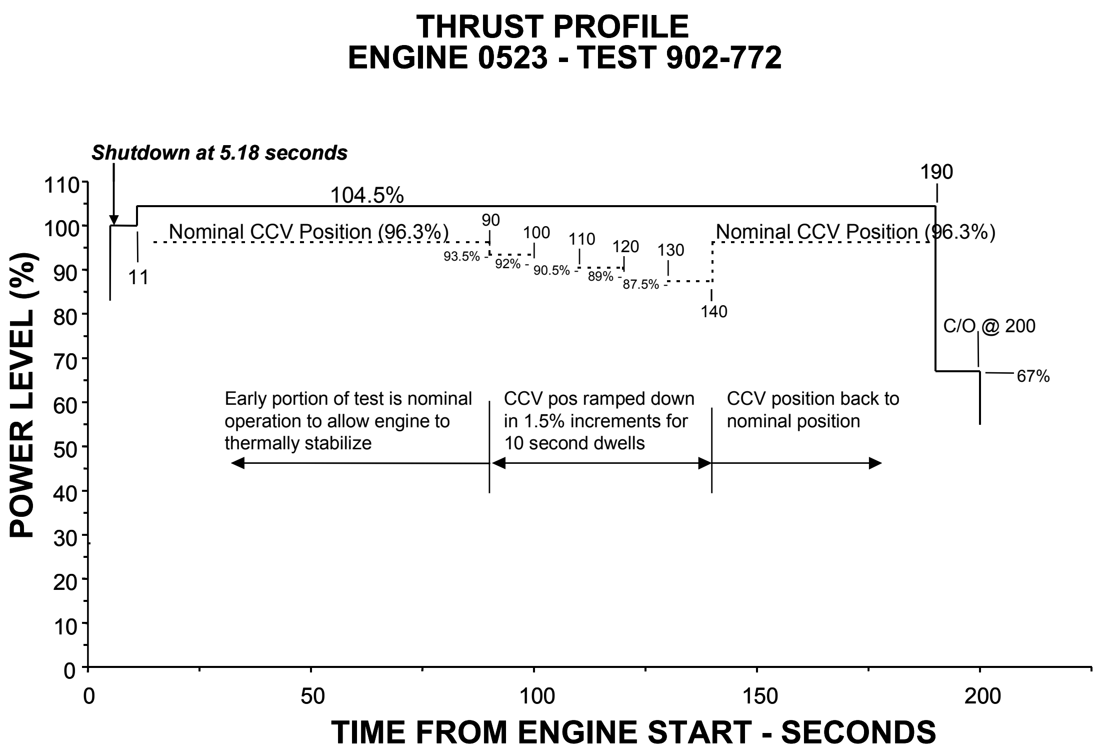


Figure 6.0-1 Test 902-772 Thrust Profile

The first indication of anomalous operation occurred 2.7 seconds into the start transient. The HPFT DS T Channel A measurement (flight instrumentation location) and the HPFT DS T measurement at KG2dT (ground test instrumentation location) began reading higher than expected. The HPFT DS T Channel B measurement and the HPFT DS T measurement at KG2cT remained nominal. All other performance parameters indicated normal engine operation at this time. At 4.04 seconds, the anomalous measurements reached the Launch Commit Criteria (LCC) limit level of 1860R; however, the limit had not yet been activated.

At 4.97 seconds, the HPFTP/AT synchronous vibration amplitudes increased sharply. The facility composite vibration redline system indicated limit violation on all four measurements at 4.996 seconds; however, the limits were not exceeded for the required 50 millisecond duration. The facility composite vibration measurements again exceeded the redline value at 5.032 seconds and remained at elevated levels for the remainder of the test. The sharp increase in vibration levels was followed by a drop in HPFTP/AT performance and a corresponding response by the engine control system attempting to recover performance.

The HPFT DS T LCC was activated at 5.04 seconds. Since HPFT DS T CH A had already exceeded the limit, the engine issued Failure Identifications (FID's) 113-445 and 113-447, accompanied by a Major Component Failure (MCF) indication at 5.08 seconds. The facility Command and Data Simulator (CADS) system was set to respond to any MCF indication before 6.6 seconds with a command to perform engine shutdown. The CADS unit issued a shutdown command and the engine entered shutdown phase at 5.18 seconds. The facility responded to the vibration redline violation by sending a shutdown command to the controller just after the CADS initiated shutdown. The turbine temperature and vibration levels continued to increase after shutdown.

The engine sustained significant hardware damage to the HPFTP/AT with less significant damage to the powerhead and Main Combustion Chamber (MCC). There was no facility damage and no personnel were exposed or injured. Damaged hardware is listed and discussed in Sections 7.3 and in Appendices E and F.

7.0 Data Analyses

7.1 Data Sources

Three separate data systems were used to investigate the failure. Engine performance data such as pressures, temperatures, speeds, and positions were recorded digitally by the Stennis Data Acquisition System (SDAS) facility recording system at 250 samples per second and by the Main Engine Controller at 25 and/or 50 samples per second. Engine vibration data was assessed utilizing data acquired and processed real-time during the test at a sample rate of 20,480 samples per second by the Real-Time Vibration Monitoring System (RVTMS). Analog tapes recorded during the test were also digitally analyzed post-test at a sample rate of 81,920 samples per second for special vibration data analysis. The Optical Plume Anomaly Device (OPAD) system was active on this test, but due to an unrelated anomaly, no data was gathered.

7.2 Integrated Timeline

An integrated timeline was developed for a detailed analysis of events occurring prior to, during, and immediately following the SSME 0523 premature shutdown. Events that occurred between the time of engine start (CADS controller start time) and the time of engine shutdown (time shutdown command is implemented by the Main Engine Controller (MEC) due to MCF), are incorporated with the events which occurred post engine shutdown. The timeline was constructed by referencing each data system to a common Inter-Range Instrumentation Group (IRIG) start time of 2000:168:13:05:03.050. Adjustments were made as needed to accommodate data staleness and/or other time correction factors. An event timeline overview is shown in Figure 7.2-1. Detailed timelines for mainstage and shutdown are in Tables 7.2-1 and 7.2-2.

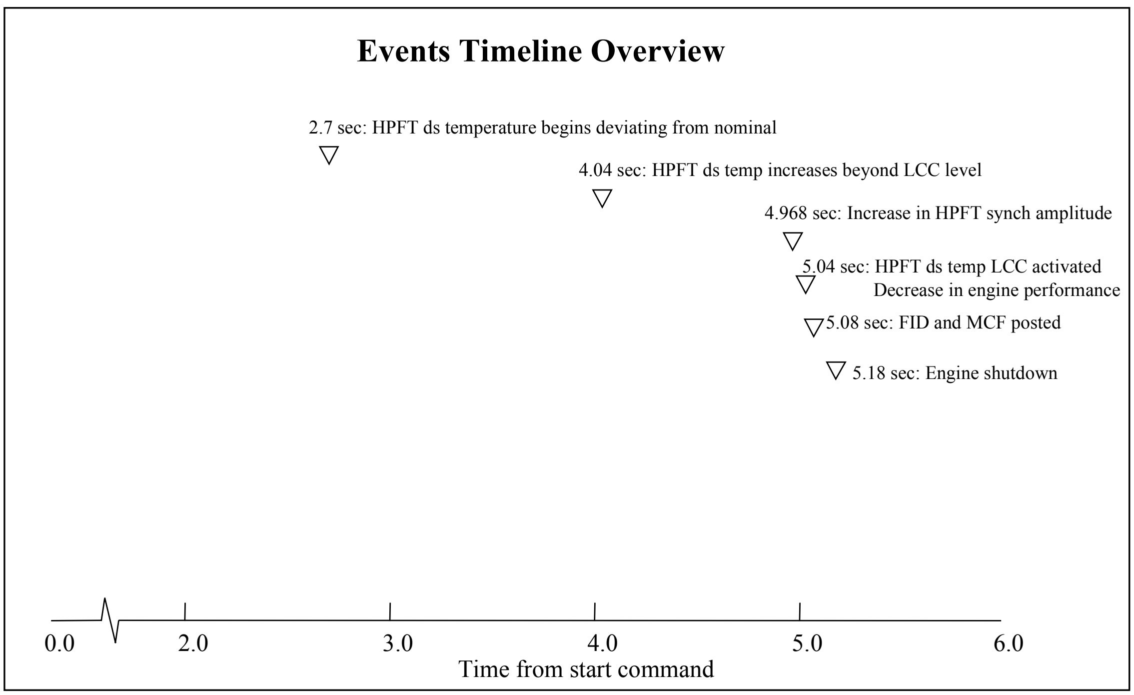


Figure 7.2-1. Events Timeline Overview

TABLE 7.2–1. Event Timeline

Time from Engine Start	Parameter Description	PID	Event	Implication/Description
0.00	CADS controller start time of 2000:168:13:03.050 (All data systems referenced to this start initiation time)	N/A		Controller start time derived from facility Inter-Range Instrumentation Group (IRIG) time and adjusted to Main Engine Controller start initiation
2.70	HPFT DS T Channel A	115,116	Incr	High Pressure Fuel Turbine discharge temperature (HPFT DS T) Channel A measurement begins to deviate from nominal. Indication of hot streak from Fuel Preburner (FPB).
	HPFT DS T KG2dT measurement	3530, 3531	Incr	HPFT DS T KG2dT measurement begins to deviate from nominal. Indication of hot streak from Fuel Preburner (FPB).
3.50	HPFTP/AT RASCOS accels	6015, 6021, 6023, 6025	Redline initiated	HPFTP/AT RASCOS accel 7 grms redline initiated.
3.84	FPOV command	175	Incr	Engine commands FPOV to open. Indication of small FPB efficiency decrease.
4.04	HPFT DS T Channel A	115, 116	Incr	HPFT DS T Channel A measurement exceeds Launch Commit Criteria (LCC) level of 1860R. *Note: LCC not active until 5.04 seconds.*

Time from Engine Start	Parameter Description	PID	Event	Implication/Description
4.968	HPFP RAD 225	N/A	Incr	Initial synchronous amplitude increase begins and achieves maximum amplitude of approximately 8.6 grms. First indication of HPFTP/AT rotor imblance.
	HPFT RAD 135	N/A	Incr	Initial synchronous amplitude increase begins and achieves maximum amplitude of approximately 19.9 grms. First indication of HPFTP/AT rotor imblance.
4.9745	HPFT RAD 135	N/A	Incr	Initial 2x synchronous amplitude increase begins and achieves maximum amplitude of approximately 24.8 grms.
4.996	HPFP RASCOS accels	6015, 6021, 6023, 6025	Exceed redline	Four of four accels exceed 7 grms redline. Cutoff requires three of four above limit for 50 msec.
4.996	HPFTP/AT N11 pressure	6033	Incr	Indicates increase in downstream pressure in coolant circuit. First sign of 1^{st} vane failure in performance data
4.9995	HPFP RAD 225	N/A	Incr	Second synchronous amplitude increase begins and achieves new maximum amplitude of approximately 17.4 grms.
5.00	HPFP FASCOS	80, 81, 82	Incr	FASCOS vibration measurements increase to 12 g.
	HPFT DS T Channel A.	115, 116	Incr	HPFT DS T Channel A measurement begins increasing at a faster rate. Indication of decrease in turbine performance.
	HPFT DS T Channel B	117, 118	Incr	HPFT DS T Channel B measurement begins increasing at a faster rate. Indication of decrease in turbine performance.
	HPFT DS T KG2cT.	466, 468	Incr	HPFT DS T KG2cT measurement begins increasing at a faster rate. Indication of decrease in turbine performance.
	HPFT DS T KG2dT.	3530, 3531	Incr	HPFT DS T KG2dT measurement begins increasing at a faster rate. Indication of decrease in turbine performance.

Time from Engine Start	Parameter Description	PID	Event	Implication/Description
5.004	HPFP RASCOS accels	6015, 6021, 6023, 6025	Decr	Three of four accels dropped below 7 grms limit. RASCOS no longer voting for cutoff.
5.012	HPFT RAD 135	N/A	Incr	Second 2x synchronous amplitude increase begins and achieves maximum amplitude of approximately 50.2 grms.
	HPFT RAD 135	N/A	Incr	Second synchronous amplitude increase begins and achieves maximum amplitude of approximately 15.2 grms.
5.016	HPFTP/AT high pressure orifice delta pressure	459-457	Decr	Change in rotor position due to change in turbine performance. Third impeller backface pressure changes from rubbing of high pressure orifice due to high vibrations.
5.02	Engine fuel flow	100,133	Decr	Indication of decrease in turbopump performance.
5.024	HPFTP/AT speed	764	Decr	Indication of decrease in of turbine performance.
	HPFTP/AT N11 pressure	6033	Decr	N11 pressure changes due to changes in downstream pressure in coolant circuit.
5.032	HPFP RASCOS accels	6015, 6021, 6023, 6025	Exceeds redline	Three of four accels exceed 7 grms redline. Cutoff requires three of four above limit for 50 msec.
5.04	HPFT DS T Channels A2, A3, B2 and B3.		LCC initiated	HPFT DS T LCC upper limit of 1860R initiated.
	FPOV command	175	Incr	Engine commands FPOV to open in response to a decrease in fuel flow.
	HPFTP/AT discharge pressure	459	Decr	Decrease in turbine performance.
5.06	MCC Pc Average	63,163	Decr	Reduction of engine system power due to loss of fuel flow.

Time from Engine Start	Parameter Description	PID	Event	Implication/Description
5.08	Failure identifications (FIDs) 113 445 and 113 447.		Posted	FID's are posted (accompanied by Major Component Failure (MCF)) in response to violation of HPFT LCC limit.
	OPOV command	176	Incr	Engine commands OPOV to open in response to a decrease in MCC Pc.
5.082	HPFP RASCOS accels	6016, 6021, 6023, 6025	Exceeds redline	Three of four accels above 7 grms redline for 50 msec. Facility redline limit criteria met.
5.084	HPOTP/AT discharge pressure	334	Decr	Indication of loss of fuel to HPOT.
5.12	HPFT DS T Channel A.	115, 116	Incr	HPFT DS T begins increasing at a faster rate. Indicates decrease in turbine performance.
5.136	HPFTP/AT speed	764	Stops decreasing	Engine system stabilizes
5.144	HPFTP/AT discharge pressure	459	Stops decreasing	Engine system stabilizes
5.160	HPFTP/AT N11 pressure	6033	Stops decreasing	N11 pressure stops decreasing due to changes in downstream pressure in coolant circuit.
5.18	Engine status word shutdown time of 2000:168:13:05:08.231			Shutdown command accepted. Engine shutdown in shutdown phase.

TABLE 7.2–2. Shutdown Event Timeline

Time from Engine Shutdown	Parameter Description	PID	Event	Implication/Description
0.0195	HPFT RAD 135	N/A	Incr	Third synchronous amplitude increase begins and achieves highest maximum amplitude of approximately 83.4 grms.
0.0258	HPFT RAD 135	N/A	Incr	Third 2x synchronous amplitude increase begins and achieves maximum amplitude of approximately 56.1 grms.
0.0320	HPFP RAD 225	N/A	Incr	Third synchronous amplitude increase begins and achieves maximum amplitude of approximately 18.5 grms.
0.080	N11 pressure	6033	Decr	N11 pressure changes due to changes in downstream pressure in coolant circuit.
0.14	HPFT DS T Channel B	117, 118	Incr	HPFT DS T Channel B measurement begins increasing at faster rate. Indication of fuel loss to FPB.
0.42	HPFT DS T Channel A	115, 116		HPFT DS T Channel A measurement reaches maximum of 2147R.
0.42	HPFT DS T Channel B	117, 118		HPFT DS T Channel B measurement reaches maximum of 1935R.
	HPFT DS T KG2cT	466, 468		HPFT DS T KG2cT measurement reaches maximum of 1684R.
	HPFT DS T KG2dT	3530, 3531		HPFT DS T KG2dT measurement reaches maximum of 2165R.
5.04	HPFTP/AT speed	764	Stop	HPFTP/AT stops. Rate of decrease indicates HPFTP/AT damage.

7.3 Post Mishap-Hardware Inspection Results

7.3.1 Engine Hardware

Following the premature shutdown of test 902-772, preliminary inspections were performed. A borescope inspection via a powerhead inspection port revealed HPFTP/AT turbine inlet damage. Based on those results, the engine was impounded and a formal investigation team formed. A summary of complete engine inspection results follows.

7.3.1.1 Powerhead

The Fuel Preburner (FPB) liner extension had erosion in the vicinity of element H15. The preburner faceplate had thermal discoloration and some minor erosion. This was a high time unit (fleetleader) so the faceplate already had some discoloration from prior testing.

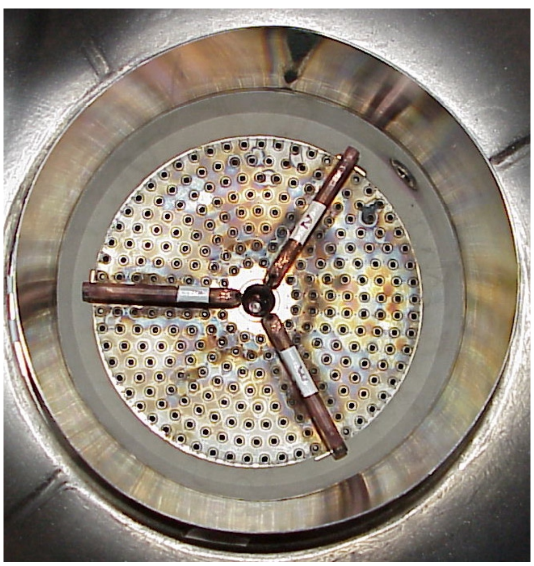


Figure 7.3.1-1 View of Fuel Preburner Faceplate with Thermal Discoloration and Minor Erosion

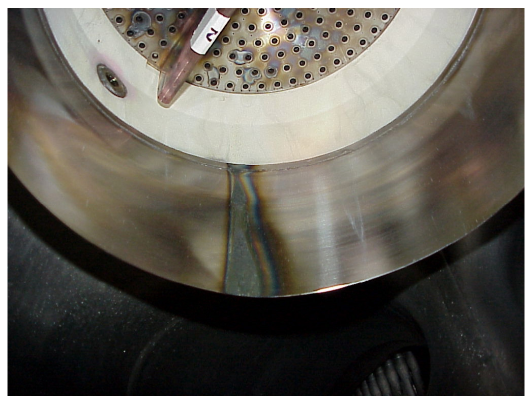


Figure 7.3.1-2 View of FPB Liner Extension Erosion

Figure 7.3.1-3 Close-up View of FPB Liner Extension Erosion

Inspections with the borescope showed white fibrous particles protruding through the holes on the FPB element sleeves. Inspection through the coolant holes on the preburner faceplate revealed contamination also. Inspection of the FPB fuel manifold showed numerous pieces of contamination lodged against and into the fuel manifold and against injector elements. The preburner injector LOX posts (LOX system) showed no anomalies.

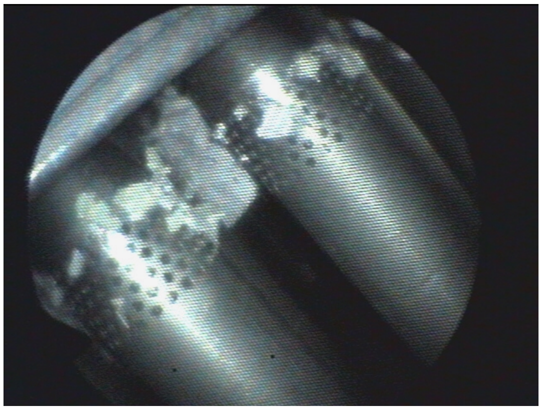


Figure 7.3.1-4 Borescope View of Contamination Protruding into Fuel Sleeve Holes

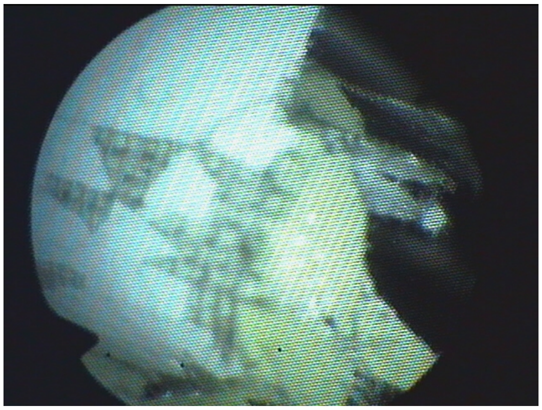


Figure 7.3.1-5 Borescope View into Fuel Cavity Revealing Heavy Contamination

Samples of contamination were collected, recorded on Inspection Discrepancy and Correction Records (IDCR's), and sent to material labs for analysis (contamination evaluation results are covered in section 7.5.2 and in Appendix D). To gain better access, a section of the FPB fuel manifold was cut away for inspection and contamination retrieval.

An inspection of the Oxidizer Preburner (OPB) also revealed fibers protruding through the injector fuel sleeve holes, as well as some blockage of the faceplate coolant holes. The degree of contamination was far less than that in the FPB. The faceplate and liner exhibited no signs of erosion. Similar to the FPB, the OPB fuel manifold was cut away for inspection and contamination retrieval.

Inspection of the main injector upon disassembly revealed no major anomalies with the exception of HPFTP/AT debris in the hot gas and fuel cavities. Minor erosion on the primary faceplate and adjacent facenuts was also noted. Inspection of the remainder of the powerhead assembly showed no significant anomalies.

