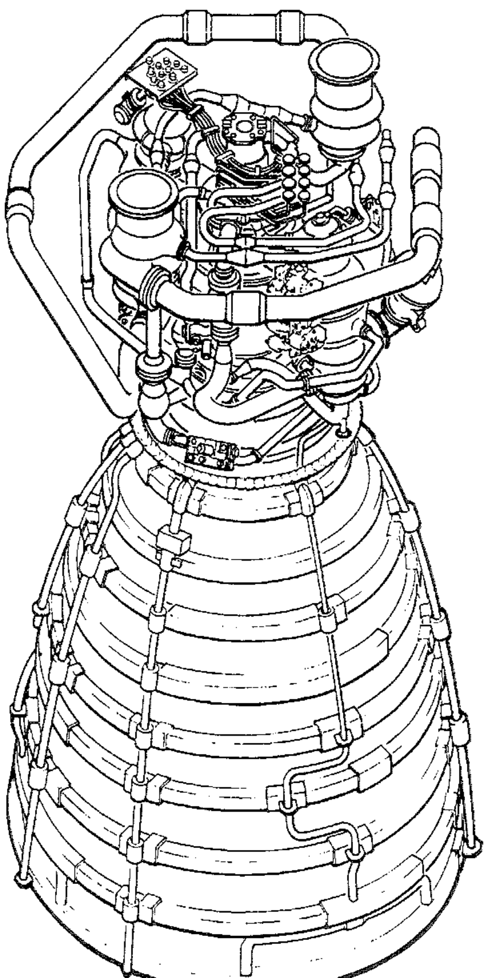
SSME



Discovery STS-103

Space Shuttle Program

SSME Flight Readiness Review

19 November 1999

Discovery STS-103

Agenda

- **Major Components**
- **Engine Performance**
- **Special Topics**
  - Main Injector Deactivation Pin Expulsion - STS-93 IFA
    - "Benign Conditions" Assessment
  - STS-93 AC Power Anomaly (Integration IFA)
  - HPFTP 1st Stage Turbine Blade Firtree Cracks
  - HPOTP/AT Eddy Current Inspection Calibration

Discovery STS-103

SSME Major Components

Engine	ME-1 (2053) *Block IIA*	ME-2 (2043) *Block IIA*	ME-3 (2049) *Block IIA*
Last Hot-Fire	**902-716**	**STS-95**	**STS-96**
Powerhead	6020	6013	6019
Main Injector	6020	2033	6011
MCC	6018	6006	6015
Nozzle	5007	5004 (1)	4028
Controller	F44	F55	F41
HPFTP	6017	6014	6110 (1)
LPFTP	5101	2130R3	4210 (1)
HPOTP/AT	8031	8021	8016R4
LPOTP	2135	6001	2133

(1) Changes from last hot-fire.

Note: Engine 2049 replaces Engine 2045 at VAB due to unacceptable FOD (broken drill bit) located between the Main Injector primary and secondary faceplates.

Discovery STS-103

SSME First Flight ECPs

SSME Program First Flight ECPs

ECP#	Description	Engines
1314R3	Main Fuel Valve Block II Redesign	2053 2043
1304	G3 seal for use with both HPOTP & HPOTP/AT	2053,2049
1315	AC34 Software Version	All
1334	LPFTP Ultrasonic Inspection of 2nd Stage Rotor Braze Joint	2053

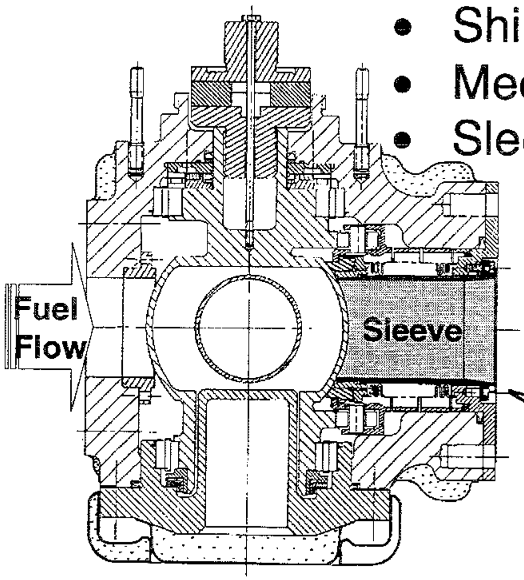
Previously Flown ECPs

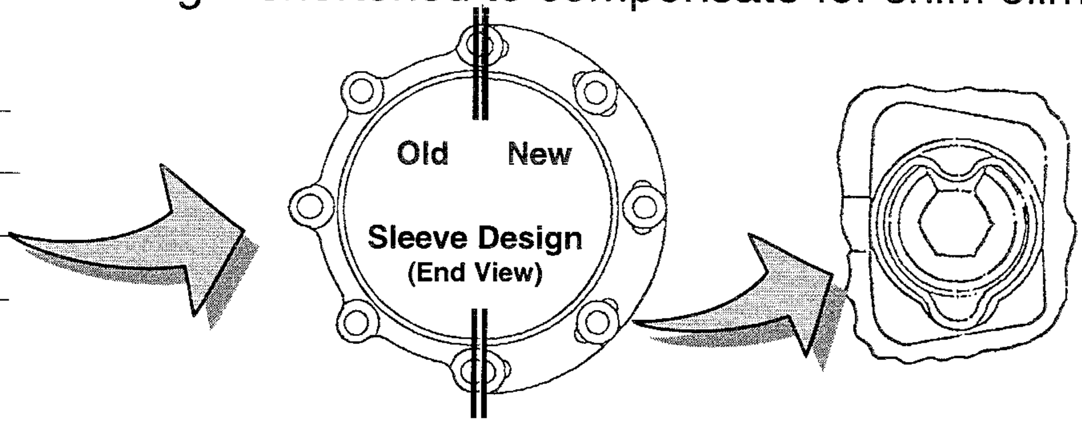
ECP#	Description	Engine	1st Flight
1367	Block II/IIA Main Injector Modification	All	STS-96
1272	Skin Temperature Sensor Harness	2043	STS-89

Discovery STS-103

ECP 1314R3 - Main Fuel Valve Block II Redesign

- **Issue**
  - HPFTP/AT vibrations loosened outlet sleeve screws. Unclamped shims may fret, break, and shed debris into fuel system
- **Solution**
  - Shims eliminated
  - Mechanical locking feature added for screw retention
  - Sleeve length shortened to compensate for shim elimination



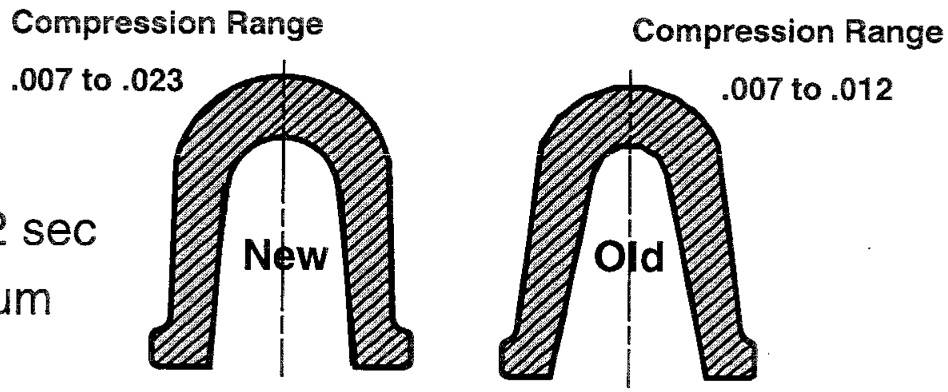


- **Certification Status** - Complete for all flight configurations
  - Certification by analysis, similarity and test
  - VCR approved - 74 starts on 7 valves, 38,836 seconds

Discovery STS-103

ECP 1304 - G3 Seal Redesign

- **Issue**
  - Material transferred from HPOTP/AT heel to powerhead flange and seal groove lapping causes seal compression outside .007 to .012 experience base
- **Solution**
  - New, "one size fits all" seal for use with both HPOTP/AT and Phase II HPOTP
    - Allows expanded compression range to cover increased seal travel on HPOTP/AT
- **Certification Status**
  - Certification complete by analysis, similarity and test
    - 7 hotfire tests on 4 seals: 3,402 sec
    - 240 cycles in lab under maximum compression
  - VCR approved