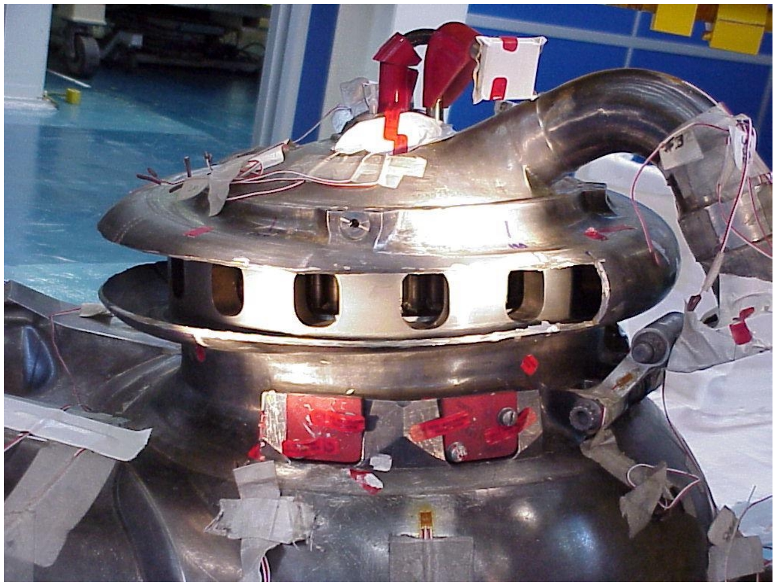


Figure 7.3.1-6 View of FPB with Fuel Manifold Cut Away for Easy Access

7.3.1.2 Main Combustion Chamber

The Main Combustion Chamber (MCC) hot gas wall forward end had flame spray, slag, and numerous dings and dents, 360 degrees around. The metallic spray has not been analyzed at this point but is assumed to be HPFTP/AT materials. The level of damage is such that it could be removed via polishing and the unit could be returned to service if necessary. The MCC was back flowed to remove any contamination lodged in the coolant channels. No anomalies were noted.

Figure 7.3.1-7 View of Flame Spray on the Forward End of MCC

Figure 7.3.1-8 View MCC Forward End Looking Towards Throat

7.3.1.3 Nozzle

No anomalies were noted during inspection of the Nozzle hot wall. A back flush was performed of the coolant circuit to dislodge and retrieve any contaminates with no anomalies noted.

7.3.1.4 Other Engine System Components

Post-test inspections showed no damage to engine lines and ducts.

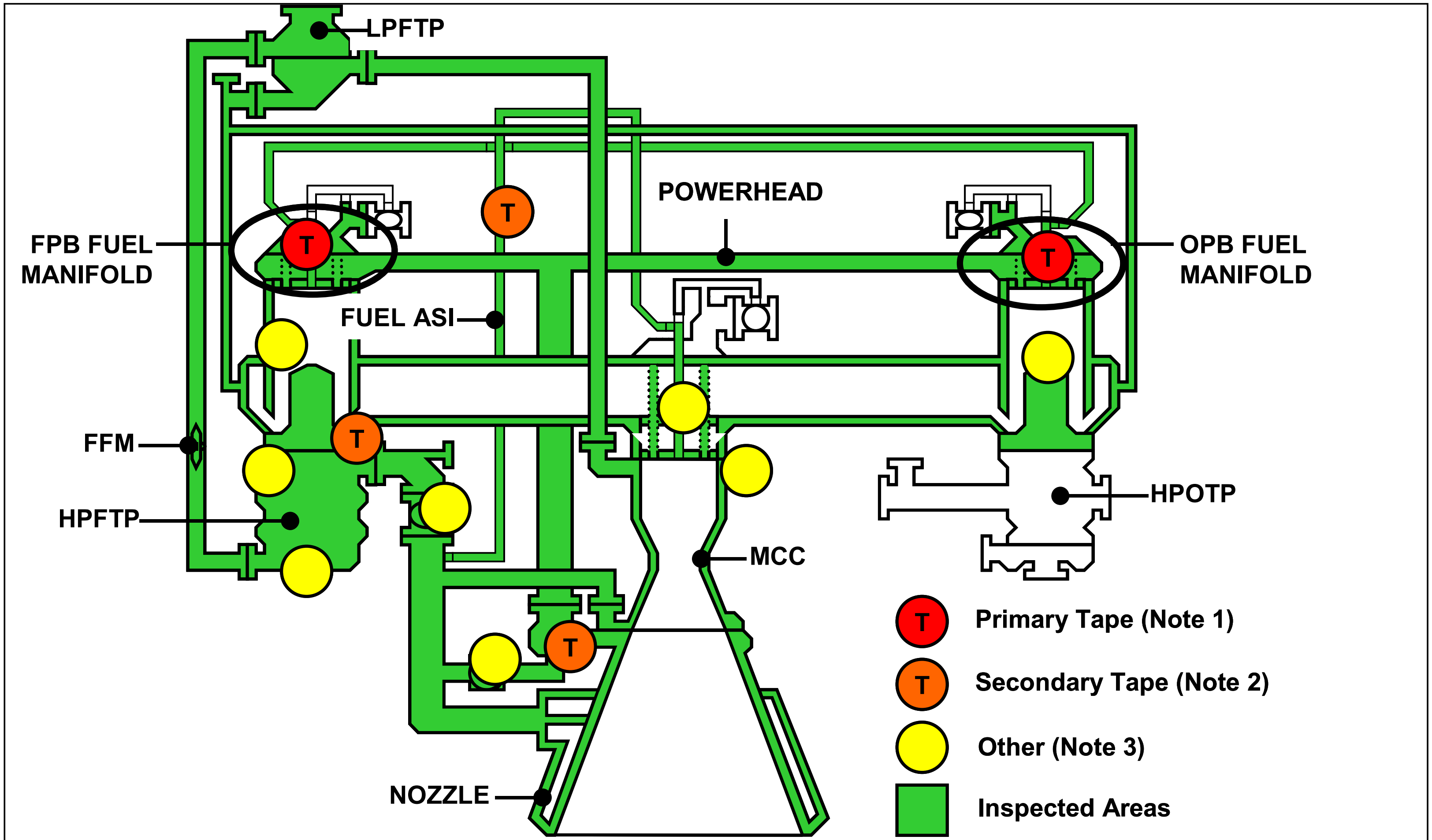
In addition to the contamination later determined to be Permacel P-670 tape (LOX tape, see Section 7.5.2) found in the FPB and OPB fuel cavities, very small amounts of similar contamination were found at joint locations F17 (mixer bowl), G6 (HPFTP/AT flange), and downstream of F5.1 (Augmented Spark Igniter (ASI) fuel supply system). These contaminants were determined to have been introduced into these areas during post-incident handling of the hardware.

Two independent borescope inspections of joint F17, one at SSC and one at Canoga Park, prior to disassembly showed no contamination. Following joint F17 separation during disassembly a single small piece of Permacel P-670 was discovered. Since the particle was not seen during the earlier borescope inspections it was determined to have fallen into the mixer during disassembly operations.

At the G6 flange, a small amount of Permacel P-670 was recovered. This contamination was recovered from one surface of a mated flange. Thus, it is a surface not exposed to engine flow conditions during engine hotfire and the joint be properly assembled with tape in place. The only time that contamination could come to rest in this location is during disassembly operations, specifically removal of the HPFTP/AT.

The small contaminant found approximately 30 inches downstream of joint F5.1 was recovered during disassembly inspections of the ASI fuel supply system. The full length of the ASI fuel system from joint F5.1 to either of the preburners is approximately 95 inches. The contamination was a single 0.020 inch diameter globule later determined to be Permacel P-670 adhesive. Based upon a flow analysis of the ASI fuel supply system (see Appendix D), experiments with Permacel P-670 adhesive in cryogenic environments, post-test handling procedures using temporary line end closures, and the lack of similar debris elsewhere in the fuel system (discussed as part of the candidate joint analysis presented in Section 7.6), it was determined that this contamination was most likely the result of post-incident processing.

Figure 7.3.1-9 highlights the results of the post-test inspections conducted on SSME 0523.



NOTE 1: Total amount of primary tape contamination estimated to be 24 square inches
NOTE 2: Secondary tape contamination believed to have occurred during post incident disassembly and inspection
NOTE 3: Other contamination consists of HPFTP/AT debris generated during the failure and insignificant amounts of various debris normally found during disassembly

Figure 7.3.1-9 Post-test Inspection Highlights and Locations of Contamination

7.3.2 Turbomachinery Hardware

7.3.2.1 HPFTP/AT

The HPFTP/AT was returned to Pratt & Whitney for disassembly. The disassembly was conducted according to the Plan of Action, located in Appendix C, which was generated by Pratt & Whitney and approved by the MSFC Investigation Board. The turbopump remained in a vertical position with the turbine-end up until the turbine-end was disassembled. The turbopump was then rotated and the pump-end hardware was removed. No torque checks or leak checks were performed. Samples of contamination were collected, recorded on Inspection Discrepancy and Correction Records (IDCRs) and sent to the materials lab for evaluation (contamination evaluation results are covered in Section 7.5.2 and in Appendix D).

The Turbine Inlet Housing (TIH) exhibited erosion on the outer diameter flowpath wall between fat strut #15 and thin strut #14. The TIH erosion was in the same circumferential location as the streak seen on the FPB liner extension. The TIH and inlet dome were splattered with aluminum from particles generated during rubbing of pump-end seals during the vibration events. The first stage vanes were eroded at two circumferential locations between TIH struts #14 and 15 as well as between TIH struts #12 and 13. First vane segment #23 (between TIH struts #14 and 15) had evidence of heavy erosion and was missing the airfoils and ID platform.

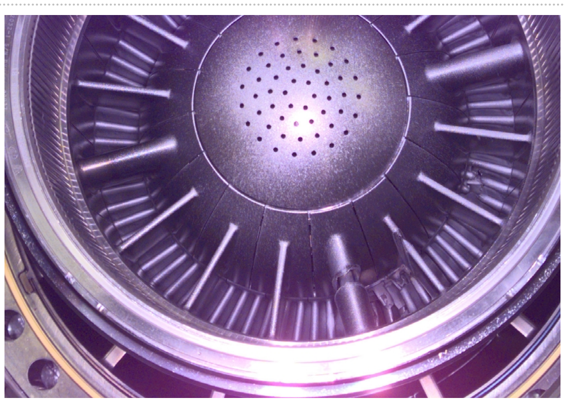


Figure 7.3.2 – 1 Inlet Dome, Eroded TIH Struts #14 and 15 and Damaged 1st Stage Vanes

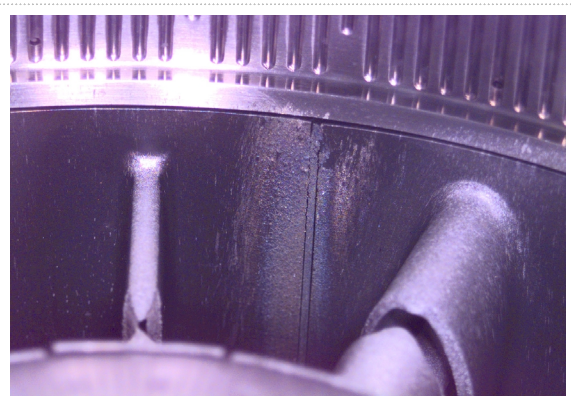


Figure 7.3.2 – 2 Erosion on Outer Flowpath Wall of TIH Between Struts #14 and 15

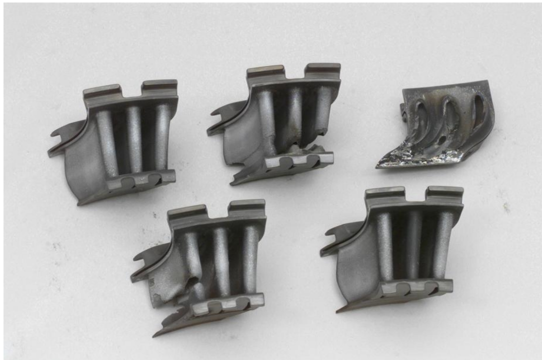


Figure 7.3.2-3 First Vane Segments #21 Though 25 Leading Edges

Figure 7.3.2-4 First Vane Segments #21 Through 25 Trailing Edges

The turbine hardware downstream of the first stage vanes (first blades, second vanes, second blades, turn-around duct, and turbine exit diffuser) was all damaged by impact and is discussed in more detail in Appendix F.

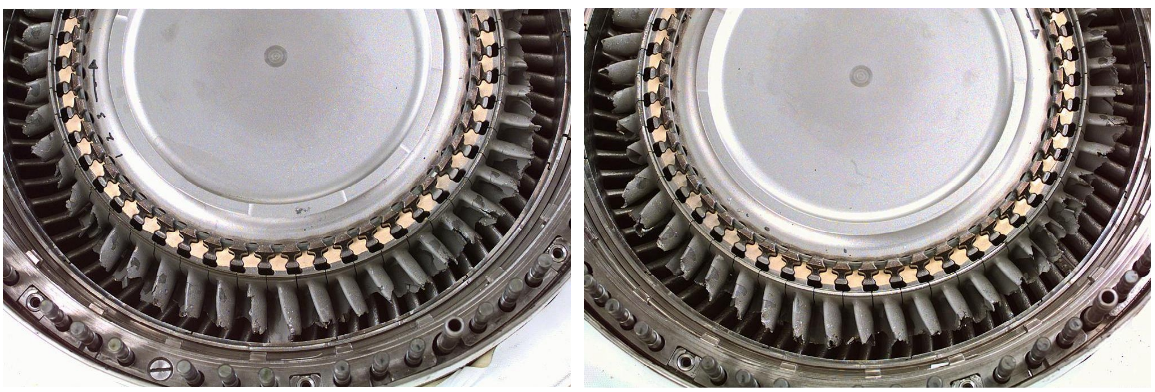
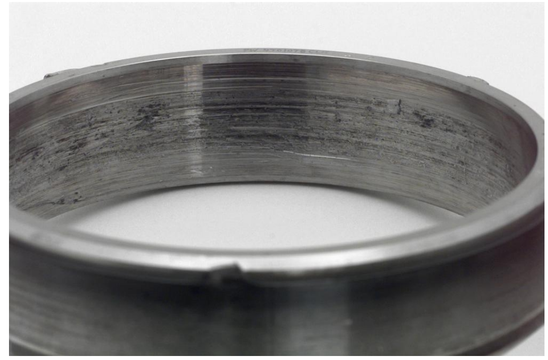


Figure 7.3.2-5 First Stage Blades

The pump-end disassembly revealed evidence of radial and axial rotor excursions. The turbine-side tip seal and third impeller were each missing approximately 0.030" of material axially indicating 0.060" of rotor motion toward the pump. The thrust balance corner seal and other pump-end seals were also heavily rubbed.

Distress to both bearings was noted. The ball bearing exhibited evidence of load path crossover on the inner race. The roller bearing failed under excessive loads during shutdown. Analysis regarding the failure mechanism and quantification of loads is being conducted under a SSME Project Office action. Further discussion of the condition of bearing components is located in Appendix F.

	
Figure 7.3.2-6 Roller Bearing Inner Race, Cage, and Rollers	**Figure 7.3.2-7 Roller Bearing Outer Race**

7.3.2.2 HPOTP/AT

The HPOTP/AT was returned to Pratt & Whitney for inspections. The inspections were conducted according to the Plan of Action, located in Appendix C, which was generated by Pratt & Whitney and approved by the MSFC Investigation Board.

The Turbine Inlet Housing (TIH) and inlet dome were splattered with silver-colored material, probably aluminum from particles generated during rubbing of HPFTP/AT pump-end seals during the vibration events. The splatter appeared similar to that appearing on the HPFTP/AT turbine inlet, but was less in quantity (see Appendix F).

Borescope inspections were performed on the pump-end ball bearing, turbine-end ball bearing, roller bearing, turn-around duct, turbine inlet housing, first and third stage blades, preburner pump inlet, pump-side and turbine-side inducers and shrouds. A torque check and intermediate seal flow check were also completed. Inspections did not reveal any anomalous conditions.

7.3.2.3. Low Pressure Turbomachinery

Inspections and torque checks were performed on the Low Pressure Oxidizer and Low Pressure Fuel Turbopumps (LPOTP and LPFTP). No anomalies were found.

7.4 Related History

7.4.1 FPB Injector

There have been two previous mishaps involving blocked fuel sleeves during the SSME program. These were tests 750-160 and 902-468.

Test 750-160 was prematurely shutdown at 3.16 seconds due to ice blockage of the FPB fuel sleeves. Water was introduced into the system during a pre-hotfire electro-discharge machining (EDM) operation on the FPB faceplate. The water froze during the start transient and blocked the FPB fuel sleeves. This caused a hot streak in the preburner, and ultimately resulted in major damage to the FPB, main injector, and nozzle. There was also damage to both high pressure turbopumps.

Test 902-428 was prematurely shutdown at 204.12 seconds due to ice blockage of the OPB fuel sleeves. An OPB baffle pin braze crack resulted in combustion in the fuel cavity, forming water/ice, which blocked the fuel sleeves. A hot streak occurred in the OPB, eroding through the HPOTP turbine housing. There was also severe erosion to one quadrant of the OPB injector.

Each of these tests shared similar data characteristics to test 902-772. A locally high mixture ratio resulted in high temperatures measured at a localized area. On both tests, preburner erosion was confined to localized areas.

A complete list of all FPB and OPB related hotfire anomalies is included in Appendix G.

7.4.2 Contamination

A search of the MSFC Problem Reporting and Corrective Action (MPRACA) database found 15 problem reports occurring since 1980 that were the result of tape-like contamination in the engine. The most recent occurrence was reported in July 1999 with final problem closure in March 2000 based on five recurrence control actions. These were changes to planning documents, internal advisory bulletin issued, relocation into new plasma spray facility, new tape supplier found with products successfully tested, and a long term study of full replacement of this type of tape to one with lesser adhesive.

Four of the occurrences did not require recurrence control since the source of the contaminant could not be identified or the contaminant could not be retrieved for analysis. Two problems resulted in development of new tooling sets to eliminate tape usage for certain procedures. The remaining eight resulted in procedure changes regarding the use of tape, increased verification of tape removal, or retraining mechanics and inspectors on current procedures.

Table 7.4-1 UCR History of Tape-like Contamination

UCR #	Closure Date	Cause	Recurrence Control
A017860	10/16/1980	Improper use of LOX tape to hold seal during assembly.	Generation of ECR 10004 – Use of seal holding tool.
A017828	7/1/1981	Alcar tape used to hold seal in place during assembly.	Mechanic disciplined for violation of procedure per department policy.
A016012	8/19/1981	Mechanic failed to remove tape after flange rework @ joint 04. Inspector failed to verify removal.	Inspectors re-instructed on procedures for controlling contamination.
A015283	4/30/1982	Tape used to mask 7524 support bellows during assembly.	Revised build MOR to add call-out for LOX tape removal and add inspection verification.
A006614	7/13/1984	Contaminate noted during post-test inspection adhering to HPFTP inner-wall. Engine was tested again without anomaly. Contaminate presumed burned during test and exited the engine through the nozzle.	None; since unconfirmed source.
A008717	11/13/1986	The blockage of boundary layer coolant holes 74, 75 & 76 was caused by inadequate cleaning/flushing of the area between the primary & secondary faceplates.	Internal letter & finding alternate method of indexing LOX post.
A020051	7/17/1989	Source of red contaminant never determined. The most probable point of introduction was during the HPOTP installation or removal either at KSC or SSC.	Procedures in place at KSC and SSC to inspect all visible surfaces of preburner after HPOTP installation. Additional training classes conducted at KSC and SSC to increase contamination control awareness.

UCR #	Closure Date	Cause	Recurrence Control
A022895	6/29/1989	Q-tip wrapped with LOX tape left in PCA Housing Inlet Port of PAV6 during PCA rebuild.	Standard set of tooling developed and ECP generated to initiate use of new tooling and provide for additional requirement to verify PCA valve during functional test.
A032459	11/9/1993	Residue from teflon tape used for temporary closures.	
A032628/ A032629/ A032630	9/29/1993	Contaminate material unconfirmed with the closest match of LOX tape. Contaminate caused surface oxidation due to abort and ensuing firex quenching and 13 day delay between abort and MCC inspection.	None – exact source of contaminant could not be determined.
A034058	3/25/1998	White vinyl tape found in “rolled” condition (not adhering) between two bearing pockets on the aft side. The only vinyl tape used is purple vinyl tape used in plating at Canoga. No source of tape could be identified.	Rocketdyne Internal Alert 19980004 was issued to all product and process team managers, including field sites.
A034168	2/10/1999	Ultimate source not revealed by investigation. Suspect LOX tape introduced during installation of line assembly.	MTR-09.04 revised to inspect integrity of LOX tape upon removal.

UCR #	Closure Date	Cause	Recurrence Control
A034246	3/30/2000	# 470 Platers tape left on the rotor during rework effort and not 100% cleaned. Poor lighting and substandard work setting also contributed to insufficient cleaning and visual examination prior to oven cure.	1) Planning revised to remove platers tape callout and replace with mask per MPP RA112-003-50 throughout MWO 2) Advisory bulletin issued to all planners to evaluate the Master's when processing MWOs for update or correction 3) New Plasma spray (DFL) lab facility built and relocation complete 4) New supplier was established for purchase of additional spec. approved tape. Tapes were purchased and tested by process engineering and were added to PSM list 5) Long term project – process engineering to study replacement of #470 platers tape with lesser adhesive type (#4731). Still in work.