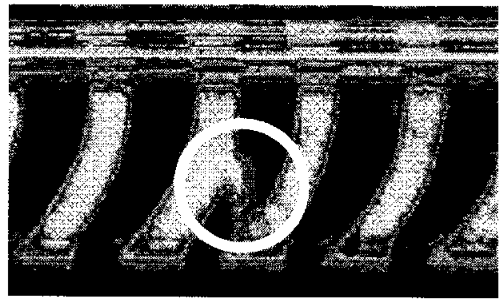


G3 Replacement Seal

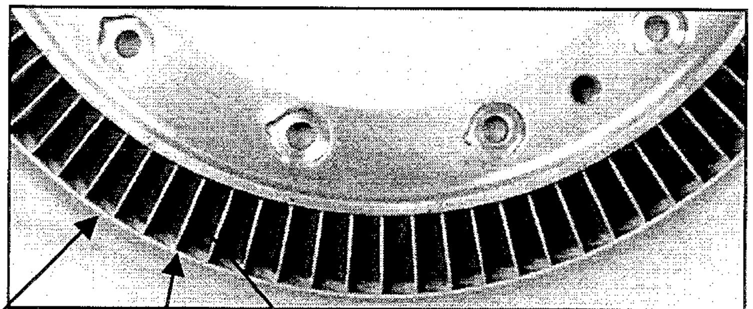
Discovery STS-103

ECP 1334 - Ultrasonic Inspection of LPFTP 2nd Rotor Braze Joint

- **Issue**
  - Shroud to vane braze joint separations found on several rotors
    - Condition attributed to braze thermal cycle changes, isolated to one purchase order
    - Standard visual and penetrant inspections failed to identify defective parts
- **Solution**
  - Improvements to dimensional tolerances and processing requirements
  - Addition of ultrasonic inspection
    - Verifies bond area
- **Certification Status**
  - Complete by similarity and test
  - VCR approved



Example of Ultrasonic Scan Showing Debond



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Discovery STS-103

ECP 1315 - AC34 Software Version

- **Background**
  - Update new flight software baseline

- **Significant Features**
  - LCC Changes - Single String Engine Ready Parameters
  - Incorporated Flight Operational Data into the Base Software
  - Incorporated multiple System Notes
  - Incorporated improved checkouts

- **Verification and Certification Status**
  - Verification completed at HSL on 4/23/99
  - VCR approved on 7/16/99
    - 5 Tests on 3 engines with 4 different controllers for 2600 seconds

Discovery STS-103

Predicted SSME Ignition Confirm Margins

Calculations use Phase II, Return to Flight database sigmas

Parameter	ME-1 (2053)	ME-2 (2043)	ME-3 (2049)
HPFTP Minimum Speed	4.9	5.4	3.6
Min/Max Ignition Pc	3.1	5.1	3.4
Antiflood Valve Min Open	20.8	21.8	20.8
HPFTP Max Turbine Temp (1760 Limits)	4.4	6.4	4.7
HPOTP Max Turbine Temp (1460 Limits)	3.5	4.0	3.8
HPOTP Min Turbine Temp (720 Min @ 4.0 secs)	6.2	5.5	5.7
Preburner Max Purge Pressure (715/100 Limits)	46.5	44.2	44.7
POGO GOX Min/Max Pressure *	18.6	11.0	21.9

* Uses no pogo hardware change database

Discovery STS-103

Predicted SSME Performance at 104.5% P.L.

At Engine Start + 200 seconds
(MR = 6.032, OPI = 69 psia, FPI = 28 psia)
Calculations use Phase II Return to Flight database sigmas

Parameter	Blk IIA Twelve Eng Avg	ME-1 (2053)		ME-2 (2043)		ME-3 (2049)	
		Predict	Sigma	Predict	Sigma	Predict	Sigma
HPFT Disch Temp A, Deg R	1585	1588	0.1	1519	-1.5	1572	-0.3
HPFT Disch Temp B, Deg R	**1595**	1596	0.0	**1494**	**[-2.4]**	1553	-1.0
HPOT Disch Temp A, Deg R	1217	1238	0.4	1155	-1.3	1267	1.1
HPOT Disch Temp B, Deg R	1228	1241	0.3	1173	-1.1	1264	0.7
HEX Interface Temp, Deg R	824	849	0.9	793	-1.1	853	1.1
HPFTP Speed, rpm	34288	34169	-0.6	34533	1.2	34374	0.4
LPFTP Speed, rpm	15641	15558	-0.4	15674	0.1	15350	-1.3
HPOTP/AT Speed, rpm	22330	22300	-0.2	22277	-0.3	22066	-1.3
LPOTP Speed, rpm	5028	4979	-0.9	5007	-0.4	5055	0.5
OPOV Position, %	63.5	63.8	0.2	62.9	-0.4	65.5	1.4
FPOV Position, %	76.4	77.4	0.8	77.6	0.9	76.2	-0.2
PBP Disch Pressure, psia	6918	6792	-1.4	6882	-0.4	6847	-0.8
HPFTP Disch Pressure, psia	5667	5677	0.3	5727	1.8	5638	-0.9
HPOTP Disch Pressure, psia	3803	3736	-1.7	3813	0.2	3794	-0.2
	HPFTP U/N	6017		6014		* 6110	
	LPFTP U/N	5101		2130R3		* 4210	
	HPOTP U/N	8031		8021		8016R4	
	LPOTP U/N	2135		6001		2133	

* Change since last flight / acceptance test
[ ] Exceeds database two sigma due to a powerhead influence

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Discovery STS-103

Predicted Redline Margins at 104.5% P.L.

Calculations use Phase II, Return to Flight database sigmas

Parameter	Redline Limit	Margin Sigma		
		ME-1	ME-2	ME-3
HPFT Discharge Temp ChA, Deg R	1860 Max	6.1	7.2	5.9
HPFT Discharge Temp ChB, Deg R	1860 Max	5.5	7.8	6.4
HPOT Discharge Temp ChA, Deg R	1660 Max	8.3	9.5	8.2
HPOT Discharge Temp ChB, Deg R	1660 Max	8.1	8.9	8.0
HPOT Discharge Temp ChA, Deg R	720 Min	8.5	5.9	8.1
HPOT Discharge Temp ChB, Deg R	720 Min	8.3	5.7	7.6
HPOTP/AT IMSL Purge Pr, psia	159 Min	4.8	5.4	5.0
HPFTP Coolant Liner Pressure, psia	3392 Max	4.3	8.3	9.0
Low MCC Pc, psid				
Command-ChA Avg	200 Max	15.6	15.3	16.1
Command-ChB Avg	200 Max	17.9	16.3	17.2
FASCOS				
HPFTP (16 GRMS)	Not Active	6.3	6.8	6.6
HPOTP (11 GRMS)		6.9	8.1	8.2

Discovery STS-103

LCC Changes

- **LCN 916**
  - Adds new HPFTP Lift-off Seal Leakage LCC (SSME-44)
    - Monitors lift-off seal leakage using a minimum HPFTP turbine temperature of 405 Deg R
      - Previously monitored by SSME-24 with a lower qualification limit of 405 Deg R
    - Makes provisions to launch with a cold T/C environment
  - HPFT Discharge Temperature Qualification LCC (SSME-24)
    - Change lower qualification limit from 405 to 360 Deg R
  - HPOT Discharge Temperature Qualification LCC (SSME-25)
    - Change lower qualification limit from 405 to 360 Deg R

Discovery STS-103

LCC Changes

- **LCN 918 / 915**
  - All measurements not utilized after engine start have been switched to single-string (only 1 of 2 measurements required)
    - Purge and Ancillary Limits (LCN 918)
      - Fuel System Purge Pressure LCC (SSME-09)
      - Propellant Valve Hydraulic Temp LCC (SSME-15)
    - Engine Ready Limits (LCN 915)
      - LPOT Discharge Pressure Engine Ready LCC (SSME-19)
      - PBP Discharge Temp Engine Ready LCC (SSME-20)
      - MOV/MFV Hydraulic Temp Engine Ready LCC (SSME-20)

Discovery STS-103

LCC Changes

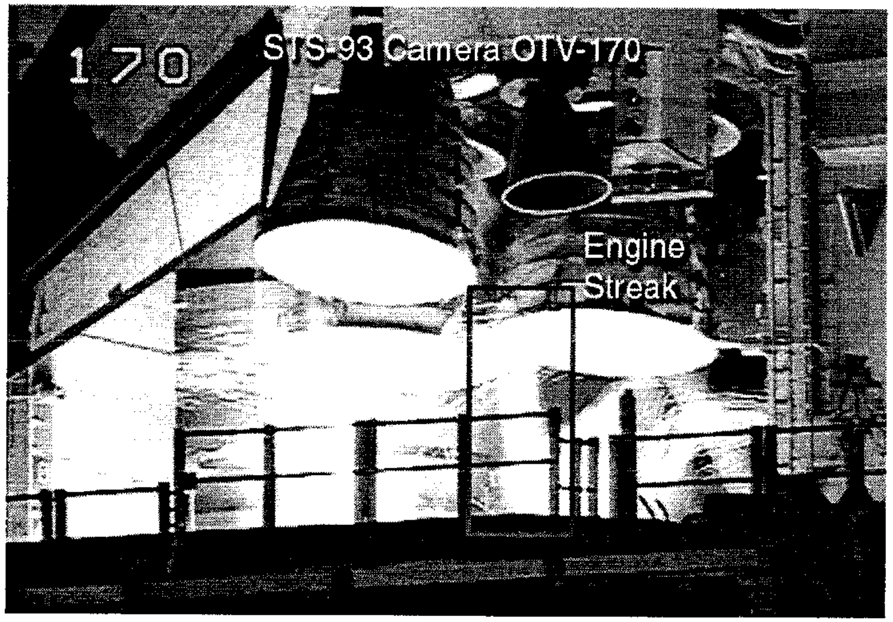
- **LCN 917**
  - Deletes LCC for Reference Junction Temperature Qualification LCC (SSME-42)
    - AC34 software uses a default value of 495 Deg R after the second sensor failure
      - Previously used the last qualified sensor value
      - 495 Deg R is an average of flight experience
    - Default value within software allows for deletion of LCC