7.5 Summary of Data Analyses

7.5.1 Engine Systems Data Analysis

7.5.1.1 Event at 2.7 Seconds

The first sign of a failure was an indication of a localized hot streak in the High Pressure Fuel Turbine (HPFT) at 2.70 seconds. The HPFT discharge temperature (HPFT DS T) Channel A measurement began deviating from nominal. A facility HPFT DS T measurement located in port KG2dT showed a similar increase. The Channel B measurement and the facility measurement located in port KG2cT continued to read nominally. Other engine performance parameters indicated nominal operation throughout the start transient. The HPFT DS T continued to increase throughout the start transient, reaching the Launch Commit Criteria (LCC) limit level of 1860R at 4.04 seconds.

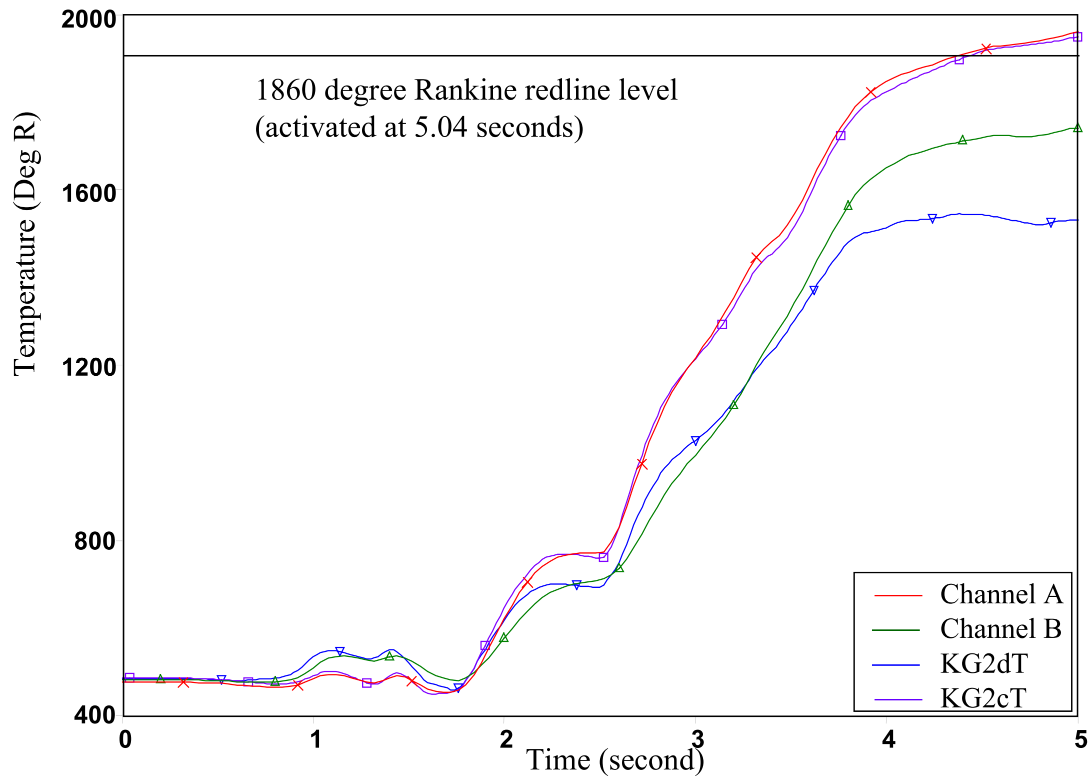


Figure 7.5.1-1 High Pressure Fuel Turbine Temperature Measurements During the Start Transient

7.5.1.2 Event at 4.97 Seconds

The second event was characterized by a sharp increase in synchronous vibration amplitude at 4.97 seconds, followed by a loss of HPFTP/AT power. The vibration amplitude increase, shown in Figure 7.5.1-2, was caused by a loss of turbine rotor material.

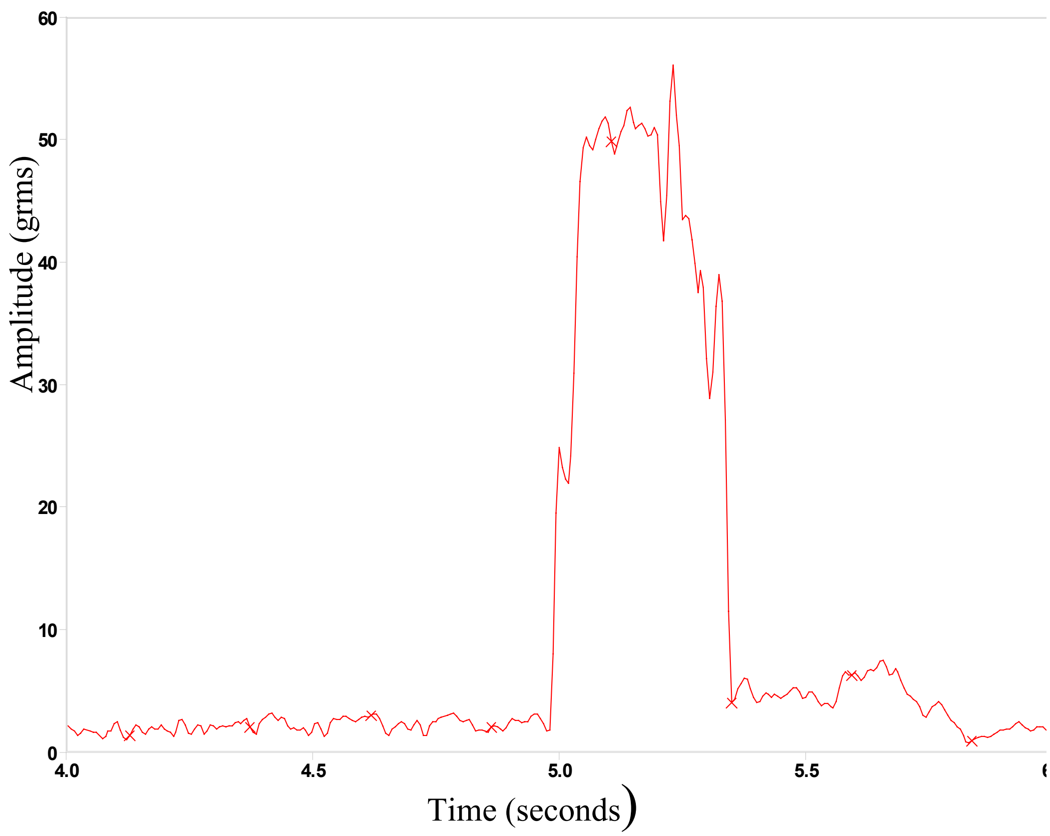


Figure 7.5.1-2 Synchronous Vibration Amplitudes

The decrease in fuel flow (Figure 7.5.1-3) caused by the loss of turbine material led to a loss of engine system power at 5.04 seconds. Main Combustion Chamber pressure (Figure 7.5.1-4) and HPFTP/AT speed (Figure 7.5.1-5) each dropped at this time.

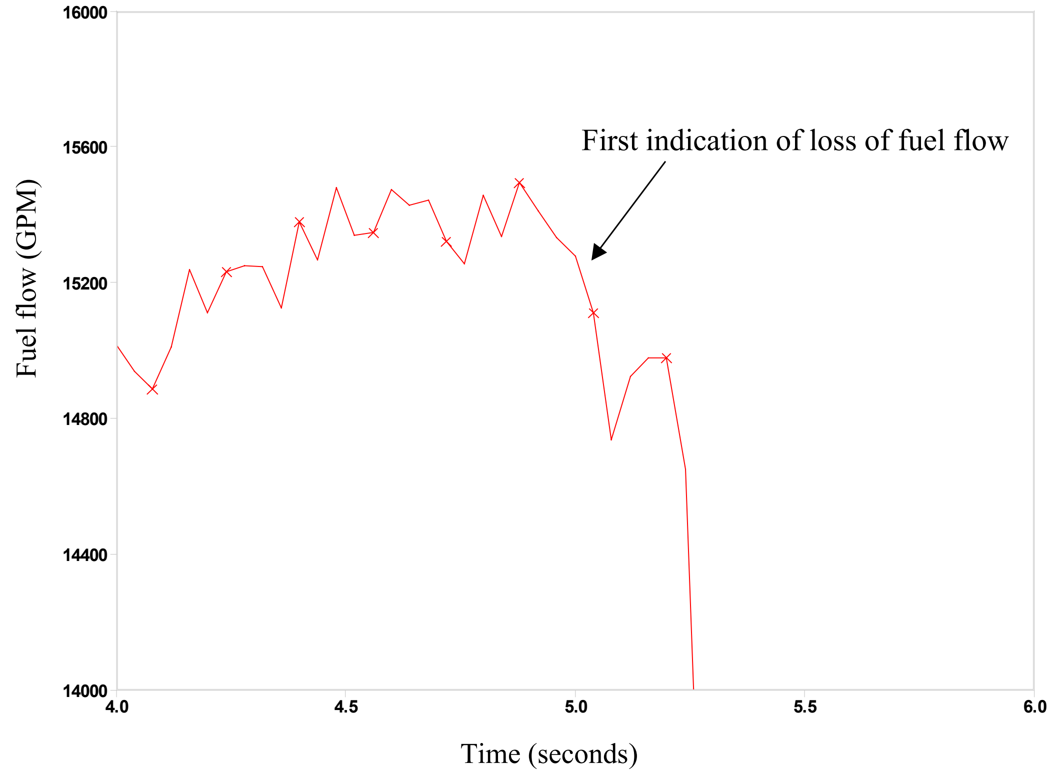


Figure 7.5.1-3 Engine Fuel Flow

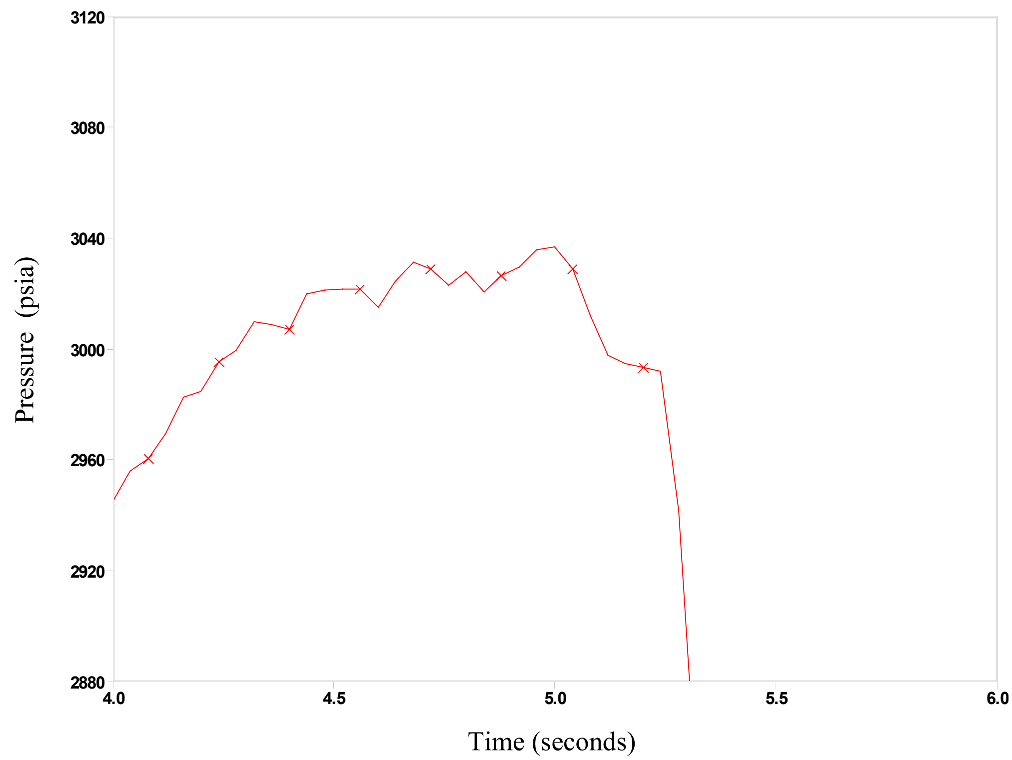


Figure 7.5.1-4 Main Combustion Chamber Pressure

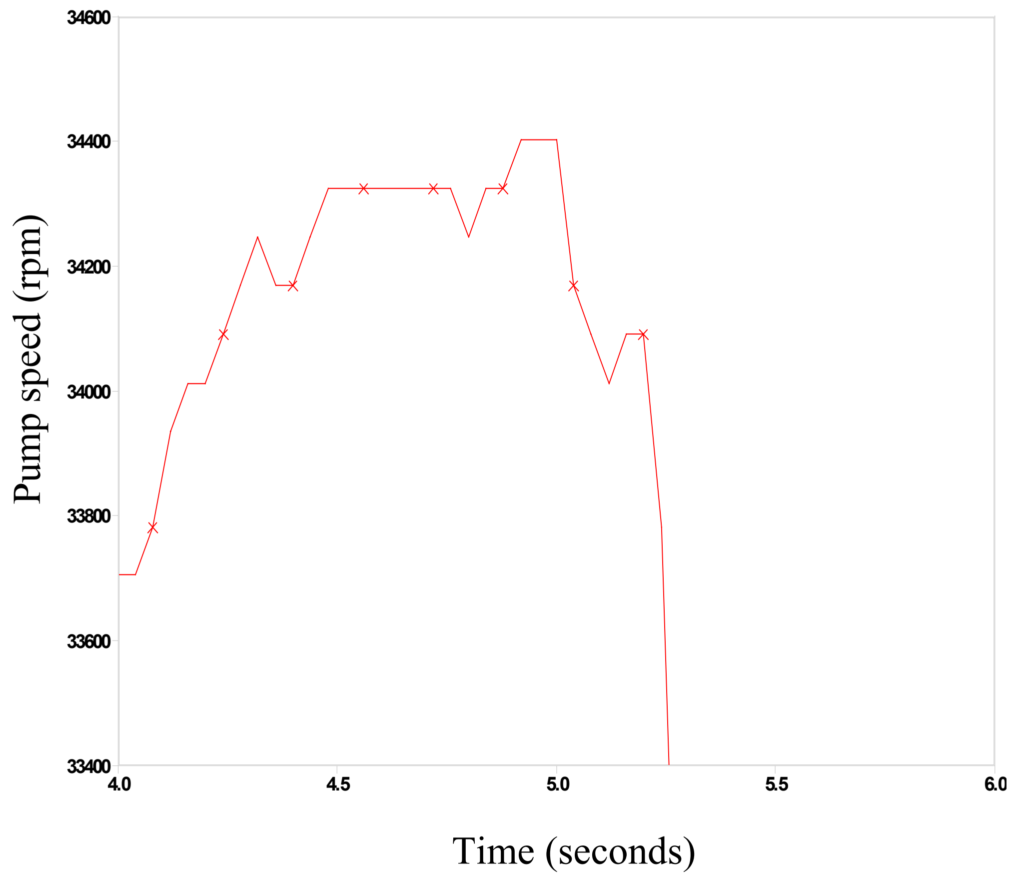


Figure 7.5.1-5 High Pressure Fuel Turbopump Speed

The HPFT DS T LCC limit was activated at 5.04 seconds. The Main Engine Controller (MEC) issued a Failure Identification (FID), accompanied by a Major Component Failure (MCF) at 5.08 seconds. The Command and Data Simulator (CADS) responded to the MCF, commanded engine shutdown, and the engine entered shutdown phase at 5.18 seconds.

7.5.2 Materials Analysis

Analysis of materials recovered during inspection and disassembly of SSME 0523 was accomplished through various techniques including but not limited to Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) and Fourier Transform Infrared Spectroscopy (FTIR). This evaluation consisted mainly of identifying particles that were removed from the engine in an effort to determine their origin.

A large amount of tape was removed from the Fuel Preburner (FPB) and a smaller amount from the Oxidizer Preburner (OPB). FTIR analysis identified this material as Permacel P-670 tape, commonly referred to as LOX tape. 3.4686 grams of tape was removed from the FPB and 0.2765 grams from the OPB. Assuming a 90% recovery, the total tape in the preburners was extrapolated to 4.1612 grams. This weight of tape correlates to approximately 24.2 square inches of the Permacel P-670.

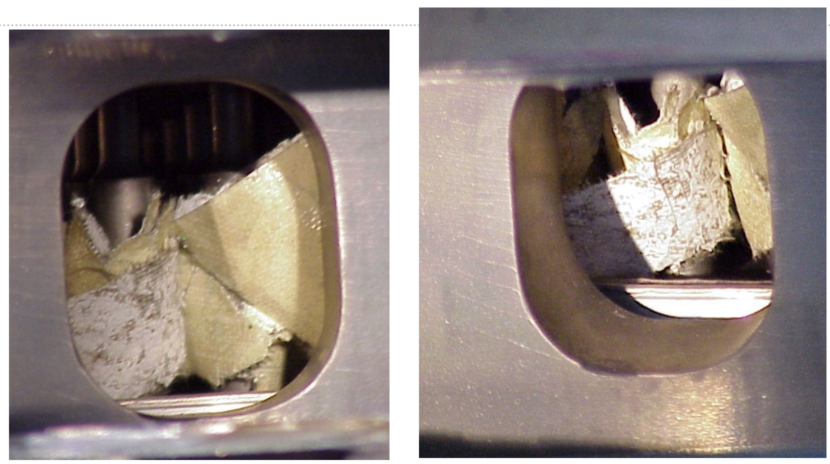


Figure 7.5.2-1 Contamination Seen in FPB Fuel Manifold Windows 4 and 5

Figure 7.5.2-2. Typical Debris Removed from the Fuel Preburner

Other particles were identified as HPFTP/AT materials and were a result of localized melting and subsequent damage to the HPFTP/AT. A metallic spray was noted on the inlet domes of both high pressure turbines and was determined to be aluminum from the pump-end of the HPFTP/AT. This was a result of rotor imbalance due to loss of turbine-end material causing the aluminum pump seals to rub. Pump-end debris was then transported through the fuel system into the preburners and sprayed into the turbine.

In summary, analysis indicates that all contamination, other than the P-670 tape, was either typical of normal engine disassembly or debris generated as a result of the engine incident. The only contamination present in sufficient quantities and sizes to block preburner fuel orifices is the P-670 tape. Hardware evaluation indicates a clean engine other than the fuel system and that the damage to the HPFTP/AT was a result of the tape contamination and resulting high-localized temperatures. Small amounts of Permacel P-670 tape determined to be introduced during post-incident handling were also found (see Section 7.3.1.4).

See Appendix D for a complete list of contamination analysis results.

7.5.3 FPB Temperature Analysis

7.5.3.1 Introduction

Inspections of SSME 0523 after the premature cutoff of test 902-772 revealed large quantities of contamination within the fuel cavity of the fuel preburner (FPB) injector. Also, there was significant thermal damage to the inlet of the High Pressure Fuel Turbine (HPFT) and a lower level of thermal damage to the fuel preburner injector faceplate itself. The following sections will examine the temperature levels necessary to produce the observed damage and whether this damage is consistent with the observed contamination.

7.5.3.2 The Observed Damage

Below are two pictures taken during post-test inspections of Engine 0523 and the HPFT.

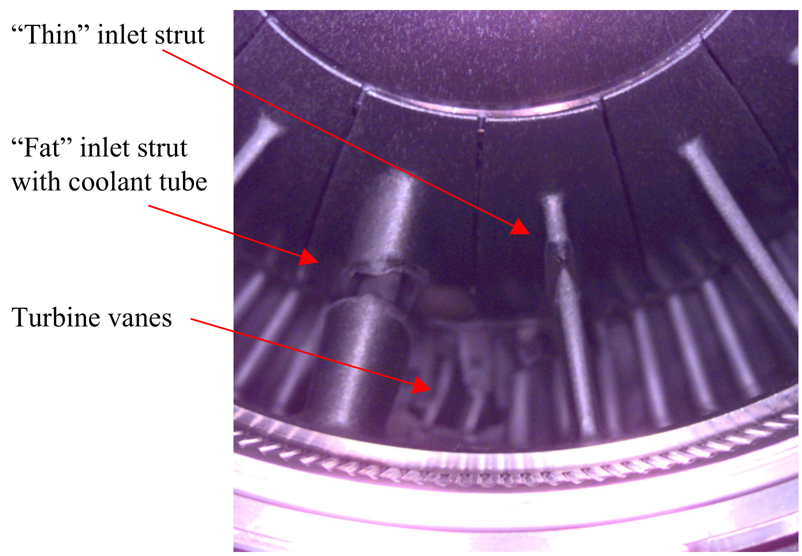


Figure 7.5.3-1. Close-up of Engine 0523 HPFT Inlet

Figure 7.5.3-1 shows a close-up view of the HPFT inlet. Shown is a narrow sector where the most damage was found. First, a "thin" inlet strut is melted through. Next, a "fat" inlet strut is melted away but the enclosed coolant tube is intact. And finally, the vanes downstream of the inlet are melted. Damage not shown in this picture includes a burning/melting of the preburner liner extension along one distinct streak. This streak was found directly above the area marked "Turbine vanes" in Figure 7.5.3-1. Also, there was another small region of melted turbine vanes to the right of the area shown in the picture.

In Figure 7.5.3-2 the FPB injector faceplate is shown. Circled are a few of the areas of faceplate erosion. Much of this erosion is no more than discoloration or minor blanching but there was some material eroded away within the upper right-hand circle. The upper left-hand circle is roughly the region that was situated directly over the damage shown in Figure 7.5.3-1.