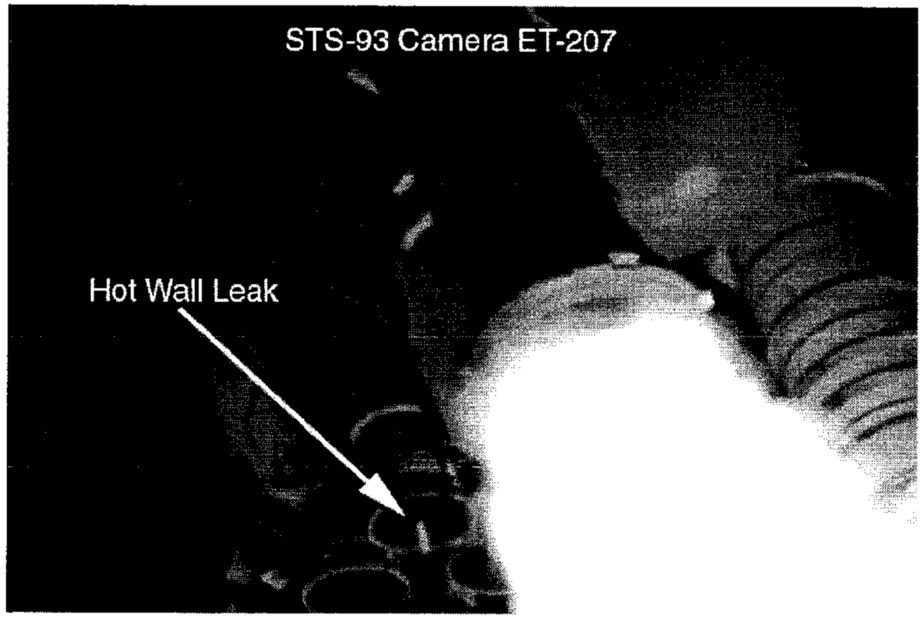
STS-93 Main Injector Pin Expulsion

- **Issue**
  - Main injector LOX post deactivation pin ejected and ruptured 3 nozzle coolant tubes at start + 5 seconds during STS-93
    - LOX low level cutoff 0.15 seconds before planned MECO
- **Background**
  - Cutoff resulted in orbiter velocity underspeed of 16 ft/sec (of ~26,000 ft/sec)
    - Well within planned mission margins - proper orbit achieved
  - Engine system responded as designed
    - Propellant mixture ratio and thrust controlled properly
    - All redline and structural margins maintained throughout flight
  - Only the second LOX low level cutoff in shuttle history (STS-51F, 7/85)
    - HPFT discharge temperature sensor failures caused premature engine shutdown
    - Other two engines ran longer to achieve orbit

STS-93 Main Injector Pin Expulsion

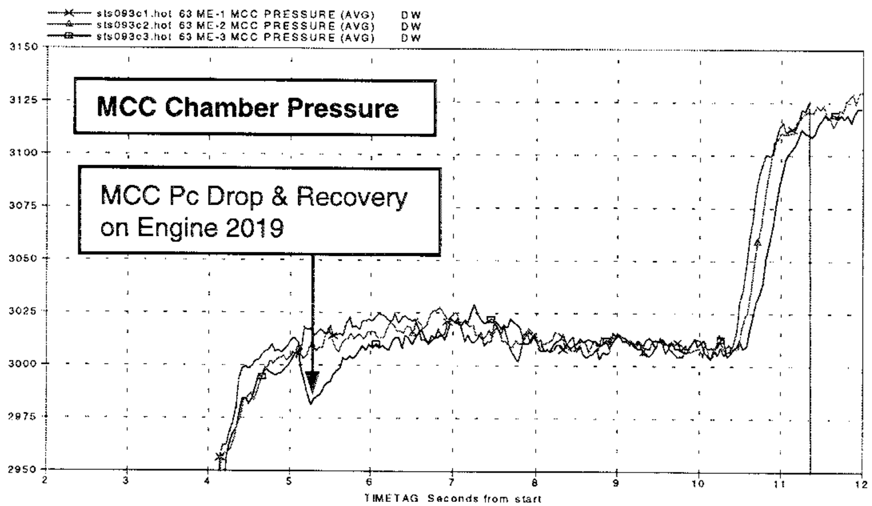
In Flight Photography

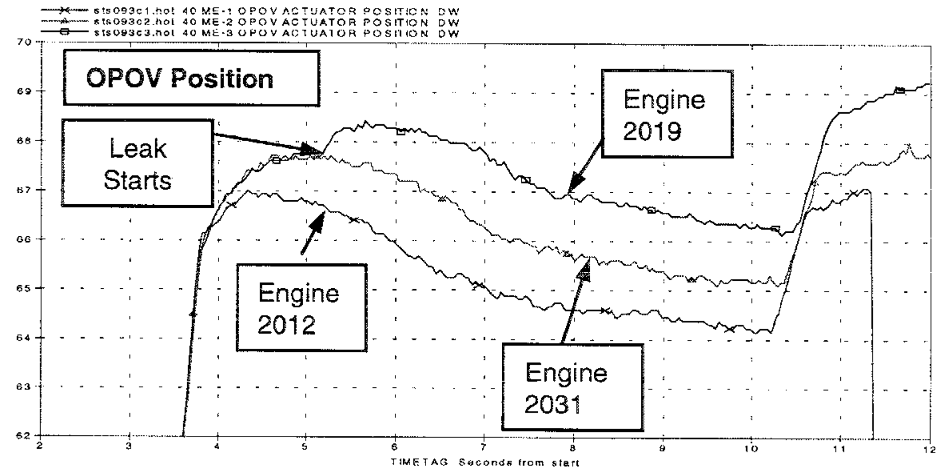


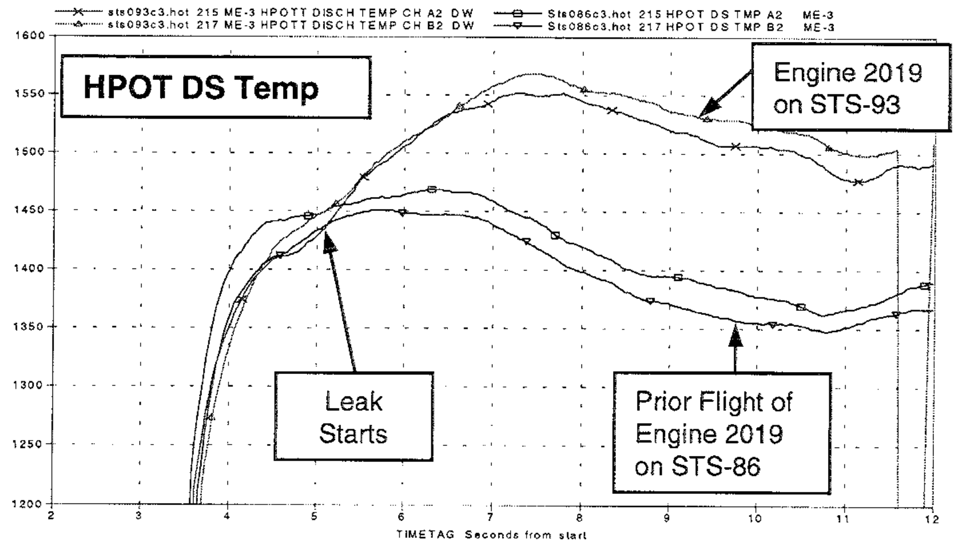


STS-93 Main Injector Pin Expulsion

Engine Performance Data







Engine system response as designed.
Proper control of mixture ratio and thrust.
All redline and structural margins maintained.

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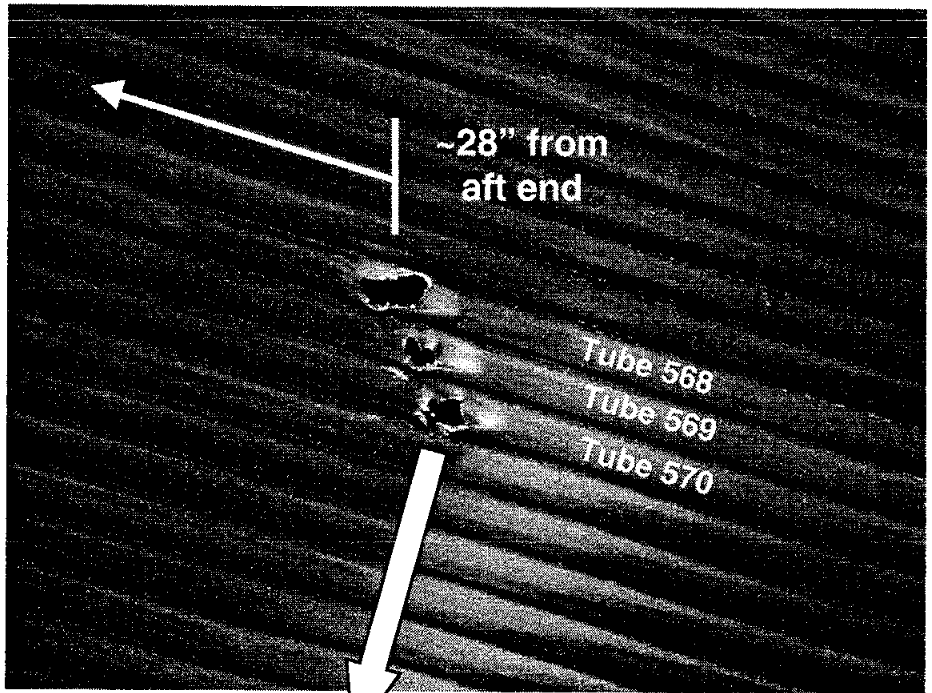
STS-93 Main Injector Pin Expulsion

E2019 Nozzle Hotwall Coolant Tube Ruptures / Leakage



Tube 570 ~5.3x

Dents noted at all 3 tube ruptures. Evidence of gold present.

- **Tube leaks confirmed upon landing**
  - 3 consecutive tube ruptures
  - 3.5 ±0.5 lbm/sec calculated leak
    - Correlates with performance data and calculated leak area
  - Results in an additional LOX usage of ~5300 lbm
    - Consistent with RSS (Downey) estimates
- **Nozzle leak was large enough to cause LOX low level cutoff**

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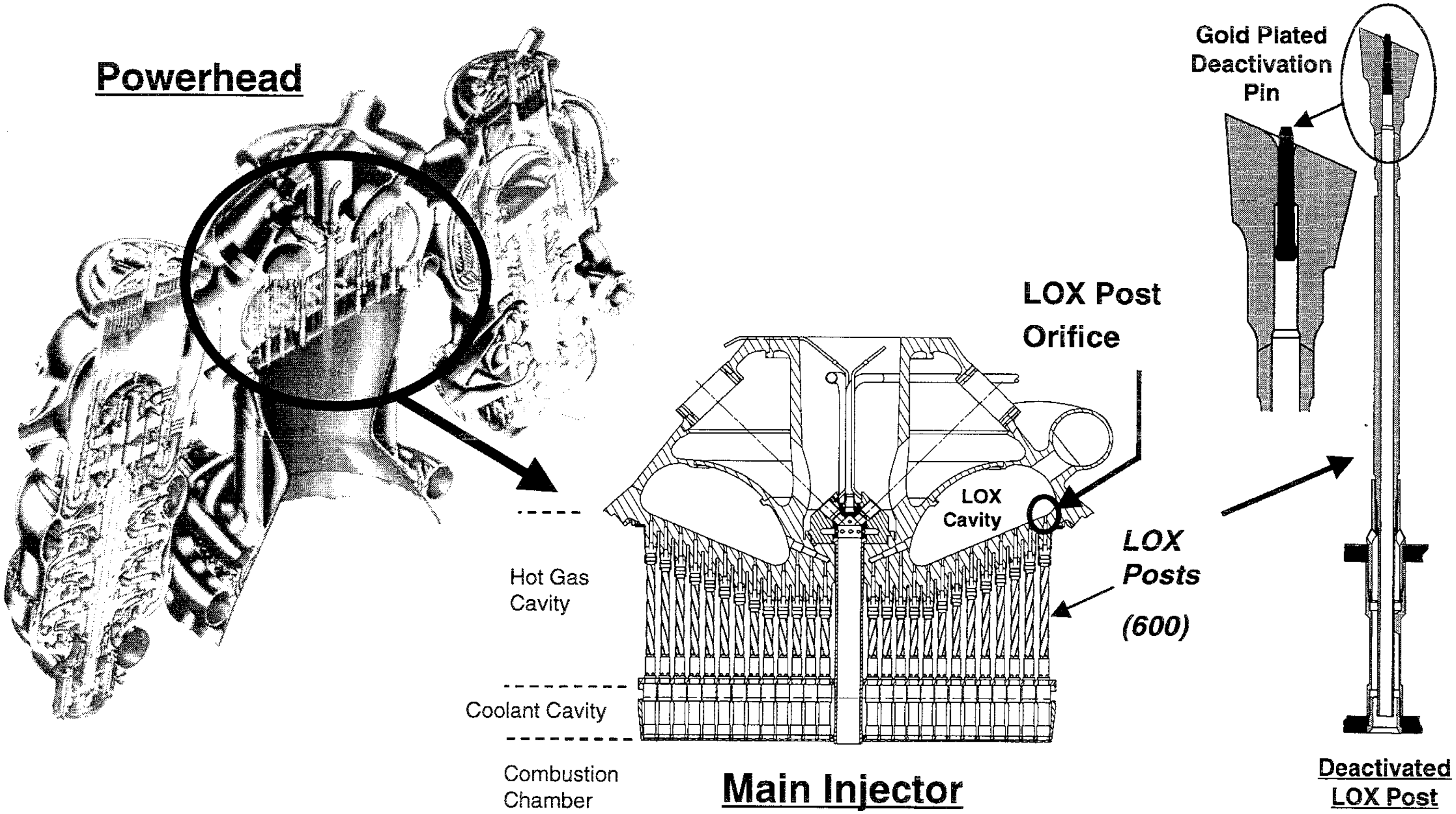
STS-93 Main Injector Pin Expulsion

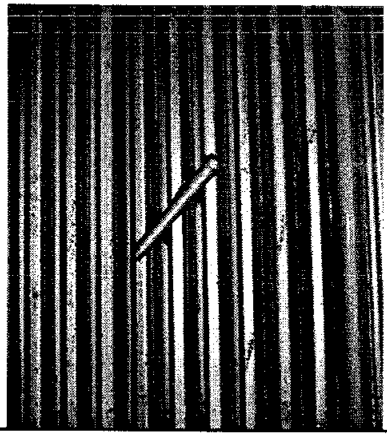
- **Investigation**
  - Post flight inspection noted loss of main injector LOX post deactivation pin and impact damage on MCC wall near throat
    - Minor impact damage (.0015" deep) on MCC directly below missing pin
      - 2.5" forward of the throat center line
  - Two E2019 LOX posts were deactivated prior to STS-93
    - Standard procedure upon LOX posts reaching calculated life limit (reference DAR 2049R1)
    - Deactivated posts were Row 13 Post 3 and Row 13 Post 32
      - Post 32 pin found missing after flight
    - Deactivation pins are gold plated Inconel 718
  - Materials analysis confirmed gold found in nozzle tube dents / ruptures matched identically gold plating on deactivation pins

STS-93 Main Injector Pin Expulsion

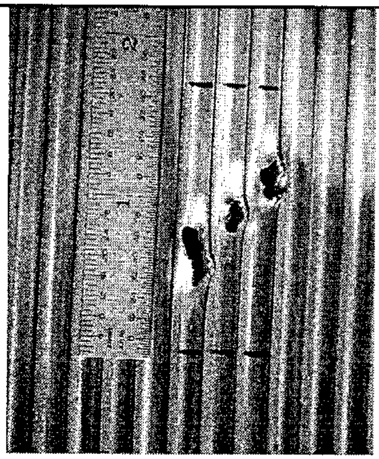
Powerhead, Main Injector and LOX Post Details



STS-93 Main Injector Pin Expulsion



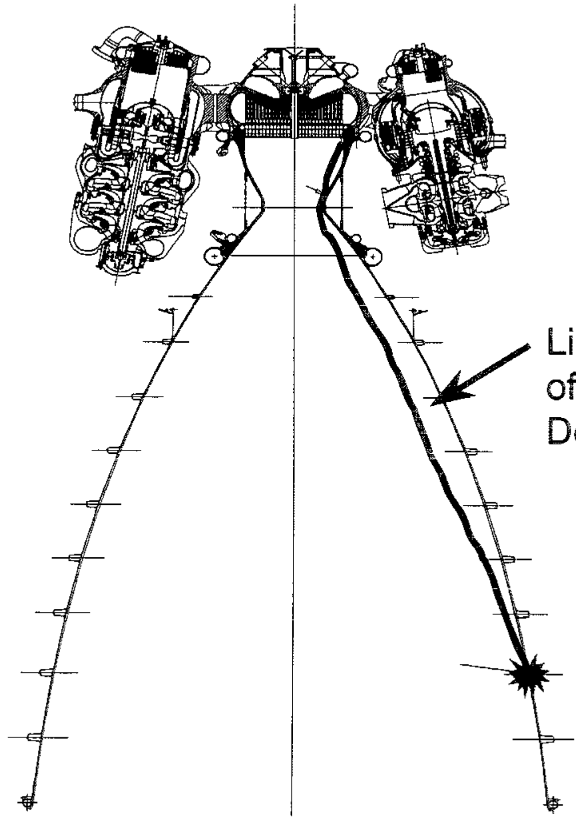
Deactivation Pin Geometry is Consistent with Ruptures