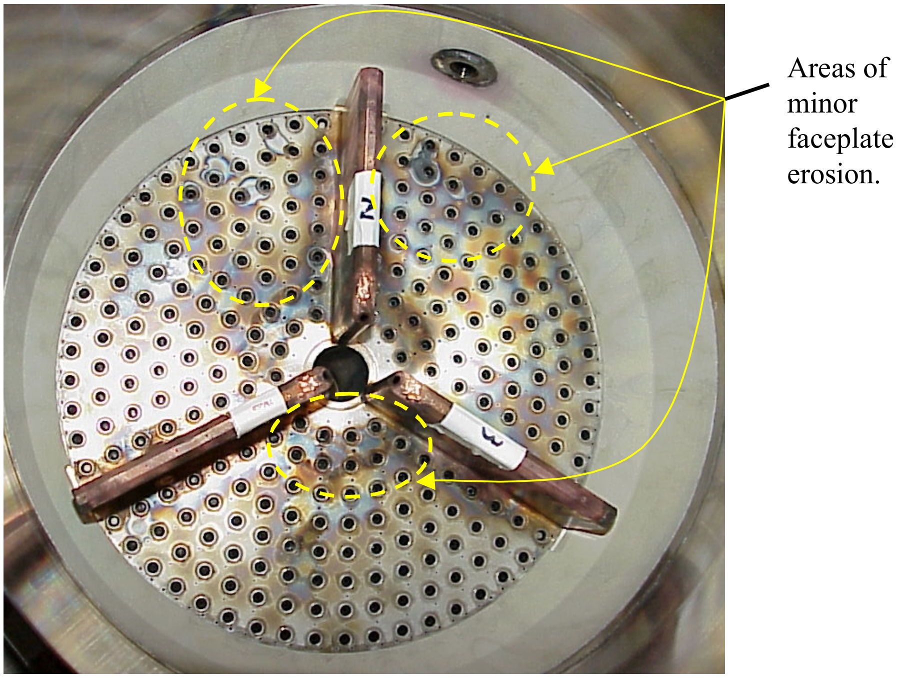


Figure 7.5.3-2. SSME 0523 FPB Faceplate

Thus, there was significant melting of the HPFT inlet structures but relatively minor erosion of the FPB faceplate.

7.5.3.3. Thermal Models of the Preburner Hot Gas Structures

The first question to be answered is, what kinds of temperatures are necessary to generate the observed hardware damage? With cryogenic liquid hydrogen and liquid oxygen as the propellants being used, the possible temperature range goes from approximately 37R to well over 6000R. In other words, it can span from liquid hydrogen temperatures to stoichiometric oxygen/hydrogen combustion flame temperatures.

According to a material survey generated by Pratt & Whitney, the metal of the HPFT vanes will begin to melt when the local metal temperature reaches approximately 2900R and the struts shortly thereafter.

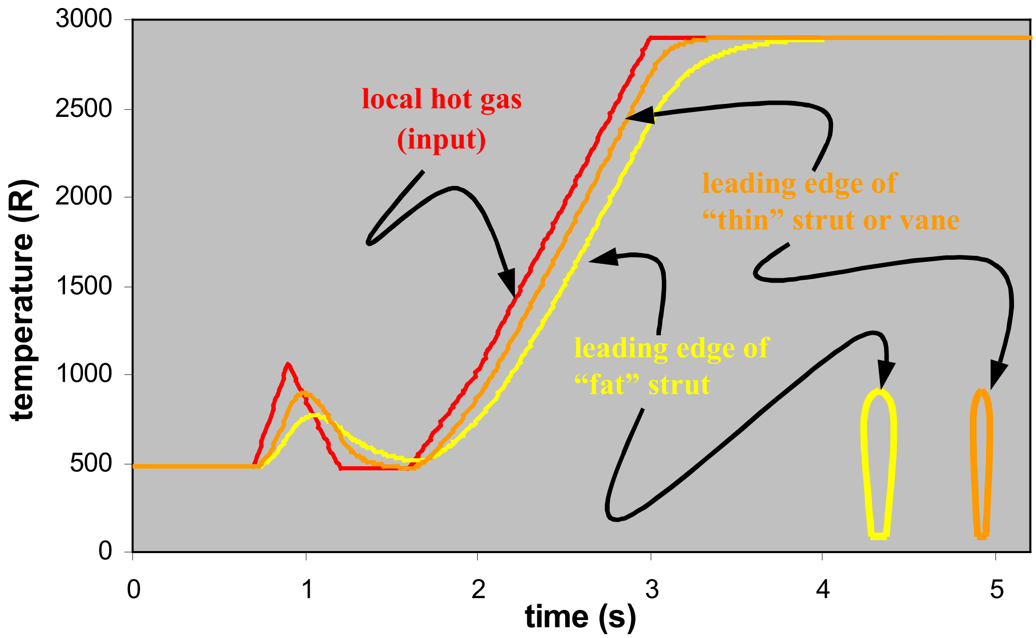


Figure 7.5.3-3 Transient Thermal Analysis of a HPFT Inlet Strut or Vane

A simple transient thermal analysis of the leading edges of the HPFT inlet structures was assembled to examine the time lag between local hot gas temperature and the heating of the metal. The results for a single hypothetical situation are presented in Figure 7.5.3-3. What is shown is a varying local hot gas temperature that represents actual extrapolated data from the 902-772 test and an assumed rise to the 2900R metal melting temperature between 2 and 3 seconds. Also plotted in Figure 7.5.3-3 are two lines representing the temperature of the leading edge of a "fat" strut and a "thin" strut or a vane as described in Figure 7.5.3-1.

The most significant conclusion to be drawn from Figure 7.5.3-3 is that if the local hot gas temperature just matches the melting temperature of the metal, the time lag before the metal actually begins to melt is, at most for the "fat" strut, 0.8 seconds. With higher local hot gas temperatures, the metal is heated to its melting point even more quickly. Thus, an extremely conservative statement regarding the melting of the HPFT inlet structures is this: If the local hot gas temperature equal to or greater than the melting temperature for at least a duration of 1 second, then there will be melting of the metal. Since all of the damage scenarios presented within this report fulfill this requirement with wide margin, this requirement never becomes a significant issue. Discussions with Pratt & Whitney engineers also confirm both the validity and the conservatism of this statement.

Another observation regarding the HPFT inlet damage is that the coolant tube enclosed within the "fat" strut did not melt through despite the fact that it is constructed of similar material to the other structures. Pratt & Whitney conducted a transient thermal analysis that showed that due to the coolant hydrogen flowing through that tube, an impinging flame would have to be approximately 4500R before it would melt. Thus, taking into account the two models described thus far, the localized hot gas temperature within the preburner necessary to cause the damage observed to the HPFT is somewhere between 2900R, which is the melting temperature of the metal, and 4500R, which is the melting temperature of the coolant tube with coolant flowing.

However, what about the injector faceplate? The FPB faceplate material is Inconel 625, which will melt at approximately 2800R. If the temperature in the preburner was somewhere between 2900R and 4500R according to the HPFT damage, then why was there not more damage done to the faceplate material with a melting temperature of 2800R? The answer lies in the fact that this was a very short test, the material was initially at ambient temperature, and the back side of the faceplate is cooled by incoming hydrogen gas. A transient thermal model was created to examine this issue. Actual test data was used to generate reasonable time history profiles for the two input boundary conditions of the hot gas and cool incoming hydrogen gas with an assumed deviation in the hot gas to localized high temperature conditions. Rocketdyne developed a similar model and obtained results consistent with those presented here.

Presented first is a sample plot, labeled as Figure 7.5.3-4, showing what a "normal" start to 5.2 seconds should have looked like for this engine with regard to temperatures of the FPB faceplate. This figure shows the hot gas temperature and the hydrogen gas temperature that serve as inputs to the model. Also shown are the warmest and coolest faceplate material temperatures. The temperature achieved in the warmest layer of the FPB material is 1440R. This is well below the melting temperature of the material as would be expected in normal operation. However, other runs were made using higher hypothetical hot gas temperatures and for many of these, the faceplate material was quickly raised to melting temperatures.

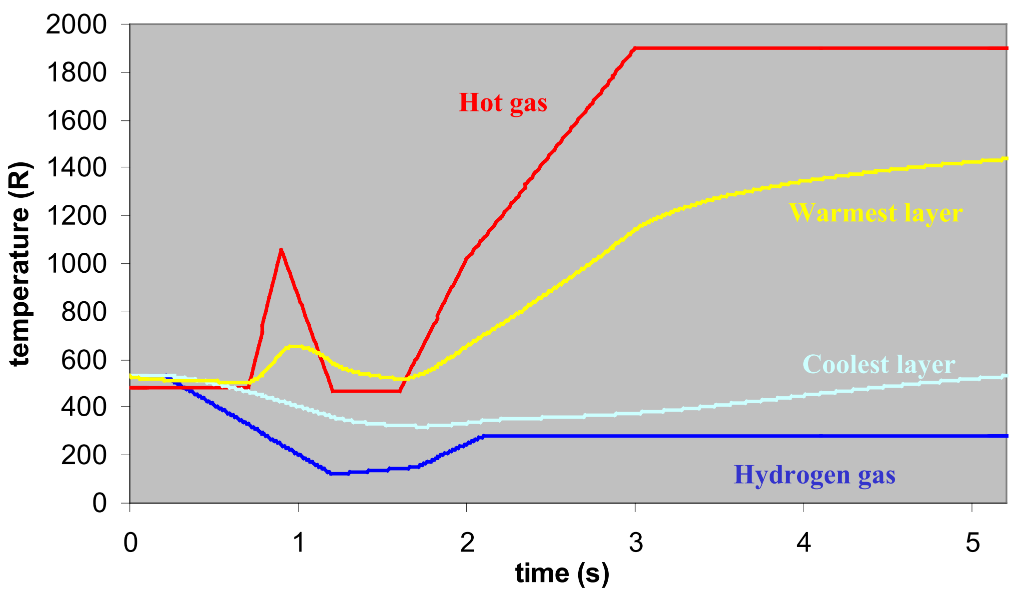


Figure 7.5.3-4 FPB Faceplate Subjected to a "Normal" Start

Figure 7.5.3-5, presents the results from a series of runs of the FPB faceplate transient thermal model. Plotted here is the peak temperature within the hottest layer of the faceplate material as a function of the local hot gas temperature. The faceplate would be at the point of incipient melting when the local hot gas temperature is approximately 3900R.

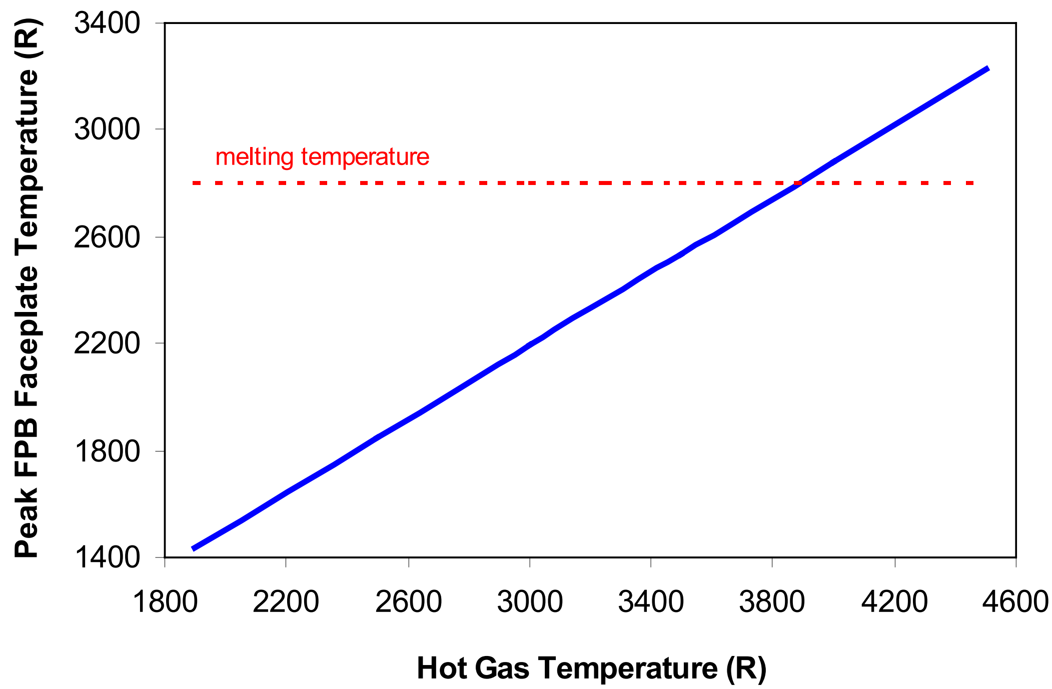


Figure 7.5.3-5 FPB Faceplate Peak Temperature as a Function of FPB Hot Gas Temperature

Thus, the peak local temperature within the FPB can be narrowed to a range of between 2900R, the temperature necessary to melt the HPFT inlet structures, and 3900R, the temperature beyond which the FPB faceplate would be expected to melt and experience significant damage.

7.5.3.4. Streamtube Model of the Preburner Injector

Shown so far are the kinds of temperatures necessary within the FPB to generate the observed thermal damage. According to the previous section, this localized temperature falls somewhere within the range of 2900R to 3900R. What has not been shown is whether these temperatures are indeed conceivable after considering the actual contamination believed to be the root cause of the SSME 0523 failure.

The contamination within the FPB fuel cavity observed post-test 902-772 is mapped out qualitatively in Figure 7.5.3-6.

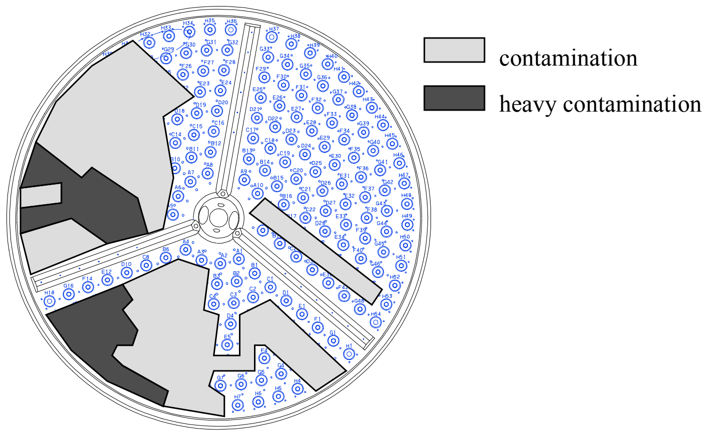


Figure 7.5.3-6. Qualitative Map of Contamination within the FPB Fuel Cavity

An element-by-element streamtube model of the FPB injector was developed to examine the effects of possible propellant blockage within the FPB injector. This is an approximate analysis. While it provides useful first-order estimations of combustion temperatures, it must noted that it cannot fully capture the three-dimensional phenomena taking place within the FPB.

Within the model, the injector is simulated as two parallel resistance networks with the individual injector elements delivering propellants into a geometrical layout similar to the actual FPB injector faceplate. Further, the whole model of the FPB injector is contained within a larger framework of a system-level flow resistance network. This broader network was integrated within the model to capture first-order system effects caused by changes to the overall resistance of the FPB fuel injection network. Iterations are performed at this level to ensure proper system balance between turbine power, pump output, and commanded total engine fuel flow. Mixing within the combustion zone from streamtube to streamtube is performed via iteration based upon element proximity and the minimization of pressure gradients across the faceplate. The calculation of combustion temperatures and pressure generation performance is estimated via curve fits of results generated by the NASA Glenn Research Center program "CEA400: Computer Program for the Calculation of Complex Chemical Equilibrium Compositions and Applications." Thus, each streamtube is modeled as an individual equilibrium combustion chamber generating hot, high-pressure combustion products.

This streamtube model was applied to the qualitative map of contamination shown in Figure 7.5.3-6 with assumptions made as to the values of relative flow area blockage for the "contamination" and "heavy contamination" categories. An example of the output from one of these runs is presented in Figure 7.5.3-7. Here it was assumed that "contamination" corresponded to 40% effective flow blockage and "heavy contamination" corresponded to 80% effective flow blockage.

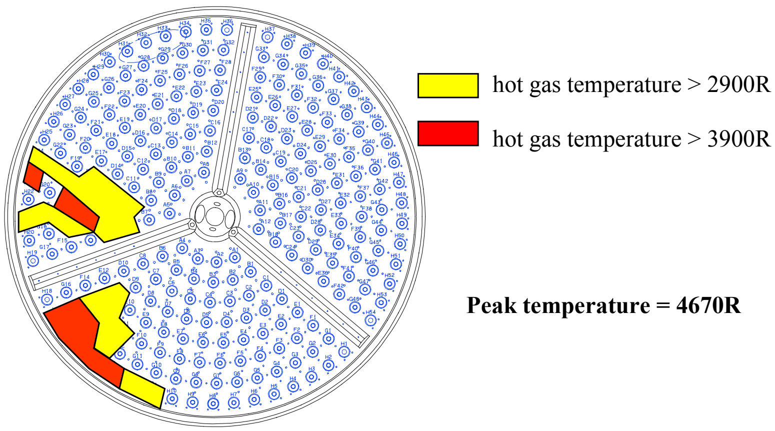


Figure 7.5.3-6. Results from FPB Streamtube Model Assuming 40% and 80% Blockage Levels.

After several runs of the model, it was determined that a maximum effective flow blockage of between 55% and 70% corresponding to the mapped regions of "heavy contamination" will result in localized regions of combustion temperatures between 2900R and 3900R. This level of blockage is consistent with the narrative descriptions of the hardware given by the engineers and technicians performing the engine disassembly inspections at Rocketdyne, Canoga Park, CA.

7.5.3.5. Conclusions

In the preceding sections the following has been demonstrated:

- The range of local FPB combustion temperatures necessary to generate the kind of damage observed on the HPFT inlet is 2900R to 4500R (due to material properties, the transient analysis of the inlet structure leading edges, and the coolant tube analysis provided by Pratt & Whitney).
- The upper limit for local combustion temperature beyond which significant FPB faceplate erosion would have been expected is 3900R (due to the transient thermal model of the FPB faceplate).
- The necessary flow blockage of each of the FPB fuel injector sleeves in the areas with "heavy contamination" to generate localized combustion temperatures between 2900R and 3900R is roughly 55% to 70% (due to the contamination mapping and the streamtube model of the FPB injector).

Thus, the observed damage is consistent with the observed contamination. See Appendix D for a complete report of these analyses.

7.5.4 High Frequency Data Analysis

7.5.4.1 Introduction

Analysis performed on the vibration data acquired from test 902-772 indicated no evidence of anomalous vibration behavior on any of the engine components prior to the initial failure event. Due to the nature of the failure and subsequent observations, the high frequency analysis focused on, but was not limited to, the HPFTP/AT vibration data. No evidence was found in the vibration data acquired from the HPOTP/AT, LPOTP, LPFTP, or the engine gimbal bearing accelerometers that indicated any involvement of those components in the failure.

Two versions of vibration data were utilized in the investigation. Primary analysis relied on vibration data that was digitized and processed real-time on the Real-Time Vibration Monitoring System (RTVMS). RTVMS digitizes the vibration data at a sample rate of 20,480 samples/second and processes the data real-time yielding frequency spectral data out to a maximum of 10,240 Hz. Secondary enhanced analyses were performed on analog tapes that were recorded during the test and digitized post-test at a much higher sample rate of 81,920 samples per second. The significant events of interest that were present in the vibration data are listed in Table 7.5.4-1 below, along with a brief description of the events. Engine start (E/S) is officially listed as 00:168:13:05:03.050 GMT.

Table 7.5.4-1 Significant High Frequency Data Events

Event/Time (GMT)	Event Description
E/S + 4.9680	HPFTP/AT pump-end (P/E) and turbine-end (T/E) accelerometers exhibit synchronous amplitude spike to 8.6 g's root mean square (grms) and 19.9 grms, respectively. The T/E 2x synchronous (2N) amplitude also exhibits a large amplitude spike to 24.8 grms ~0.007 seconds later.
E/S + 5.0120	HPFTP/AT T/E 1N and 2N amplitudes exhibit another large amplitude spike to 15.2 grms and 50.2 grms, respectively.
E/S + 5.1995	HPFTP/AT T/E 1N amplitudes spike to 83.4 grms. P/E 1N amplitude levels spike to 18.5 grms 0.0125 seconds later.

7.5.4.2 HPFTP/AT Analysis

In terms of the vibration data, there was no evidence of any abnormal operation of the HPFTP/AT during the start transient portion of test 902-772. Upon reaching mainstage and until E/S + 4.968 seconds, there was also no evidence of anomalous vibration behavior in any of the HPFTP/AT accelerometer data.

At E/S + 4.968 seconds, however, the HPFTP/AT accelerometer data from both the pump-end (P/E) and turbine-end (T/E) exhibited large amplitude spikes in the synchronous (1N) frequency response data. Amplitudes achieved 8.6 grms and 19.9 grms, respectively. These amplitude levels were predominantly below 0.5 grms prior to the event. The synchronous frequency response is located in the spectra at a frequency equivalent to pump speed and is generated by vibration imparted to the pump housing due to rotation of the shaft. This response is highly indicative of the rotordynamic health of the pump and is a measure of unbalance in the rotordynamic system.

Approximately 0.007 seconds after the initial event, the T/E accelerometers exhibited a large 2x synchronous (2N) amplitude spike to 24.8 grms. Typically, the 2N response is an indicator of rubbing in the turbopump. All of the aforementioned events are believed to have been generated by a loss of turbine blade material induced by impact from a portion of the first stage turbine vanes. Some loss of rotordynamic balance occurred and rubbing ensued in the HPFTP/AT.

The accelerometer data exhibited yet another large amplitude change in the 1N and 2N response amplitudes, primarily in the T/E data, approximately 0.044 seconds later. At this point (E/S + 5.012 seconds), the T/E 1N response spiked to 15.2 grms with the 2N response spiking to 50.2 grms. Heavier rubbing occurred at this time in the HPFTP/AT with more blade material being liberated and the balance of the rotor continuing to degrade.

The accelerometers exhibited the final amplitude increase at E/S + 5.1995 seconds (0.1875 seconds after the second amplitude spiking observation) where the T/E 1N amplitude spiked to 83.4 grms. At this point, the majority of the damage to the turbine blades had been incurred and rotordynamic balance of the HPFTP/AT had been grossly affected. It is also at this point where failure of the HPFTP/AT roller bearing occurred due to the large radial load which was imparted to the bearing. All of the previous amplitude observations can be seen in Figures 7.5.4-1 and 7.5.4-2. These figures show both the P/E and T/E 1N and 2N amplitude data cross-plotted with the HPFT discharge temperature (HPFT DS T) data.

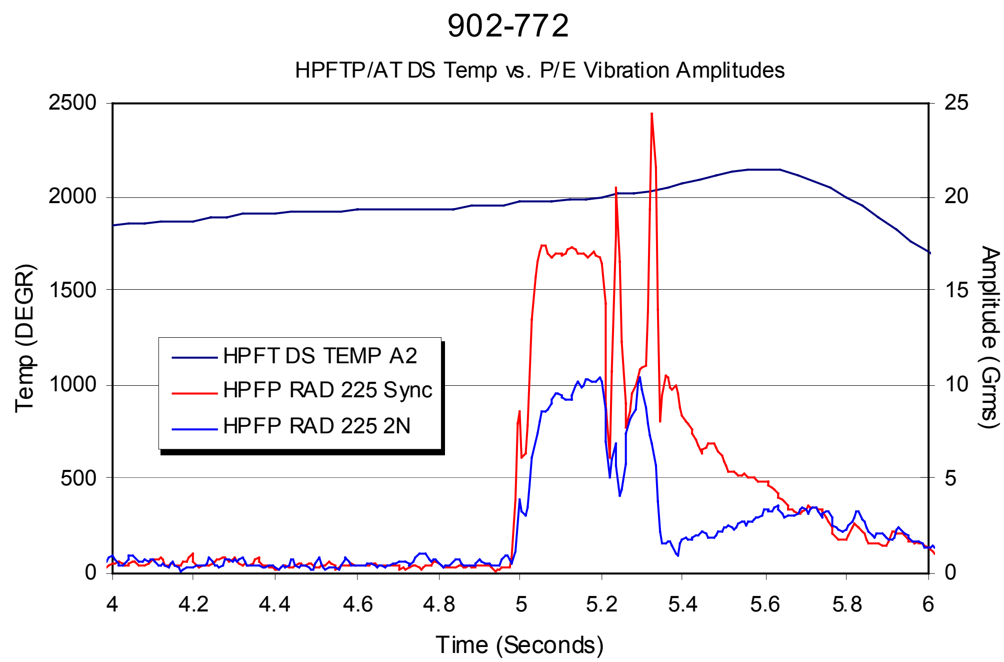


Figure 7.5.4-1 HPFTP/AT Pump-End 1N and 2N Amplitude Trackings with Turbine Discharge Temperature

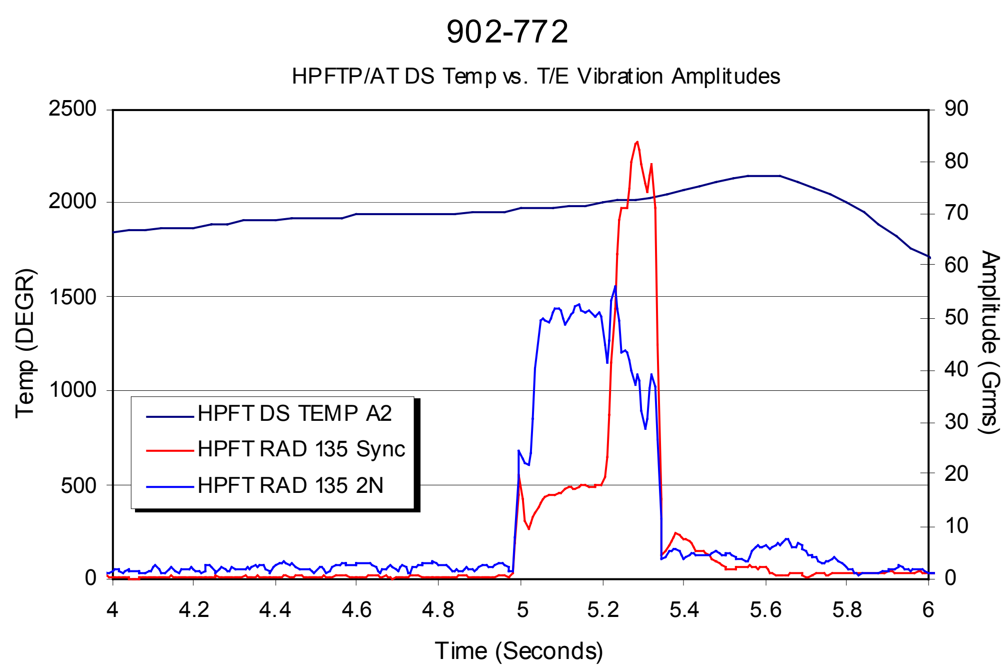


Figure 7.5.4-2 HPFTP/AT Turbine-End 1N and 2N Amplitude Trackings with Turbine Discharge Temperature

7.5.4.3 HPOTP/AT, LPFTP, LPOTP, Gimbal Bearing, and Fuel Flowmeter Analysis

Detailed examination of the data acquired from the accelerometers on the HPOTP/AT, LPFTP, LPOTP, gimbal bearing, and fuel flowmeter did not reveal any vibration anomalies that were relevant to the cause of the failure. All pertinent data from these components was considered to be nominal. Some of the related HPFTP/AT 1N and 2N amplitude observations could be seen in the spectral data of the HPOTP/AT and LPFTP due to feedthrough of these HPFTP/AT signatures through the engine powerhead to these respective engine components.

Enhanced time domain analysis was performed on the engine fuel flowmeter measurement to ascertain whether or not the flowmeter was impacted by any debris associated with the engine failure. Furthermore, the flowmeter data was examined to determine if fuel flow had reversed after the failure occurred. This measurement was digitized from the analog tape at a sample rate of 81,920 samples/second and was scrutinized from engine start to engine cutoff plus 7.0 seconds (~12 seconds of data). In-depth examination of the waveform produced by the flowmeter blade passage response (4 pulses per revolution of the flowmeter from four flowmeter blades) revealed no evidence of perturbation of the waveform pulse response. Impacts on the flowmeter blades by debris would have produced perturbations or inconsistencies in the waveform pattern. Therefore, there is no evidence that the flowmeter was struck by debris during or after the failure. Furthermore, there was no evidence that the flowmeter ceased rotation until it came to rest after engine shutdown. No evidence therefore exists to indicate reversal of fuel flow in the engine. Figure 7.5.4-3 reveals a portion of the fuel flowmeter waveform examined for this investigation.

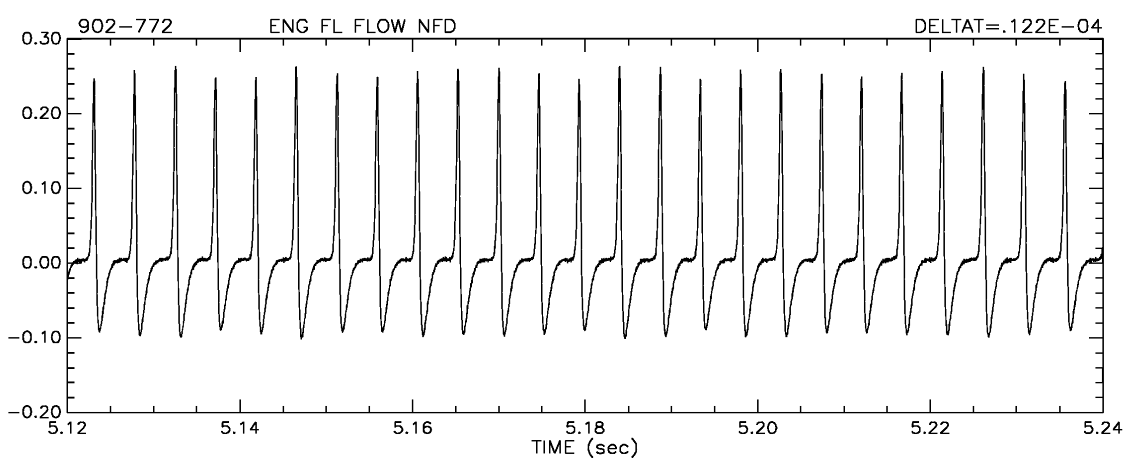


Figure 7.5.4-3 Engine Fuel Flowmeter Instantaneous Waveform

7.5.5 Main Engine Controller, Software, and Command and Data Simulator Analysis

The Block II Controller and Test Software Version AAAC35, with the engine operational data to support the hybrid SSME (standard throat MCC, HPOTP/AT, HPFTP/AT), were used for Test 902-772. The Block II Controller/Software controlled the engine and detected system failures per the software requirements. All actions and responses taken by the Controller/Software were proper and correct for the Test Software Version AAAC35. The Command and Data Simulator (CADS) actions and responses were also proper and correct.

The HPFT DS T redline limits from Start + 5.04 thru 5.78 seconds were set for 1860R for the HPFT DS T Channels A2, A3, B2, and B3. At Start + 5.04 seconds, this HPFT temperature redline was activated. At this time the Channel A HPFT temperature was above the redline limit of 1860R. At 5.08 seconds, the HPFT DS T Channels A2 and A3 had exceeded the redline value of 1860R for three consecutive major cycles. The Controller issued two Failure Identifications (FIDs) with Major Component Failure (MCF) set in the Engine Status Word (ESW) of the Vehicle Data Table (VDT). These FIDs were 113-445 (HPFT DS T Channel A2) and 113-447 (HPFT DS T Channel A3). As the result of the MCF, the CADS initiated the Shutdown Enable and Shutdown Commands sequence to the controller. As the result of receiving the Shutdown Enable and Shutdown commands, the Controller Software initiated the Engine Shutdown sequence at 5.18 seconds. The engine avionics and software all performed nominally during the test.

The VDT from the SSME Controller with the ESW set to MCF was at the Controller time of 5.080 seconds from Engine Start. The VDT is transmitted to the CADS in the fourth minor cycle of the Controller major cycle (20 milliseconds) beginning at approximately 17 milliseconds from the beginning of the major cycle and is completed 2.048 milliseconds later at approximately 19 milliseconds from the beginning of the major cycle.

The CADS has three processors: the Record Processor (RP), the Command Processor (CP) and the Display Processor (DP). Upon receipt of the VDT with the ESW set to Major Component Failure, the Record Processor takes from 10 to 20 milliseconds to notify the Command Processor. The Command Processor takes from 0 to 5 milliseconds to begin transmitting the Shutdown Enable and Shutdown commands to the Controller. The Shutdown Enable and Shutdown commands sequence is transmitted up to 25 times or until the CADS recognizes that the Controller/Engine is in the Shutdown sequence. There is a 30 milliseconds time interval between each command.

Upon receipt of the Shutdown Command by the Controller, there are 5 to 25 milliseconds until the Controller begins the Engine Shutdown Sequence. This time is dependent on when in the Controller Major Cycle the command is received.

For Test 902-772, the VDT with the ESW set to MCF has a Controller time of 5.080 seconds. The last VDT with the Controller/Engine in mainstage is 5.160 seconds. The first VDT with the Controller/Engine in shutdown is 0.020 seconds. Thus, the Controller/Engine entered the Shutdown Sequence at 5.180 seconds from Engine Start or 0.100 seconds from the VDT with MCF set.

7.6 Fault Tree Analyses

A detailed fault tree (Figure 7.6-1) was constructed to graphically depict possible scenarios leading to the damage observed in the High Pressure Fuel Turbine (HPFT) following Test 902-772. A matrix (Table 7.6-1) corresponding to the fault tree blocks was built to collect and document rationale to disposition each fault.

The fault tree process led to the conclusion that the HPFT damage was caused by tape in the Fuel Preburner (FPB) fuel manifold. In order to establish how the tape entered the engine, a matrix (Table 7.6-2) was assembled of SSME 0523 fuel system joints. The size of each joint was recorded in the matrix along with an assessment as to whether or not there was a path from each to the FPB fuel manifold. Joints with a path to the FPB fuel manifold that were large enough to allow the amount of tape observed were identified as "candidate points of entry."

Candidate joints were entered into a matrix (Table 7.6-3) and evaluated against the following criteria:

1) Is the joint located upstream of the engine Fuel Flowmeter (FFM)? If yes, the likelihood that it was the point of entry is lowest since no indications of tape passing through the FFM were observed in the data. Also, no tape was found at the FFM, the High Pressure Fuel Pump (HPFP), the Main Combustion Chamber (MCC), or the nozzle. Note that tape entering upstream of the FFM would be subjected to the fuel system chill and become very brittle and more likely to fragment and disperse throughout the fuel system.
2) Is the joint located upstream of the HPFP discharge? If yes, the likelihood that it was the point of entry is the next lowest since no tape was found at the HPFP, the MCC, or the nozzle. Again note that tape entering upstream of the HPFP would be subjected to the fuel system chill and become very brittle.
3) Is the joint located upstream of the MFV? If yes, the likelihood that it was the point of entry is low since tape entering upstream of the MFV would still be subjected to the fuel system chill and become very brittle and none was found at the MCC or the nozzle.
4) Is the joint located upstream of the diffuser? If yes, the likelihood that it was the point of entry is medium since no tape was found at the MCC or the nozzle.
5) Is the joint located downstream of the diffuser? If yes, the likelihood that it was the point of entry is high since it has a straight path to the FPB fuel manifold and would not be found at other locations in the engine.

In addition to evaluating the candidate joints by location, documentation for each joint was reviewed to see which had been exposed to tape during the assembly process. In all cases where tape was placed into a joint, documents indicated it had been removed and later verified by an independent inspection.

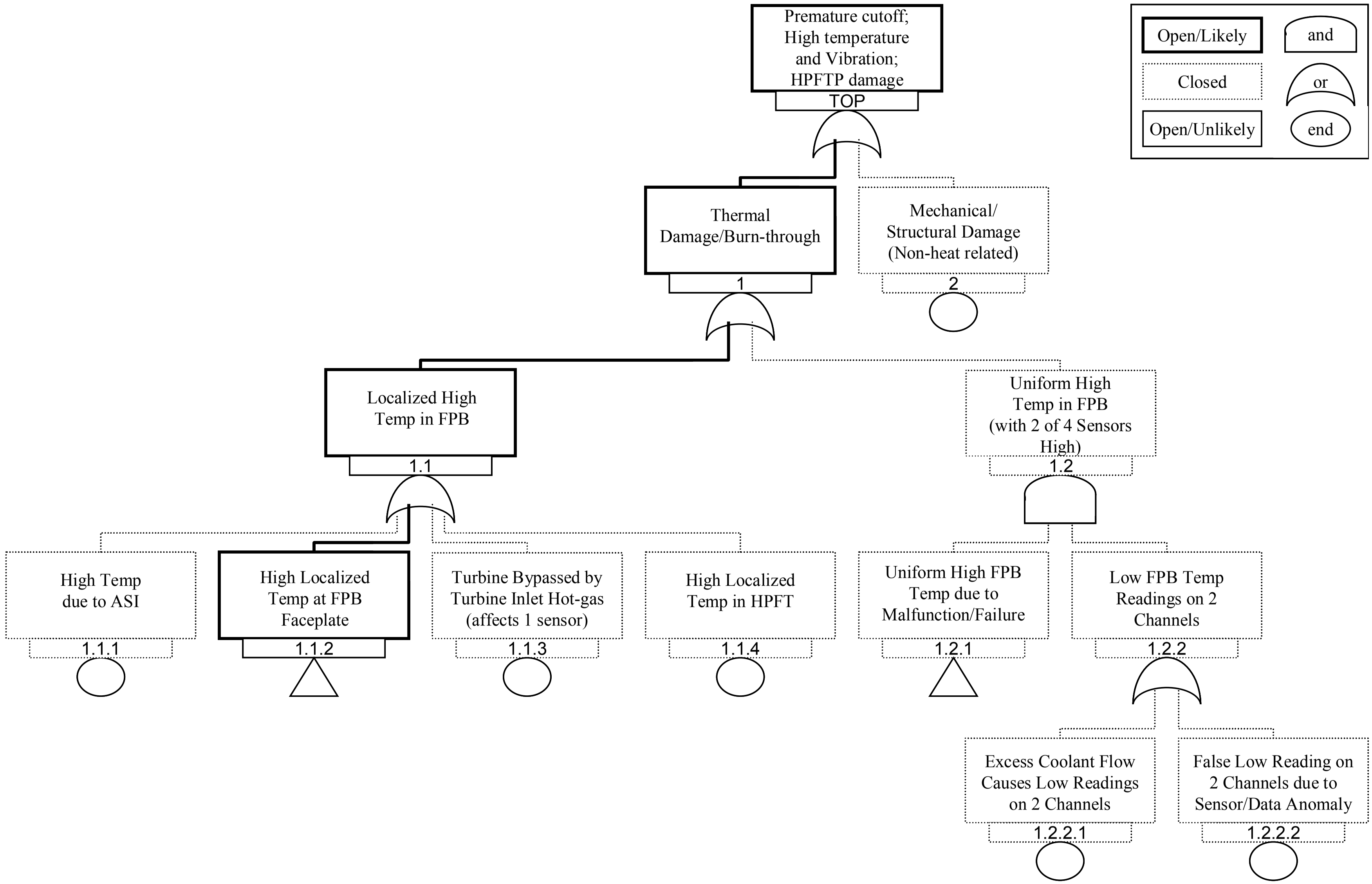


Figure 7.6-1 Test 902-772 Fault Tree Analysis (Page 1 of 4)

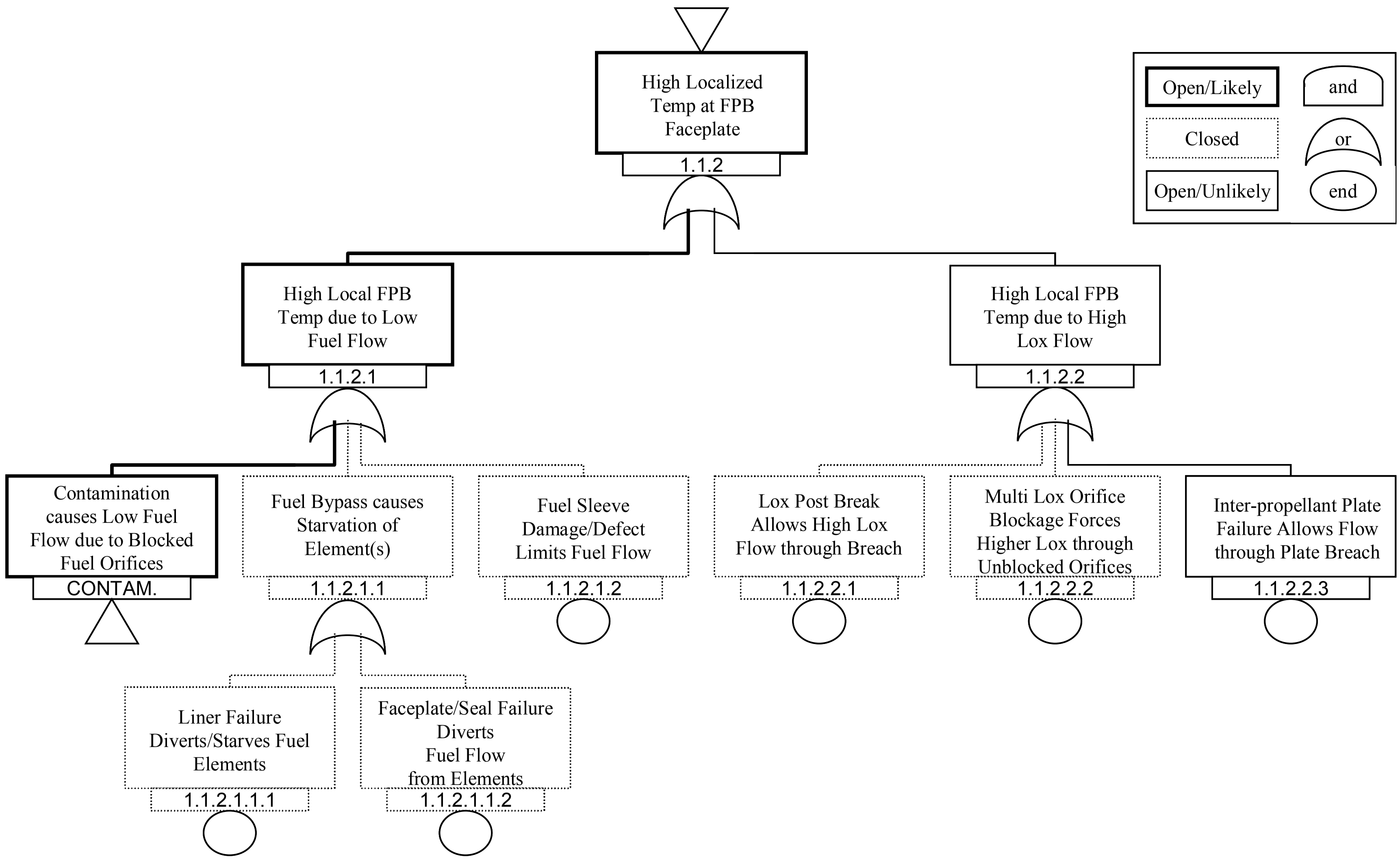


Figure 7.6-1 Test 902-772 Fault Tree Analysis (Page 2 of 4)