- **Pin use common on earlier SSME configurations**
  - 212 deactivated posts
  - 18 prior occurrences of loss with no hardware damage
- **Design and process improvements have eliminated need to deactivate posts**
  - All future flights (Block IIA) use new design
  - There are no pinned posts remaining in flight fleet
    - E2048 has been returned to Canoga for replacement of Powerhead

STS-93 Main Injector Pin Expulsion

- **Failure Scenario**
  - Pin expelled during engine start as pressure builds in LOX dome (~5 sec)
  - Pin strikes MCC hot wall and entrains in hot gas flow stream at throat
  - Pin traverses across flow streams and strikes the nozzle tubes ~28 inches forward of aft manifold
  - Puncturing of the wall results in fuel leakage, increased LOX usage, and early depletion of the LOX supply
- **Fault tree analysis completed**
  - No other credible scenarios



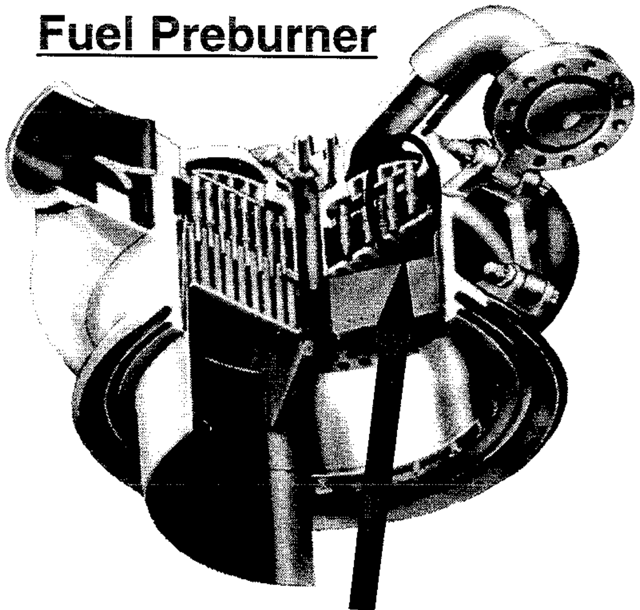
STS-93 Main Injector Pin Expulsion

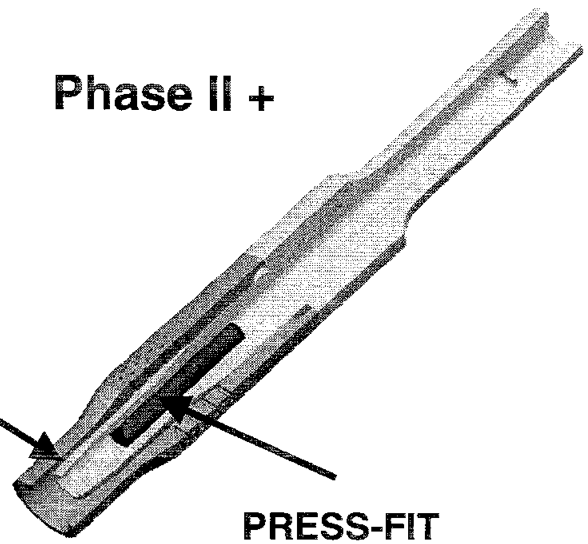
Other "Friction Retained" Hardware and/or FOD Sources

- **Engine system reviewed for comparable "friction retained" hardware and/or FOD sources**
  - Preburner post plugging reviewed
    - Both FPB and OPB LOX posts also deactivated using pins
      - LOX Post swage and subsequent weld provides positive retention feature
      - No loss of this pin configuration in program history
  - Review of remaining engine components revealed no credible projectile FOD threat
    - Lee jets, lift-off seal carbon noses, nozzle fatigue arrestor bolts, G3 nuts, etc.
    - Captive environments or other positive mechanical retention features prevent ejection

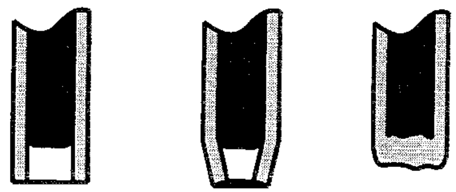
STS-93 Main Injector Pin Expulsion

Fuel Preburner LOX Post Deactivation





> ***Swage and subsequent weld provides positive retention feature.***



STS-93 Main Injector Pin Expulsion

- **Rationale for Flight**
  - No SSMEs in flight fleet with deactivated main injector LOX posts
    - Cause of STS-93 anomaly no longer exists
  - Entire engine system reviewed for other potential friction retained FOD sources
    - No credible projectile threats uncovered

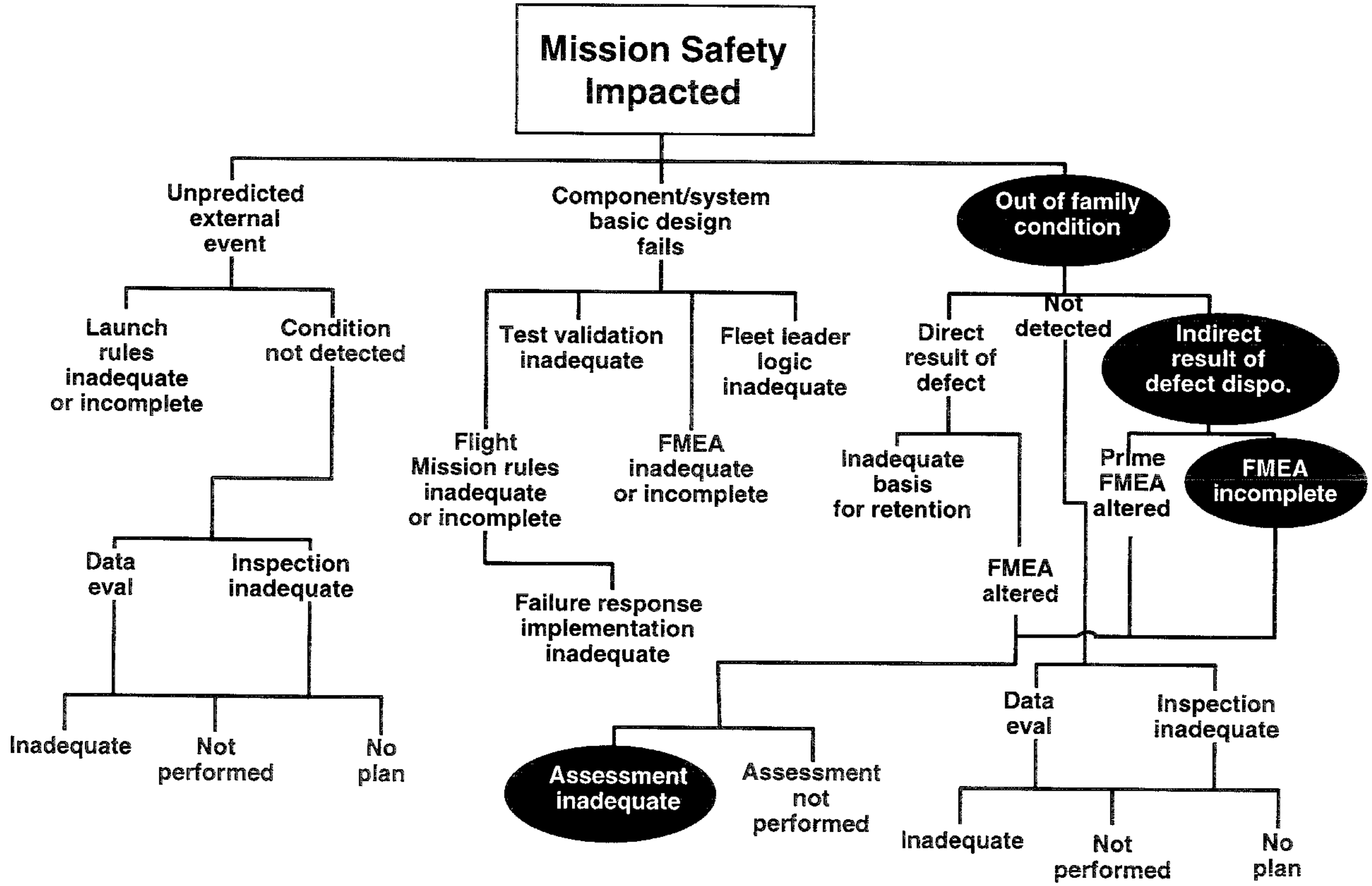
STS-93 Anomaly Corrective Action

Engine Wide Assessment of "Benign Conditions"