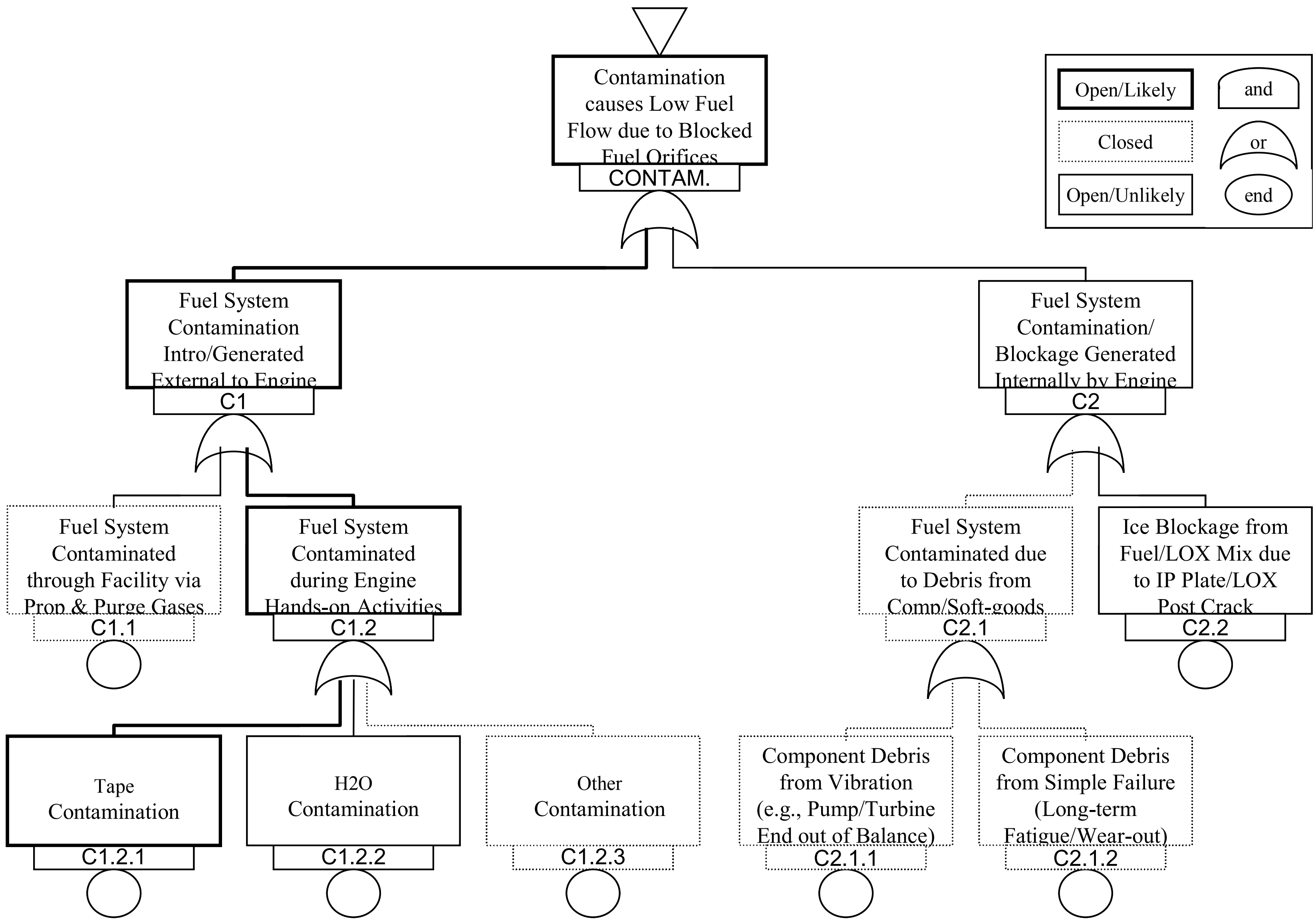


Figure 7.6-1 Test 902-772 Fault Tree Analysis (Page 3 of 4)

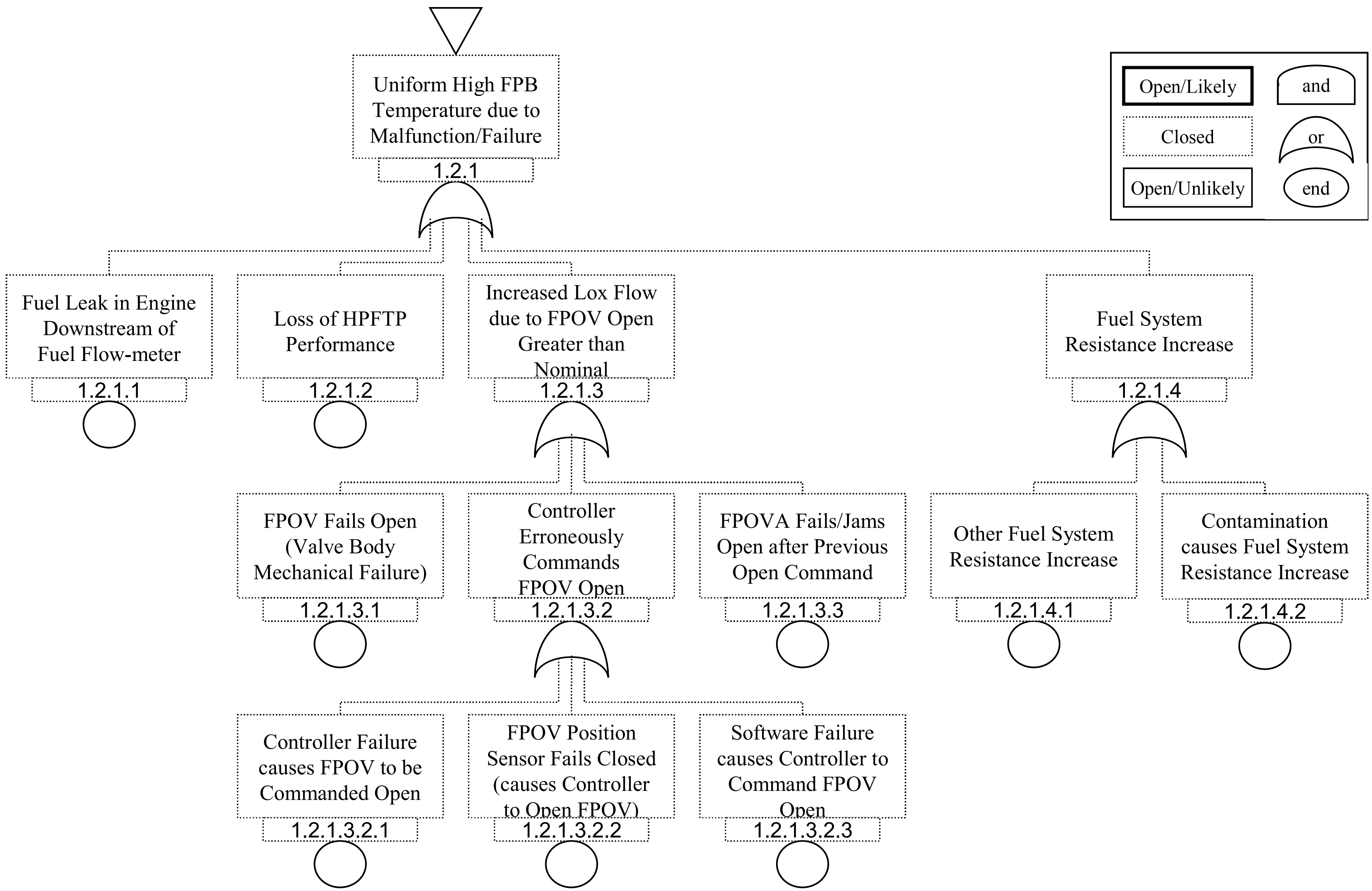


Figure 7.6-1 Test 902-772 Fault Tree Analysis (Page 4 of 4)

Table 7.6-1 Fault Tree Matrix

Block	Description	Status	Pro	Con
TOP	Premature Shutdown--High Temp & Vibration HPFT Damage			
1	Thermal Damage/Burnthrough		Thermal damage to HPFT inlet housing struts and vanes was observed during inspection.	None
1.1	Localized High temperature in FPB		High HPFT discharge temperatures (HPFT DS T) were observed in two of four HPFT DS T sensors. Erosion in a streak down the FPB liner was observed.	None
1.1.1	High Temp due to ASI	Closed	None	Although ASI LOX orifice erosion was observed, it was assessed as a slight progression of a previously documented condition. It was determined that the minor amount of erosion found could not have caused the high temperature observed during the test. No other ASI defect, damage, contamination, or other condition that could have resulted in the high temperature was observed. Also, the HPFT dome was visually inspected and no signs of it being exposed to a high temperature were observed. Note: A high temperature due to an ASI problem usually results in erosion or discoloration of the dome.
1.1.2	High Localized Temps at Fuel Preburner Faceplate		Minor faceplate erosion of FPB and thermal discoloration was observed during visual inspections.	None

Block	Description	Status	Pro	Con
1.1.2.1	High Local FPB Temp due to Low Fuel Flow		Erosion observed on the faceplate and FPB liner, and thermal damage to the turbine are in the vicinity of the greatest concentration of contamination found in the FPB fuel manifold. The contamination was "wrapped" around the fuel sleeves of some elements, reducing their fuel flow.	None
1.1.2.1.1	Faceplate/Seal Failure Diverts/Starves Fuel Flow From Elements	Closed	None	Minor erosion and discoloration of the faceplate was observed as a result of fuel sleeve contamination. However, no faceplate/seal defect, damage, contamination, or other condition that could cause it to divert fuel flow from the fuel elements was observed.
1.1.2.1.2	Fuel Sleeve Damage/Defect Limits Fuel Flow	Closed	None	The ends of the fuel sleeves were borescoped during inspections for contamination of the fuel manifold. During contamination retrieval, a large section of the manifold inlet volute was removed allowing additional borescoping of the fuel sleeves. The fuel sleeve orifices were grossly contaminated but no damage or defect to some of them that could limit fuel flow to the others was observed.
1.1.2.2	High Local FPB Temp Due to High LOX Flow		None	Reference lower blocks 1.1.2.2.1, 1.1.2.2.2, and 1.1.2.2.3

Block	Description	Status	Pro	Con
1.1.2.2.1	LOX Post Break Allows High LOX Flow Through Breach	Closed	None	A LOX post crack allows fuel and LOX to mix and burn above the faceplate. The crack allows higher LOX flow to the affected element which can not only cause a hot streak, but will also damage the element. The ends of the LOX posts and fuel sleeves were borescoped during inspections for contamination of the fuel manifold and no erosion, slag, or burning of the injector elements that would indicate the presence of a LOX post break was observed.
1.1.2.2.2	Multi LOX Orifice Blockage Forces Higher LOX Flow Through Unblocked Orifices	Closed	None	The LOX orifices were borescoped during inspections for contamination of the fuel manifold. No blockage was found that could force higher LOX flow through unblocked orifices.
1.1.2.2.3	Interpropellant Plate Failure Allows LOX Flow Through Plate Breach		None	Interpropellant plate leak test performed. No anomalies were noted.
1.1.3	Turbine Bypassed by Turbine Inlet Hot Gas (affects one sensor)	Closed	None	No indications of turbine hot gas bypass were observed during teardown inspections. Metallic deposits were noted on the turbine bellows heat shield, however, the shield exhibited normal, uniform colorations. The bellows liner and seals, and the bellows itself were reported as nominal. No evidence of the preburner streak was observed on the bellows liner that is between the bellows and the preburner liner.

Block	Description	Status	Pro	Con
1.1.4	High Localized Temp in HPFT	Closed	None	Teardown inspections revealed that the only indication of a high localized temperature in the HPFT was damage to the TIH struts and wall, and first stage vanes in the vicinity of the preburner liner and faceplate erosion. The front side of the disk was nominal with no signs of coolant loss. The gold plate was present on the blade fir-trees except in areas where high loads are suspected. E30
1.2	Uniform High Temp in FPB with 2 of 4 Sensors High		None	Reference lower blocks 1.2.1 and 1.2.2
1.2.1	Uniform High FPB Temp Due to Malfunction/Failure		None	Reference lower blocks 1.2.1.1, 1.2.1.2, 1.2.1.3, and 1.2.1.4

Block	Description	Status	Pro	Con
1.2.1.1	Fuel Leak in Engine System Downstream of Fuel Flow Meter	Closed	None	MCC and Nozzle leak tests have not been completed, but the condition of the fuel system with respect to leaks has been reported to be acceptable based on visual inspection. MCC hotwall channel cracks were observed during initial inspections, but they appear similar to previously documented conditions and are not believed severe enough to have caused a significant increase in the HPFT DS T. Data analysis and a review of test video support the conclusion that no significant leak existed. The analysis indicated that if the 200R increase in HPFT DS T observed during the test was due to a fuel leak downstream of the flowmeter, it would have been accompanied by a 340R increase in HPOT discharge temperature and a 8% increase in OPOV position. By contrast, the observed deltas from the predicted HPOT discharge temperature and OPOV position were approximately 53R and 1.6%, respectively.
1.2.1.2	Loss of HPFTP/AT Performance	Closed	None	Data analysis indicated nominal HPFTP/AT performance from engine start to cutoff. Pump delta pressure over speed squared versus volumetric flowrate over speed was reported to be within family when compared to the database.

Block	Description	Status	Pro	Con
1.2.1.3	Increased LOX Flow Due to FPOV Open Greater than Nominal	Closed	None	Data analysis indicated nominal FPOV/FPOVA performance during all phases of operation. With the exception of the hot streak in the fuel preburner, engine performance was nominal. No unusual transient characteristics were observed except for the rapid decline in HPFTP/AT speed during shutdown. The FPOV position was within 2.6% of its predicted value, however, part of this error is due to this being the first test of this hardware combination and the fact that the prediction had to be revised for engine start plus 5 seconds. OPOV position was within 1.6% of its predicted value. When MCC Pc began to fall as a result of fuel turbine blade failure, the FPOV responded as expected to a command to open. A full disassembly of the FPOV/FPOVA has not been performed, but there have been no reports of damage to either component during their removal from the engine. Reference Block 1.2.2.2 rationale with respect to control related issues.
1.2.1.3.1	FPOV Fails Open (Valve Body Mechanical Failure)		None	Reference higher block 1.2.1.3
1.2.1.3.2	Controller Erroneously Commands FPOV Open		None	Reference higher block 1.2.1.3
1.2.1.3.2.1	Controller Failure Causes FPOV to be Commanded Open		None	Reference higher block 1.2.1.3.2

Block	Description	Status	Pro	Con
1.2.1.3.2.2	FPOV Position Sensor Fails Closed (Causes Controller to Open FPOV)		None	Reference higher block 1.2.1.3.2
1.2.1.3.2.3	Software Error Causes Controller to Command FPOV Open		None	Reference higher block 1.2.1.3.2
1.2.1.3.3	FPOV Actuator Fails/Jams Open After Previous Open Command		None	Reference higher block 1.2.1.3
1.2.1.4	Fuel System Resistance Increase		None	Reference lower blocks 1.2.1.4.1 and 1.2.1.4.2
1.2.1.4.1	Other Fuel System Resistance Increase Mechanism	Closed	None	No discernible effect on engine performance due to a fuel system resistance increase was observed in the digital data. Data analysis indicated that if the 200R increase in HPFT DS T was due to a fuel system resistance increase, it would have been accompanied by a 1500 rpm increase in HPFTP/AT speed and a 1100 psi increase in HPFP discharge pressure. By contrast, the observed deltas from the predicted HPFTP/AT speed and HPFP discharge pressure were approximately 245 rpm and 42 psi respectively.

Block	Description	Status	Pro	Con
1.2.1.4.2	Contamination Causes Fuel System Resistance Increase	Closed	None	Gross contamination was found around the fuel sleeves in the fuel preburner fuel manifold. It had no discernible effect on engine performance. Reference Block 1.2.1.4.1 rationale. Overall engine performance effects due to fuel sleeve contamination is small in part because the fuel is gaseous when it reaches the manifold.
1.2.2	Low Fuel Preburner temperature Readings On 2 Channels		None	Reference lower blocks 1.2.2.1 and 1.2.2.2
1.2.2.1	Excess Coolant Flow Causes Low Readings on 2 Channels	Closed	None	Two HPFT DS T channels were over 180R above of their expected values. The other two channels were within 50R their expected values. Other engine performance parameters were also within expected values. This, and the known presence of a hot streak in the FPB (Reference Block 1.1 and subs rationale) indicates that the two "lower" sensors were reading accurately and were not being influenced by excess coolant flow. The HPFT is not a candidate source for excess coolant since all four HPFT coolant tubes are intact

Block	Description	Status	Pro	Con
1.2.2.2	False Low Readings on 2 Channels Due to Sensor/Data System Anomaly	Closed	None	A complete review of the data recorded during pretest checkouts, during the hotfire, and post-test was completed by Avionics Engineering at SSC. The data review indicated that all electrical systems on the engine and in the facility were functioning normally. This includes the CADS and its interface to the facility and the engine, the controller, actuators, transducers, and other interfacing hardware that might be related to this incident.
2	Mechanical/Structural Damage (Non-Heat Related)	Closed	None	Disassembly inspections and data analyses reveal that structural damage to the HPFTP occurred after and as a result of thermal damage. There is no evidence of 1st vane mechanical failure. All vane retention OD features are intact. ID platforms and airfoils experienced thermal damage. Pump performance characteristics were nominal. All bearing frequencies were nominal prior to cut-off. The turbine-end roller bearing failed due to high loads during shutdown.
CONTAM	Contamination Causes Low Fuel Flow by Blocking Fuel Orifices		Inspections revealed gross contamination of the FPB fuel sleeve orifices.	None
C1	Fuel System Contamination Introduced/Generated External to the Engine		LOX tape contamination found in preburners is foreign to the engine.	None

Block	Description	Status	Pro	Con
C1.1	Fuel System Contaminated Through Facility via Propellants and Purge Gases	Closed	None	All fluid interfaces between the facility and the engine fuel system were inspected and sampled. This includes the engine inlet, F1; the fuel bleed, F4.3; the fuel tank pressurization, F9.3; the helium inlet, P1; and the GN2 inlet, N1. The frantz screen in the fuel feedline was also inspected. No "out-of-spec" condition was found.
C1.2	Fuel System Contaminated During Engine "Hands On" Activities		A review of records and statements confirms the use of LOX tape in and around Engine 0523's fuel system.	None
C1.2.1	Tape Contamination		Materials analyses confirm that the major contaminant found in the preburner fuel manifolds is LOX tape. Insignificant amounts of other contaminants generated during the failure or resulting from assembly operations were also found. Reference Block C2.1.1 rationale.	None

Block	Description	Status	Pro	Con
C1.2.2	H2O Contamination		None	There were no special operations performed on E0523 following its last test prior to 902-772 which would have subjected it to water contamination. The drying procedures used to dry E0523 and verify that it was dry prior to 902-772 has been used successfully on all engine configurations (Phase II, Block I, Block II, and Block IIA). E0523 was dried and verified dry prior to test 902-772 per normal procedures. Two tests where engines were damaged by water contamination occurred early in the program (1980 and 1982) prior to implementing the current drying procedure.
C1.2.3	Other Contamination	Closed	None	Extensive visual inspections and borescoping of the engine were performed and contaminants were collected and analyzed. Normal contamination was observed, but besides LOX tape, no significant amounts of foreign contaminants were found.
C2	Fuel System Contamination/Blockage Generated Internally by Engine		None	Reference lower blocks C2.1 and C2.2
C2.1	Fuel System Contaminated Due to Debris from Components/Softgoods		None	Reference lower blocks C2.1.1 and C2.1.2

Block	Description	Status	Pro	Con
C2.1.1	Component Debris from Vibration (e.g., Pump or Turbine End Out of Balance)	Closed	None	Small amounts of HPFTP/AT material have been found throughout the fuel system. Some of the material was shed due to HPFTP/AT rotor imbalance and rub as a result of losing turbine blades. It is believed that the turbine vanes were cut in two and the inner portion fell into the blades causing them to fail. Additional debris was generated when other HPFTP/AT piece-parts, such as the roller bearing, broke as the failure progressed. The amount of component material found could not significantly affect preburner element performance.
C2.1.2	Component Debris from Simple Failure (Long-term Fatigue/Wear-out)	Closed	None	Reference Block C2.1.1 rationale. Evidence suggests that all component failures resulted from the high preburner temperature. No other component failures have been reported.
C2.2	Ice Blockage Formed From Fuel/LOX Mix Due to Interpropellant Plate/LOX post crack		None	Reference Block 1.1.2.2.3 rationale. The ends of the LOX posts and fuel sleeves were borescoped during inspections for contamination of the fuel manifold and no erosion, slag, or burning of the injector elements that would indicate the presence of a LOX post break was observed. Reference Block 1.1.2.2.1 rationale.