- **Issue**
  - Engine wide concerns raised by the expulsion of the Main Injector LOX Post Pin on STS-93 and subsequent mission impact
- **Background**
  - As a result of the above a number of actions & recommendations were identified to address adequacy of flight fleet
  - Actions addressed the hardware, software and the processes used to assess flight engine acceptability

STS-93 Anomaly Corrective Action

E2019 LOX Post Pin Expulsion Fault Tree



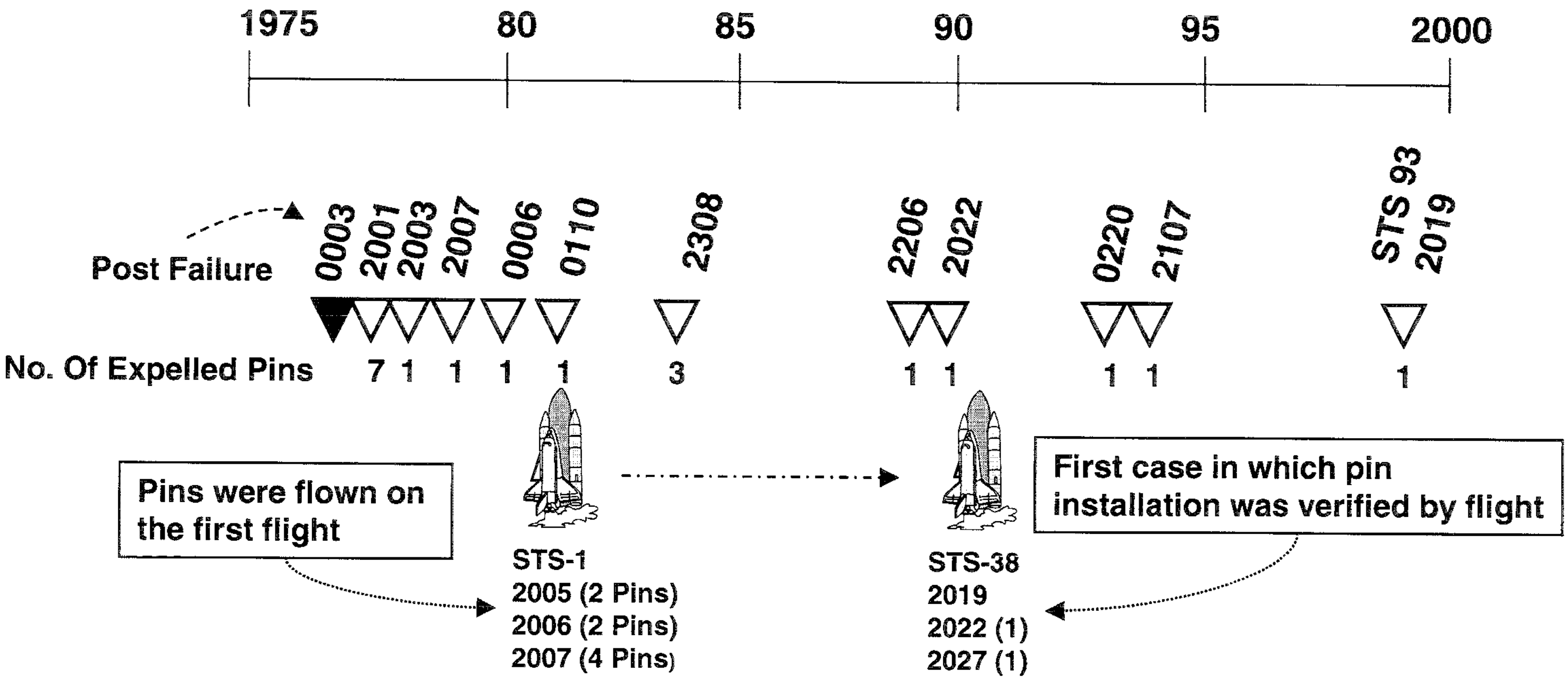
STS-93 Anomaly Corrective Action

E2019 Lox Post Pin Expulsion - System "Escape"

- **Routine, repetitive repair condition**
  - Long history was not reassessed since early in SSME program
- **Benign effects were assumed for pin expulsion and were not challenged . . . worst possible effect not fully explored**
  - Focused only on Crit 1 failure of Main Injector
  - Ignored potential Crit 3 failure due to ruptured nozzle tubes
    - Added complexity of LOX low level cutoff not considered
- **DAR defined "plans to restore limited life component" as pinning the post after life expended . . . embedded repair not reassessed in today's system (via Primary Material Review Board)**
- **DAR / pinning technical basis went back to early 1980's, and was not reflective of current sensitivity to FOD**

SSME Main Injector LOX Post Pins

Lox Post Pinning Timeline



79 of 95 flights have included engines with pinned posts

STS-93 Anomaly Corrective Action

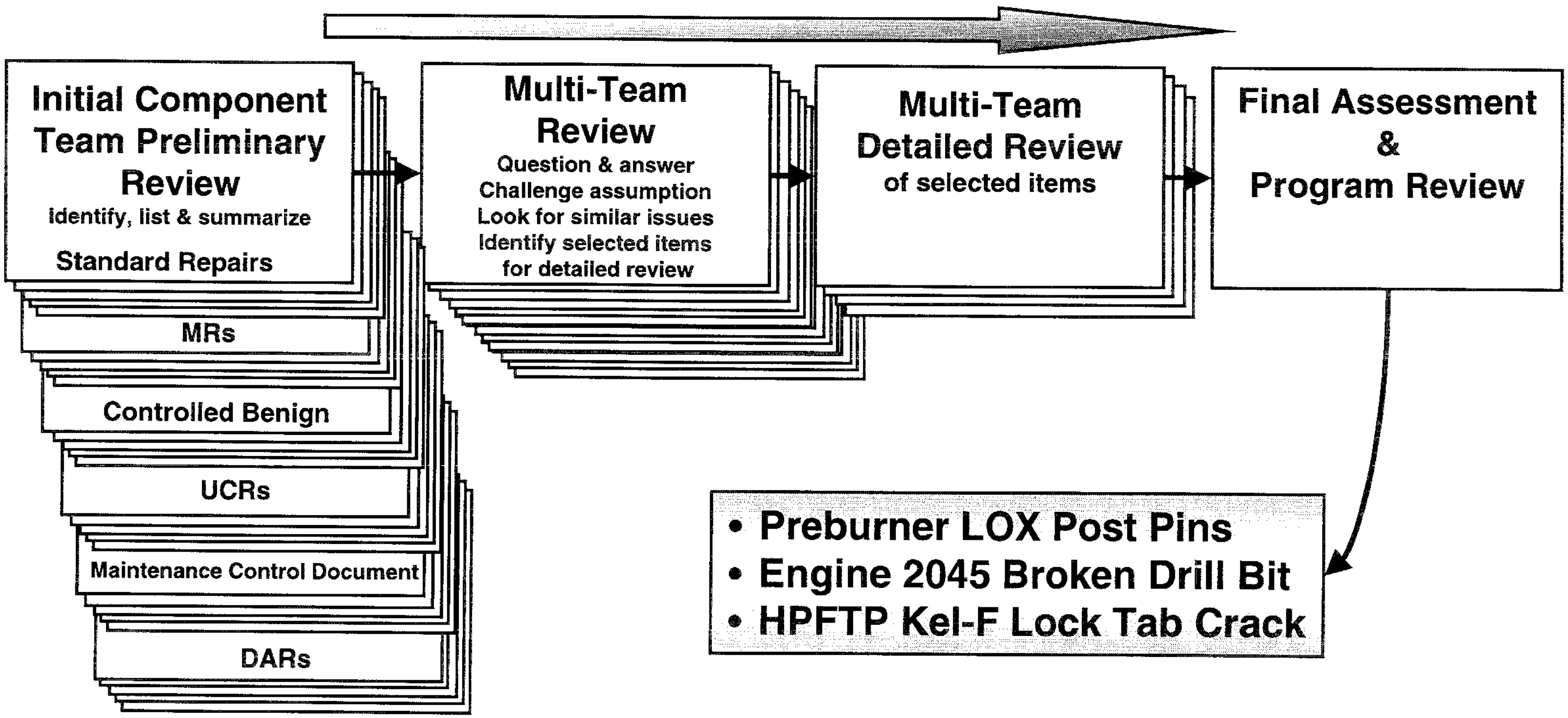
Assessment Groundrules

- **Identify routine or repetitive repairs which would impact mission safety if assessment was inadequate**
  - Consider structural failures, leakage, etc.
- **Identify conditions, routine / repetitive repairs which, historically, have resulted in loose pieces**
  - Ensure proper assessment for worst case effect on the engine
- **Identify repair processes which introduce new piece(s) with the potential for coming loose**
  - Provide rationale that such pieces will not become FOD
- **Review identified "benign" conditions & verify rationale reflects lessons learned from STS-93**
  - Consider benign controlled & UCR conditions with no recurrence control
- **Review DARs on flight engine hardware**
  - For "Plans to Restore Limited Life Components"
  - Ensure limit and rationale reflect today's assessment, analysis, etc.