Table 7.6-2 All Joints Matrix

Joint	Description	Size	Path	Comment
F1	LPFTP Inlet	12.06"	Y	
F1.1	LPFTP Shaft Speed Sensor Port	0.375"	N	
F2	LPFTP Discharge/LPFTP Discharge duct	5.2"	Y	
F2.2	LPFTP Discharge Pressure Sensor line	0.44"	Y	
F2.2.1	LPFTP Discharge Pressure Sensor line to Sensor	0.44"	Y*	*Path back to HPFP inlet
F2.3	LPFTP Discharge Temperature Sensor	0.44"	Y	
F3	LPFTP Discharge Duct to HPFTP/AT Inlet	5.2"	Y	
F3.1	HPFTP/AT Shaft Speed Sensor	0.385"	Y	
F3.1.4	Ball Bearing Borescope Access	0.5"*	Y	*0.010" to 0.012" internal clearance
F3.4	HPFTP/AT Torque Access Port	1.197"*	Y	*0.010" to 0.012" internal clearance
F4	HPFTP/AT Discharge to HPF Duct	3.4"	Y	
F4.1	HPFTP/AT Discharge Duct Pressure Line	0.44"	Y	
F4.1.1	HPFTP/AT Discharge Duct Pressure Line to Sensor	0.44"	Y*	*Path back to HPFP discharge
F4.1.2	HPFTP/AT Discharge Duct Facility Sensor	0.44"	Y	
F4.2	HPF Duct to Fuel Bleed Duct	2.35"	Y	
F4.2.1	Fuel Bleed Duct to Articulating Fuel Bleed Duct	1.18"	N	
F4.3	Articulating Fuel Bleed Duct to Interface	1.18"	N	
F5	Main Fuel Valve Inlet	2.5"	Y	
F5.1	Fuel ASI to Fuel ASI Filter	0.615"	Y	
F5.1.1	Fuel ASI Filter to Fuel ASI line	0.6"	N	
F5.2	Fuel ASI Line to MCC	0.124"	N	
F5.3	Main Fuel Valve to Actuator	N/A	N	
F6	MFV to Nozzle Diffuser	2.7"	Y	
F6.1	Fuel System Purge Line to Nozzle	0.375"	Y	
F6.1.1	Fuel System Purge Line to Nozzle	0.437"	Y	
F6.1.2	Fuel System Purge Line to Nozzle	0.1345"	Y	
F6.4	Fuel Diffuser to MCC Coolant Manifold	1.86"	Y*	*Path back to diffuser
F6.6	Plate to Coolant Manifold Boss	0.44"	Y*	*Path back to diffuser
F6.6.1	MCC Body (Coolant Manifold Port)	N/A	N	

Joint	Description	Size	Path	Comment
F6.10	Plug to Nozzle Fuel Manifold Drain	0.25"	Y*	*Path back to diffuser
F6.11	Plug to Nozzle Fuel Manifold Drain	0.25"	Y*	*Path back to diffuser
F6.13	CCVA to CCV	N/A	N	
F7	MCC to LPFTP Turbine Drive Duct	2"	N	
F7.1	MCC Coolant Outlet Temperature Sensor	0.44"	N	
F7.1a	MCC Coolant Outlet Pressure Sensor	0.44"	N	
F7.2	LPFTP Turbine Drive Duct Port	0.44"	N	
F8	LPFTP Turbine Drive Duct	2"	N	
F9	LPFTP Turbine Discharge Duct	8.3"	N	
F9.1	LPFTP Turbine Discharge Duct Torque Access Port	0.54"	N	
F9.2	LFPTP Turbine Discharge Duct to Tank Pressurant Duct	0.62"	N	
F9.3	Fuel Tank Pressurant Duct to Interface	N/A	N	
F10	LPFTP Turbine Discharge Duct to HGM	2.7"	N	
F11	CCV to Nozzle	3.755"	Y	
F12.1	Plate to HGM boss	0.44"	Y	
F16	HGM to MCC	N/A	N	
F17	Mixer Bowl to FPB Supply Duct	4.1"	Y	
F20	HPFTP/AT Balance Cavity Pressure	0.81"*	Y	*0.0228" internal clearance
F21	FPB ASI Fuel Supply Line to FPB	0.178"	N	
F22	ASI Fuel Supply Line to FBP ASI Fuel Line	0.375"	N	
F23	ASI Fuel Supply Line to OBP ASI Fuel Line	0.375"	N	
F25	ASI Fuel Line to OPB	0.1802"	N	
N11	Turbine Area Drying Purge	0.28"	N	
N11.3	Turbine Housing Drying Purge	0.562"	N	
N11.4	Turbine Housing Drying Purge	0.562"	N	

(shaded)	Denotes that a joint is either less than 1" or it does not have a path to the FPB fuel manifold.

Table 7.6-3 Candidate Joint Matrix

Joint	Description	Likelihood (See Note)	Upstream of: FFM	HPFP	MFV	Diffuser
F1	LPFP Inlet	LOWEST	Y	Y	Y	Y
F2	LPFP Discharge to LPFD	LOWEST	Y	Y	Y	Y
F3	LPFD to HPFP Inlet	LOWER	N	Y	Y	Y
F4	HPFP Discharge to HPFD	LOW	N	N	Y	Y
F4.2	HPFD to Fuel Bleed Duct	LOW	N	N	Y	Y
F5	HPFD to MFV Inlet	LOW	N	N	Y	Y
F6	MFV to Nozzle Diffuser	MEDIUM	N	N	N	Y
F6.4	Fuel Diffuser to MCC Coolant Manifold	MEDIUM	N	N	N	Y
F11	CCV to Nozzle	HIGH	N	N	N	N
F17	Mixer Bowl to FPB Supply Duct	HIGH	N	N	N	N

Notes: Each candidate joint is greater than 1" and has a path to the FPB fuel manifold. Likelihood is based on joint location. Refer to paragraph 7.6 for rationale.

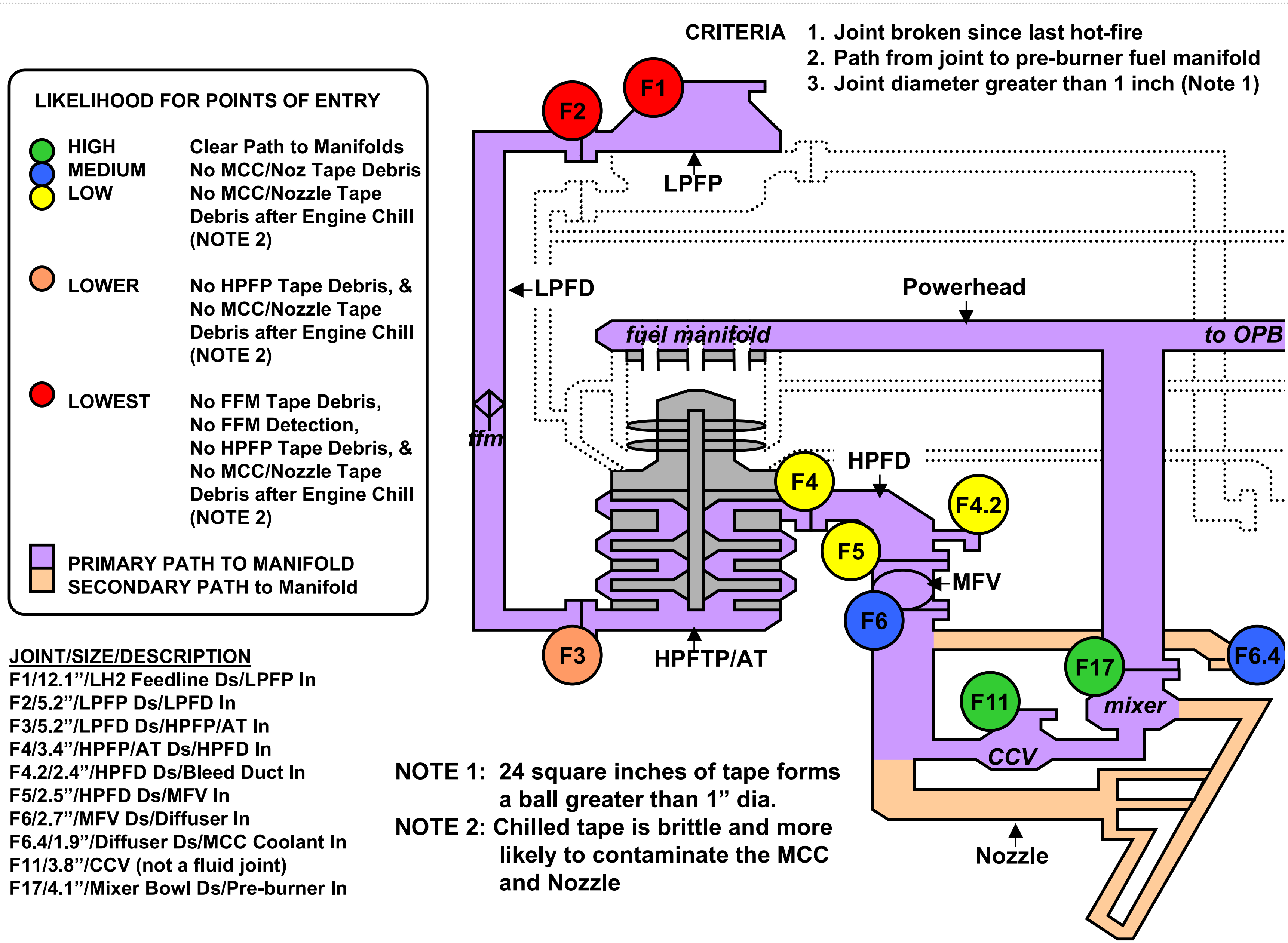


Figure 7.6-2 Candidate Fuel System Points of Entry

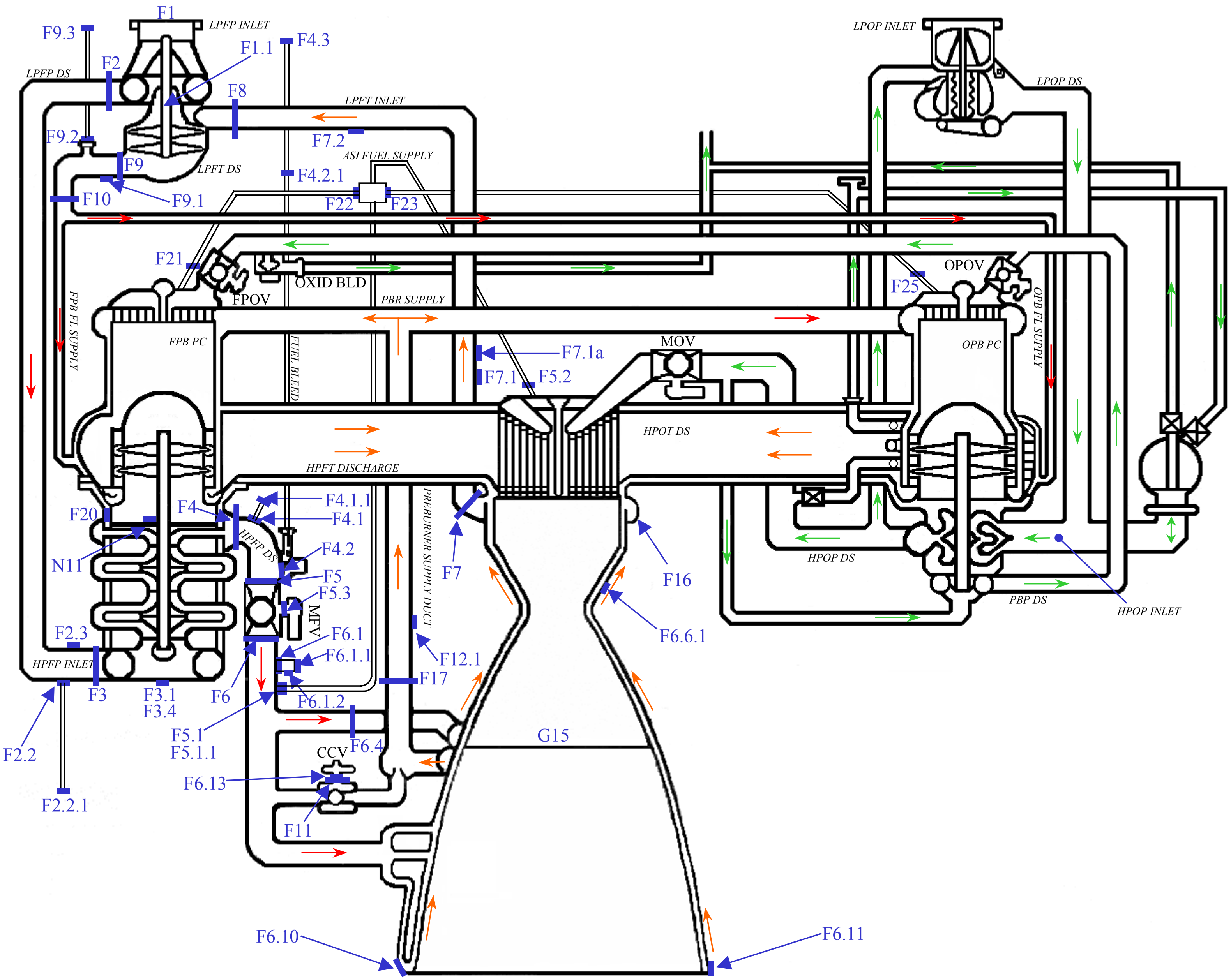


Figure 7.6-3 Fuel System Joints

7.7 Engine Operations Timeline

The timeline of operations on SSME 0523 between the incident hotfire, 902-772 and its previous test, 904-363 was reviewed for indications of when LOX tape contamination could have been introduced into the fuel system. During this time, the engine was partially disassembled, returned to Canoga Park for further disassembly, and reassembled in a different configuration. SSME 0523 was built as a hybrid Block I/II engine (standard throat MCC, HPOTP/AT, and HPFTP/AT) intended to demonstrate safe operation of the flight HPFTP/AT at the HPFT Discharge Temperature redline condition (1860R) for approximate mission duration. A detailed timeline of operations on all fuel system joints is shown in Appendix G.

Prior to the most recent build, SSME 0523 was used for Block IIA development testing on test stand B-1. The final test of the series was conducted on October 5, 1998 for a duration of 520 seconds. No contamination issues were identified post-test.

Following completion of the test series, the engine was moved to Building 3202 at Stennis Space Center (SSC). Hardware was removed from the engine over the next few months to support other engines at SSC or returned for rework. Hardware removed from the engine included all four turbopumps, numerous ducts and lines, igniters, harnesses, and sensors. Other hardware removed during engine processing was protected with closures and set aside, but remained allocated to the engine.

When SSME 0523 was selected for the redline demonstration, the engine was returned to Canoga Park on February 18, 2000, along with removed hardware that was still allocated to the engine.

Additional disassembly was performed at Canoga Park, including removal of the MCC and nozzle. Complete disassembly of the engine was not required since most of the engine components (harnesses, small lines, sensors, etc.) were reused. All major fuel joints were separated during disassembly.

The configuration of SSME 0523 was established with an approved and released modification drawing specifically for this engine rather than a released configuration. Completion of the modification drawings took longer than expected thereby delaying the start of engine build. The delay compressed the build schedule, and two extended shifts were used for the final part of engine assembly. Delays in planning also resulted in operations being conducted out of sequence. Engine partial disassembly was accomplished at two different locations, SSC and Canoga Park. However, a complete disassembly was never accomplished.

The engine was reassembled at Canoga Park during April and May 2000. The engine was shipped to SSC on May 16, 2000 with all major components installed except for the high pressure turbopumps. Pump simulators were installed for delivery.

Records indicate that all major joints in the fuel system were borescoped before installation except the powerhead joints. The period of time between borescope inspection and mating of the joints varied from the same day up to six days for F17, ten days for F6 and F11, and nineteen days for F3 and F4. During build operations at Canoga Park, fuel joints F2, F6.4, and F17 were lapped utilizing internal tape barriers. A summary of the engine operations affecting the fuel joints of primary concern is shown in Figure 7.7-1, including lapping, borescope inspections, and installation of the major fuel hardware replacements detailed below.

The Powerhead U/N 6004 was a Phase II+ configuration with a single tube heat exchanger, and is the Phase II+ fleetleader in starts and seconds. The Main Injector U/N 4020 had solid fuel sleeves in all 13 rows, and 37 Boundary Layer Coolant (BLC) holes opened for testing with a standard throat MCC. The Fuel Preburner had a Block II liner extension. The powerhead was borescope inspected post-test 904-363 at SSC and closures were installed on all open joints. No borescope inspections of the powerhead were performed during subsequent engine assembly.

The standard throat MCC U/N 2026 was retired from Block I flight SSME 2042 with nominal MCC coolant resistance and minimal hot-wall liner leakage.

The Nozzle U/N 4014 was a ground test unit with welded steerhorns and stubouts that was retired from the flight program. The nozzle has been hotfired in the development program for several years, most recently on SSME 2015.

The Main Fuel Valve (MFV) S/N 4924200 was previously hotfired on SSME 0522 and reworked to incorporate the sleeve redesign.

The Low Pressure Fuel Duct (LPFD), High Pressure Fuel Duct (HPFD), and Coolant Control Valve (CCV) had been removed, but remained allocated to SSME 0523. Pump simulators were removed at SSC and high pressure pumps were installed prior to test. During SSC pre-test processing, fuel joints F1, F3, and F4 were lapped utilizing internal tape and Aclar barriers. A list of fuel joints affected during engine operations at SSC is included in Figure 7.7-1.

The HPFTP/AT U/N 8109R1 was rebuilt at P&W. Joints F3 and F4 were borescope inspected and the turbopump was shipped to SSC on May 4, 2000.

Review of engine operations at both Canoga Park and SSC shows that there were numerous opportunities for the introduction of contamination at locations throughout the fuel system. However, there is no documented evidence to indicate the source of the LOX tape contamination. All records reviewed indicate that lapping barriers were removed, joint closures were installed and removed properly, and hardware was inspected according to established procedures.

The MSFC Mishap Investigation Team conducted on-site visits to Rocketdyne and Pratt & Whitney. A review was conducted of the Manufacturing Operations Record (MOR Books) at Rocketdyne and Space Propulsion Assembly Operation Sheets (SPAOS) at Pratt & Whitney. Specifically under consideration were fuel system operations. The purpose of the review was to identify any anomalies or deviations in the build or inspection process and to determine if any tape could have been introduced in the engine during engine or pump assembly operations. A special emphasis was placed on reviewing the following:

1. Fuel joints broken or covers removed for any reason.
2. Closures used and verification for closure removal.
3. Verification of borescope or visual inspection prior to installation.
4. Internal use and removal of LOX tape.
5. Any unusual processes in the fuel system.
6. Work transferred from Canoga Park to SSC and from Pratt & Whitney to SSC.

It was determined by the team that several items from Rocketdyne, Canoga Park, had been shipped to SSC as open items. Specifically joints F3 and F4 were delivered on the engine with open paper work. It was discovered that these joints were shipped with simulator turbopumps attached and the paperwork was subsequently closed at SSC with no anomalies found. In all areas of the engine where tape was used, paperwork indicates removal was verified by borescope inspection, visual inspection, or both.

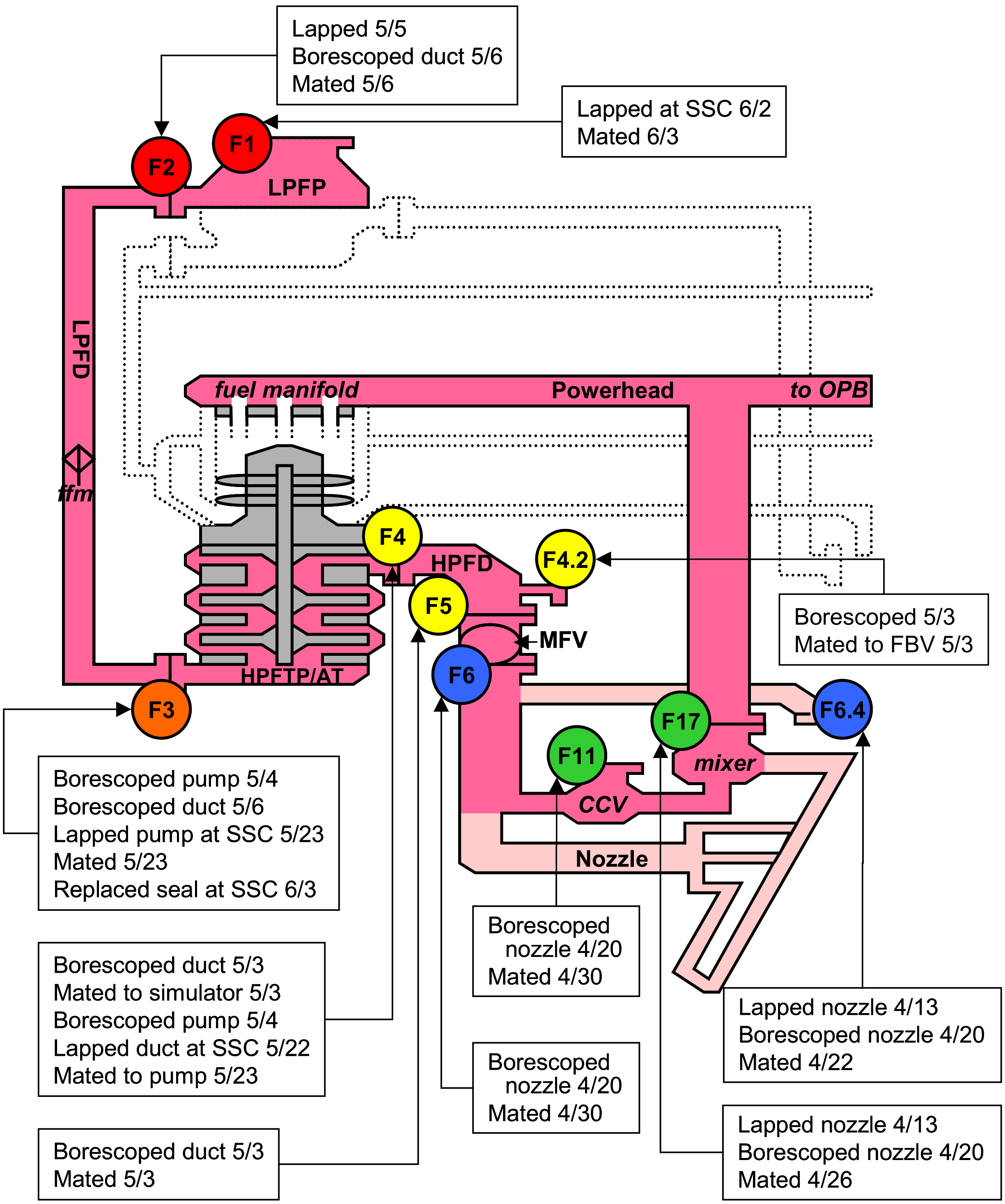


Figure 7.7-1 Summary of Pre-Test Operations on Fuel System Joints

8.0 Most Probable Failure Scenario

During the assembly of SSME 0523, tape was introduced into the fuel system during some "hands on" process (temporary closure, contamination barrier, unintentional introduction, etc.). A list of the probable locations of introduction is discussed in Section 7.6. The tape contamination went unnoticed and was left in the fuel system during the remainder of assembly and pre-test activities.

On June 16, 2000, Stennis Space Center conducted test 902-772. SSME 0523 was to be tested for a scheduled duration of 200 seconds. At engine start the tape contamination was forced downstream in the fuel system, eventually coming to rest as debris in both the Fuel Preburner (FPB) injector and Oxidizer Preburner (OPB) injector. The amount of debris in the FPB was sufficient to block multiple fuel inlet holes of several FPB injector elements in localized areas.

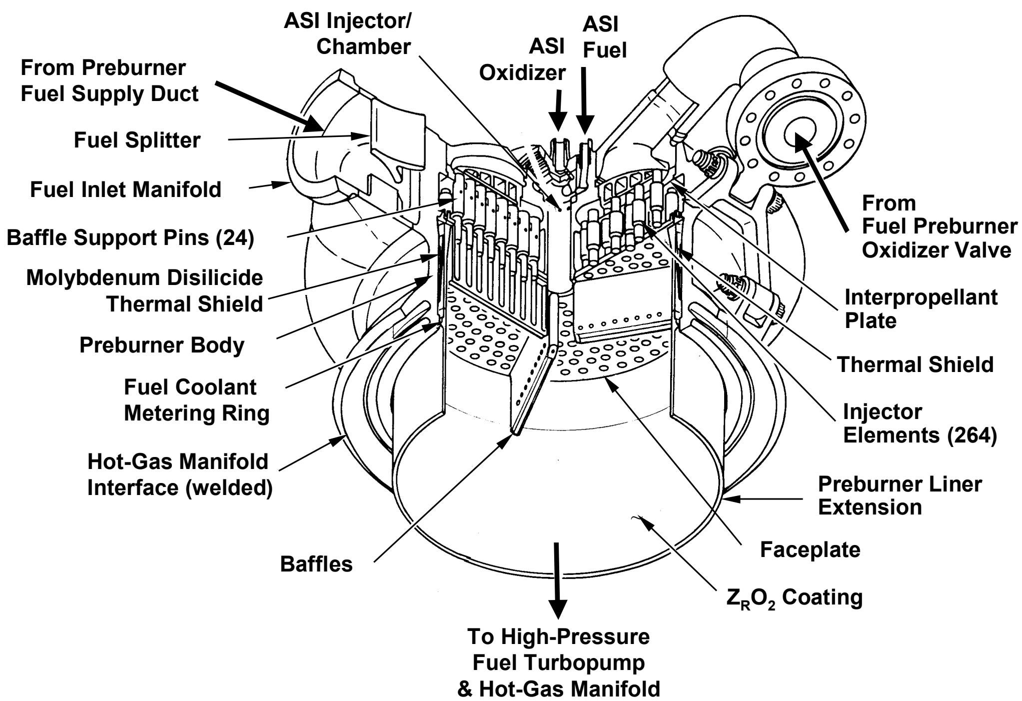


Figure 8.0-1 Schematic of the FPB Injector Assembly

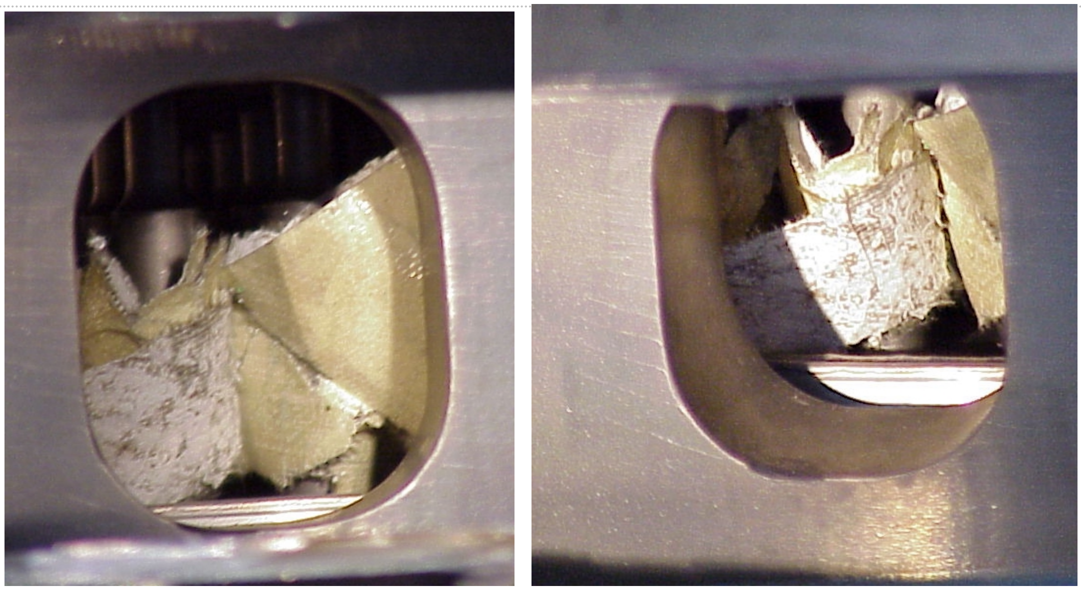


Figure 8.0-2 Tape Contamination Observed Through FPB Fuel Manifold Windows Upon Disassembly

This blockage caused a localized high mixture ratio area in the preburner without affecting overall engine system performance. Data analysis indicates a localized temperature increase occurred in the vicinity of HPFT DS T Channel A measurement and the HPFT DS T measurement at joint KG2dT beginning at approximately 2.7 seconds.

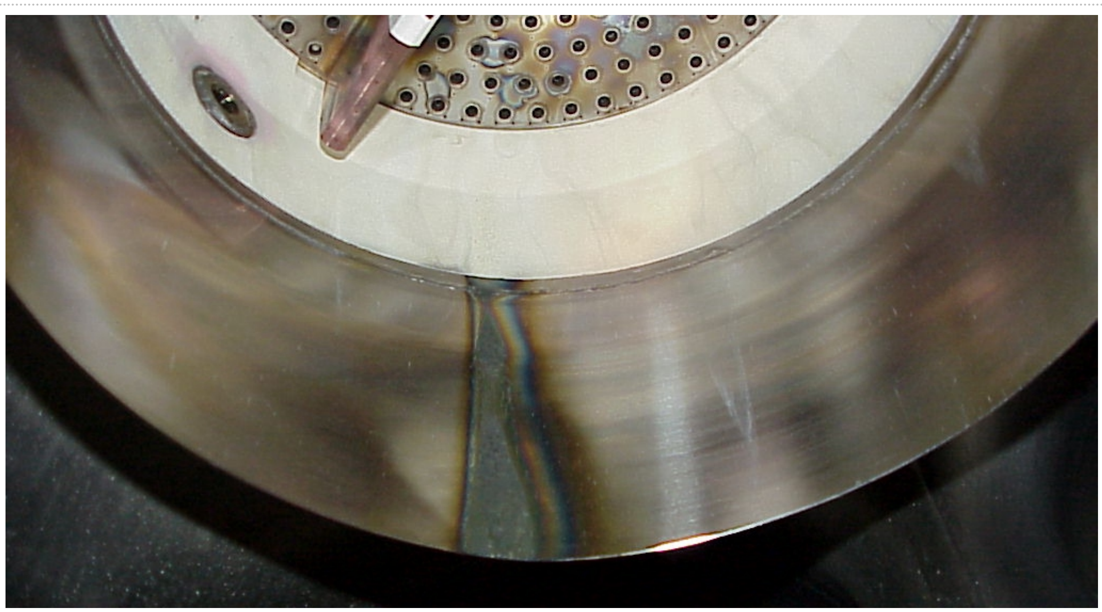


Figure 8.0-3 Fuel Preburner Liner Streak

The localized temperature increase caused melting of the turbine inlet housing struts and first stage vanes in the HPFTP/AT. At 4.97 seconds, all three airfoils on first stage vane segment number 23 were melted through the chord, causing local structural failure of that segment of vanes. The inner platform of vane segment number 23 fell into the hot gas flow stream impacting the first stage blades. This caused the first stage blades to fail creating significant HPFTP/AT rotor imbalance. Data analysis indicates synchronous vibrational level increases of approximately 8 grms on the pump end and 20 grms on the turbine end.

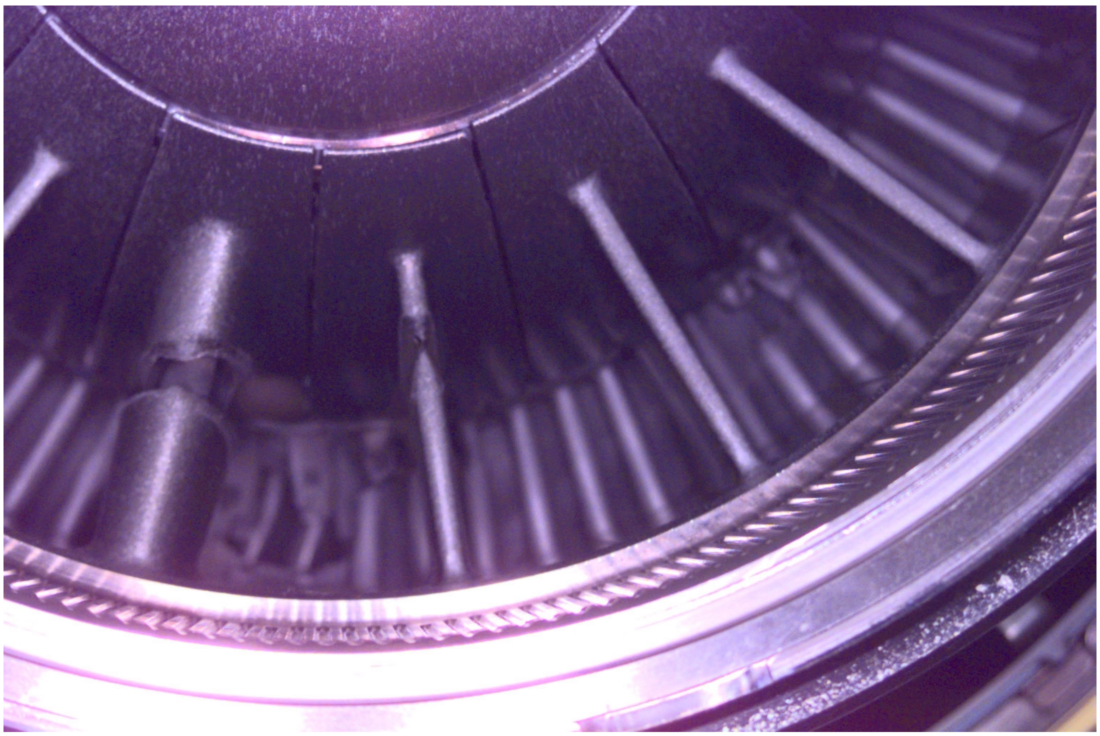


Figure 8.0-4 HPFTP/AT 8109R1 Turbine Inlet Damage

At 5.04 seconds, the HPFT discharge temperature (HPFT DS T) Launch Commit Criteria (LCC) was activated. At 5.08 seconds, two Failure Identifications (FID's) were issued indicating that HPFT DS T Channel A2 and HPFT DS T Channel A3 had exceeded the 1860R redline. These FID's were accompanied by a Major Component Failure (MCF) indication. The facility Command and Data Simulator (CADS) was set to respond to any MCF indication before 6.6 seconds with a command to perform engine shutdown. The CADS unit issued a shutdown command and the engine entered shutdown phase at 5.18 seconds.

The engine powered down nominally with the exception of the HPFTP/AT. During the shutdown transient, severe imbalance and excessive loading of the roller bearing caused it to fail. The HPFTP/AT spindown was much faster than nominal due to internal damage.

It stopped at approximately 4 seconds after shutdown. Spindown duration is nominally between 10 and 12 seconds.

The severe imbalance on the turbine-end of the HPFTP/AT caused significant damage to the turbine and pump. The debris generated from the turbine and pump sides of the HPFTP/AT was spread throughout the fuel and hot gas systems of the engine.

9.0 Findings, Observations, and Recommendations

9.1 Principal Finding

During the processing and assembly of SSME 0523, Permacel P-670 tape contamination was introduced into the fuel system. The tape came to rest as debris in the fuel manifold of the FPB, causing a localized high mixture ratio in the FPB. The resulting hot streak impinged on the turbine inlet housing struts and first stage vanes. A vane segment burned through and the inner section fell into the first stage blades. This caused rotor imbalance and significant turbine and pump damage.

Recommendation

Verify that all systems are free of foreign object debris prior to hotfire. Limit the opportunity for contamination introduction by minimizing the use of potential contaminants and using permanent closures on joints where applicable. Keep joints closed at all times when access is not required to perform work.

9.2 Finding

There are inadequacies in handling of, accounting for, and inspecting for loose materials used to process and rebuild an engine during normal operations. These loose, non-serialized materials are used in a variety of ways to aid in engine assembly and processing.

Recommendation

Implement an improved method of dealing with loose, non-serialized materials to ensure full accounting. Additional inspections and checkouts should be considered to verify that the engine is contamination free prior to any hotfire.

9.3 Finding

The use of “LOX” tape and Aclar as barriers for contamination provides the opportunity for an escape in processing whereby the material may be left in the engine.

Recommendation

The use of reusable barriers, which can be controlled and accounted for, should be investigated.

9.4 Observation

Normal processing paperwork and discrepancy disposition paperwork are sometimes ambiguous and open for interpretation by the persons performing the work. Similar planning is used for engine processing at the Rocketdyne facility at Canoga Park, the facility at Stennis Space Center, the engine processing facility at KSC, and at the Pratt & Whitney facility at West Palm Beach.

Recommendation

Provide clear instructions in processing paperwork and discrepancy paperwork. Use positive identification of engine hardware to ensure that the work is being done on the correct part.

9.5 Observation

Electronic paperwork system at SSC can be edited with no traceability. On IDCR #1 of SSME 0523, information was changed and no record of the change was recorded.

Recommendation

Correct electronic paperwork systems to either prevent changes or provide a clear tracking of change activities. Further, ensure that all SSME documentation changes can be tracked.

9.6 Observation

Earlier activation of either the HPFT discharge temperature LCC limit or the Real Time Vibration Monitoring System (RTVMS) would have likely reduced or prevented the HPFTP/AT damage and subsequently other incident related damage (MCC slagging, etc.).

Recommendation

Review both the HPFT discharge temperature LCC and the RTVMS to determine if the current activation time and limit value are appropriate. Further, a review of all post engine start LCC's and ignition confirm limits should be performed to ensure consistency with current flight safety philosophy.

9.7 Observation

SSME 0523 was built to a schedule that appeared to be accelerated when compared to the nominal operating mode and associated span times for comparable levels of recent SSME assembly operations.

Recommendation

Although there was no finding or observation directly linking the FPB contamination issue (LOX tape) to schedule pressures, the Board recommends that the SSME program and contractor team examine SSME assembly activity scheduling to ensure a work environment that does not contribute to future issues and problems. In general, the agency and its contractor teams need to avoid schedule practices that create undue risk.

9.8 Observation

Post-test inspection indicated that the roller bearing was damaged during the incident. Past HPFTP/AT turbine failures with similar turbine damage have not resulted in any damage of the roller bearing.

Recommendation

SSME Project Office should understand the mechanism causing the roller bearing failure and ensure that the conditions experienced were outside the designed capability of the roller bearing.

9.9 Observation

While removing a section of the FPB fuel manifold to gain access for a more thorough inspection, the thinned section exhibited an audible indication of possible stress relief.

Recommendation

SSME Project Office should investigate evidence to ensure that SSME 0523 powerhead structural properties were adequate. Ensure that an unacceptable condition does not exist in the flight fleet.

10.0 Terms and Acronyms

Acronym	Definition
ACTS	Automated Configuration-data Tracking System
AFV	Antiflood Valve
ARC	Ames Research Center
ASI	Augmented Spark Igniter
BLC	Boundary Layer Coolant
BOGS	Blade Outer Gas Seals
CADS	Command and Data Simulator
CCV	Coolant Control Valve
CCVA	Coolant Control Valve Actuator
CP	Command Processor
DP	Display Processor
E/S	Engine Start
EDC	Engine Diagnostic Console
EL	Electrical Lockup
ESW	Engine Status Word
FASCOS	Flight Accelerometer Safety Cutoff System
FFM	Fuel Flowmeter
FID	Failure Identification
FOD	Foreign Object Debris
FPB	Fuel Preburner
FPOV	Fuel Preburner Oxidizer Valve
FPOVA	Fuel Preburner Oxidizer Valve Actuator
FTIR	Fourier Transform Infrared
GMT	Greenwich Meridian Time
GPM	Gallons per Minute
GRC	Glenn Research Center
grms	Acceleration of Gravity-Root Mean Square
HEX	Heat Exchanger
HGM	Hot Gas Manifold
HPFD	High Pressure Fuel Duct
HPFP	High Pressure Fuel Pump
HPFT	High Pressure Fuel Turbine
HPFT DS T	High Pressure Fuel Turbine Discharge Temperature
HPFTP	High Pressure Fuel Turbopump
HPFTP/AT	High Pressure Fuel Turbopump/Alternate Turbopump
HPOP	High Pressure Oxidizer Pump
HPOT	High Pressure Oxidizer Turbine
HPOTP	High Pressure Oxidizer Turbopump
HPOTP/AT	High Pressure Oxidizer Turbopump/Alternate Turbopump
IMSL	Intermediate Seal

Acronym	Definition
ID	Inner Diameter
IDCR	Inspection Discrepancy and Correction Record
IR	Infrared
IRIG	Inter-Range Instrumentation Group
JSC	Johnson Space Center
KSC	Kennedy Space Center
lbm	pound mass
LCC	Launch Commit Criteria
LOX	Liquid Oxygen
LPFD	Low Pressure Fuel Duct
LPFP	Low Pressure Fuel Pump
LPFT	Low Pressure Fuel Turbine
LPFTP	Low Pressure Fuel Turbopump
LPOP	Low Pressure Oxidizer Pump
LPOT	Low Pressure Oxidizer Turbine
LPOTP	Low Pressure Oxidizer Turbopump
LTMCC	Large Throat Main Combustion Chamber
M/S	Mainstage
MCC	Main Combustion Chamber
MCF	Major Component Failure
MEC	Main Engine Controller
MFV	Main Fuel Valve
MFVA	Main Fuel Valve Actuator
MOR	Manufacturing Operations Record
MOV	Main Oxidizer Valve
MOVA	Main Oxidizer Valve Actuator
MPRACA	MSFC Problem Reporting and Corrective Action
MRD	Material Review Disposition
MSFC	Marshall Space Flight Center
NDE	Nondestructive Evaluation
NFL	Non-Flight Limitation
NPG	NASA Procedures and Guidelines
OD	Outer Diameter
OMA	Optical MultiChannel Analyzer
OPAD	Optical Plume Anomaly Detection
OPB	Oxidizer Preburner
OPOV	Oxidizer Preburner Oxidizer Valve
OPOVA	Oxidizer Preburner Oxidizer Valve Actuator
P&W	Pratt & Whitney
P/E	Pump End
Pc	Chamber Pressure
PID	Parameter Identification
PSD	Post-Shutdown
psi	pounds per square inch

Acronym	Definition
psia	pounds per square inch absolute
R	Rankine
RASCOS	Redline Accelerometer Safety Cutoff System
RP	Record Processor
RPL	Rated Power Level
RTVMS	Real Time Vibration Monitoring System
SDAS	Stennis Data Acquisition System
SEM/EDS	Scanning Electron Microscopy / Energy Dispersive Spectroscopy
SLE	Shutdown Limit Exceeded
SPAOS	Space Propulsion Assembly Operation Sheets
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
T/E	Turbine End
TAD	Turnaround Duct
TED	Turbine Exit Diffuser
TVC	Thrust Vector Control
T-Ref	Controller Time Reference
U/N	Unit Number
VDT	Vehicle Data Table