STS-93 Anomaly Corrective Action

Engine Wide Assessment Process

Approach employed a progressively more detailed review



STS-93 Anomaly Corrective Action

Engine Wide Assessment Summary

Component	Standard Repair Spec.	Routine / Repetitive MRs	Controlled Benign Spec.	UCR Review	Maintenance Control Document	DARs
Powerheads	✓	✓	✓	✓	✓	**None**
Ducts	✓	✓	**None**	✓	**None**	✓
LTMCC	✓	✓	**None**	✓	**None**	**None**
Nozzle	✓	✓	**None**	✓	✓	✓
Turbomachinery	✓	✓	✓	✓	✓	✓
HPOTP/AT	✓	✓	**None**	✓	na	✓
Assy Ops	✓	✓	✓	✓	✓	✓
Controller	**None**	**None**	**None**	✓	na	**None**
Systems	na	na	na	✓	na	na
Quality/S&MA	na	na	na	✓	na	na

✓ **Complete**

STS-93 Anomaly Corrective Action

Engine Wide Assessment Results

- **Results from the Preliminary Component & Multi-team Review**
  - All standard or routine repetitive repairs assessed considering worst case failure mode
    - No change to CIL retention rationale
  - Repairs typically are based on a long, history of occurrence and are therefore part of the engine history
    - Often incorporated as a result of MR history
    - Nozzle coolant tube repair specification to be modified to clarify repair types and limitations
  - Review of UCRs, Benign Conditions, MCD & DARs identified no additional actions as a result of the reassessment

STS-93 Anomaly Corrective Action

Engine Wide Assessment Results

- **Results of Detailed Reviews**
  - Several issues currently being addressed with design improvements (e.g., MFV shim failure)
  - Others have been the subject of recent, significant reassessments including the customer (e.g., Nozzle tube leakage/Engine 0524)
  - Three issues were identified and elevated for Program Review
    - Preburner LOX post plugging
      - Positive retention, demonstrated successful history
    - Engine 2045 broken drill bit
      - Removed engine from STS-103 (replaced with E2049)
    - HPFTP Kel-F Lock Tab Crack
      - Demonstrated successful history and tolerance to max, worst case FOD

STS-93 Anomaly Corrective Action

Engine Wide Assessment Results

- **Software System Notes Review**
  - System Notes (SN) used to report problems or request changes involving the operational software, its documentation or its development environment
  - System Note review initiated in April 1999 to implement all open conditions
    - Some "benign" System Notes have been deferred since initiation of the Block II controller program (1993)
    - All open SNs have been reviewed for implementation (124 total)
      - 72 closed
      - Remaining 52 have been assessed with no safety of flight impact
  - System Notes "benign" conditions confirmed
    - Problem reporting validated

STS-93 Anomaly Corrective Action

Engine Wide Assessment - Conclusions

- **Review of standard, routine, repetitive repairs confirms that all are developed based on sound technical grounds & validated with analysis and/or significant hot fire experience**
  - All have been scrutinized as the result of increased sensitivity, new designs (e.g.,Block I, IIA, II) or recent issues (E0524 Nozzle failure)
    - Nozzle coolant tube repair specification to be modified to clarify repair types and limitations
- **No UCRs identified which lent themselves to new or additional recurrence control**
- **No other DARs with rework defined to restore component life**
  - All DARs reviewed reflected current assessment, analysis, etc.
- **Software problem reporting process validated**

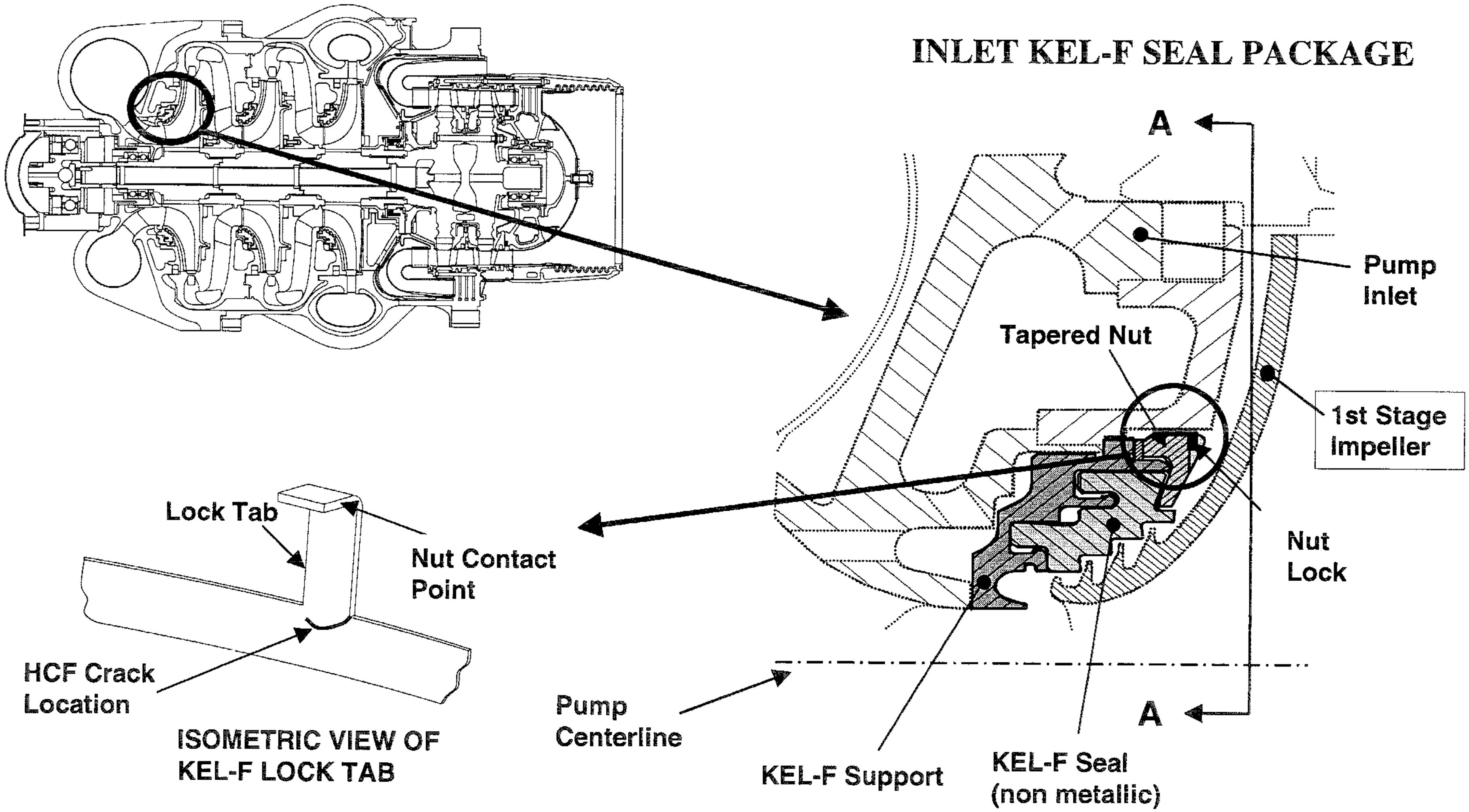
HPFTP 6012R1

KEL-F Lock Tab Crack

- **Issue**
  - Pump inlet KEL-F seal subassembly lock tab cracked - concern for foreign object damage/debris (FOD)
- **Background**
  - Lock tab broke by overload while being bent back during disassembly
    - Cracked 90% through by high cycle fatigue after nut rotation and "pinching" of lock tab
  - Lock tab damage and/or loss caused by nut rotation and contact with seal package lock
  - Nut designed to tighten by fluid torque

HPFTP 6012R1

KEL-F Seal Package

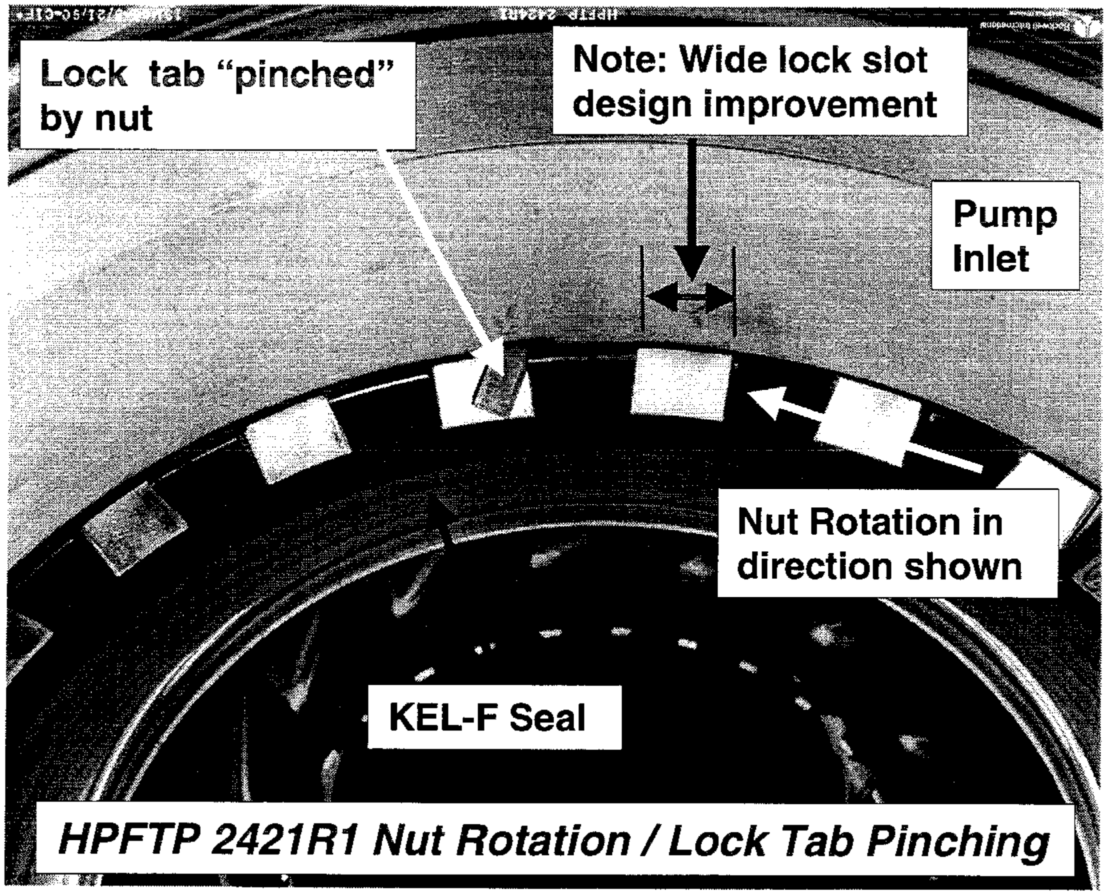


HPFTP 6012R1

KEL-F Lock Tab Crack

- **Metals utilized in inlet sub assembly contribute to nut rotation**
  - Incoloy 903 / titanium thermal "mismatch"
- **1990 design improvements implemented reduced occurrences of lock damage and loss**
  - Increased torque
  - Increased nut slot width

View A-A



HPFTP 2421R1 Nut Rotation / Lock Tab Pinching

HPFTP 6012R1

FOD Assessment Approach

- **Approach to Assess FOD included: pump internal components and engine system - areas limited by size of FOD and pump/engine system restricting orifice, the ability of FOD to damage hardware, performance effects (blockage), and a review of experience with FOD in fuel system**
- **Assessment on pump performed for blockage and impact concerns**
  - FOD up to 5 times mass of lock tab experienced - impact damage only
  - Demonstrated design robustness - non FOD related
    - Impeller remained intact - 2 cases of fractured labyrinth seal
    - Main housing structural integrity maintained with loss of piece of diffuser vane leading edge
  - Lock tab is below impact mass calculated to cause breakage or shear out damage

HPFTP 1st Stage KEL-F Lock Tab Crack

Assessment of Engine System FOD Tolerance

- **No engine blockage or impact concerns**

Areas Assessed	*Worse Case FMEA/CIL*	*Worse Case Experience*
Main Fuel Valve	1*	Complete Mission
Nozzle Coolant Tubes	1R**	Complete Mission
MCC Coolant Channels	3	Complete Mission
ASI Supply Filter	3	Complete Mission
Pre-burners	3	Complete Mission

* For On Pad Abort Seal Leakage Only - Mitigating Precautions: Automated Abort Sequence closes propellant pre-valves, vents the engine, turns on firex and aft compartment purges to prevent open air detonation.

** Worse Case is 3.8 lbm/sec leakage results in Criticality 3 condition

HPFTP 6012R1

KEL-F Lock Tab Crack

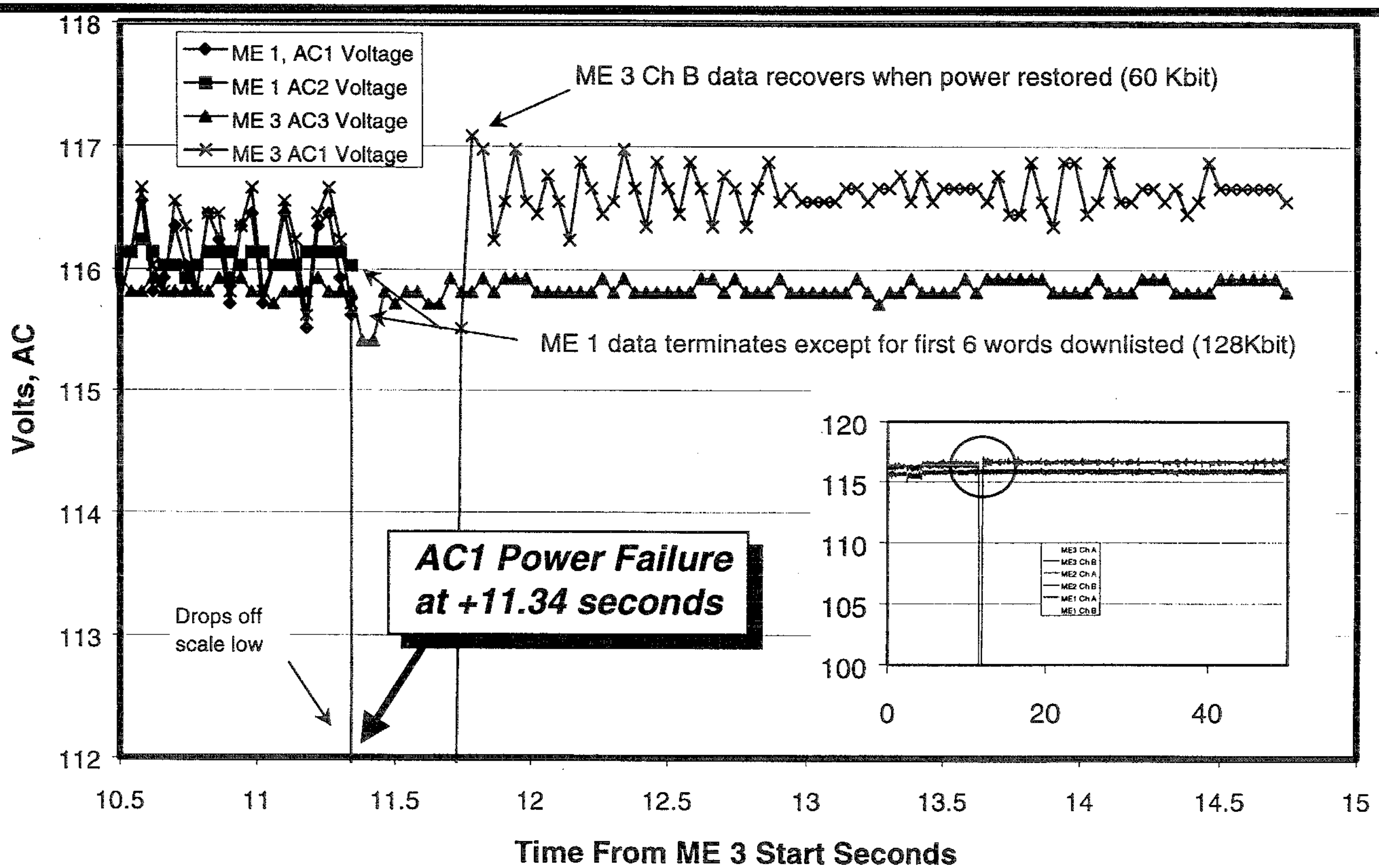
- **Flight Rationale**
  - Analytical assessment predicts no pump or engine system impact failures
  - FOD Tolerance Demonstrated
    - Pump
    - Engine System
    - Design robustness

STS-93 AC Power Anomaly

- **Issue**
  - Electrical power failure resulted in loss of redundancy and reduced data recording
- **Background**
  - At engine start +11.34 seconds, orbiter power to the engine controller failed (orbiter midbody wiring short)
  - Each engine supplied by redundant power supplies
  - Engines responded as designed
    - ME-1 and ME-3 continued operation on single channel
      - ME-1 backup channel resumed control but with limited orbiter data transmission and recording
      - ME-3 backup channel disqualified for engine control

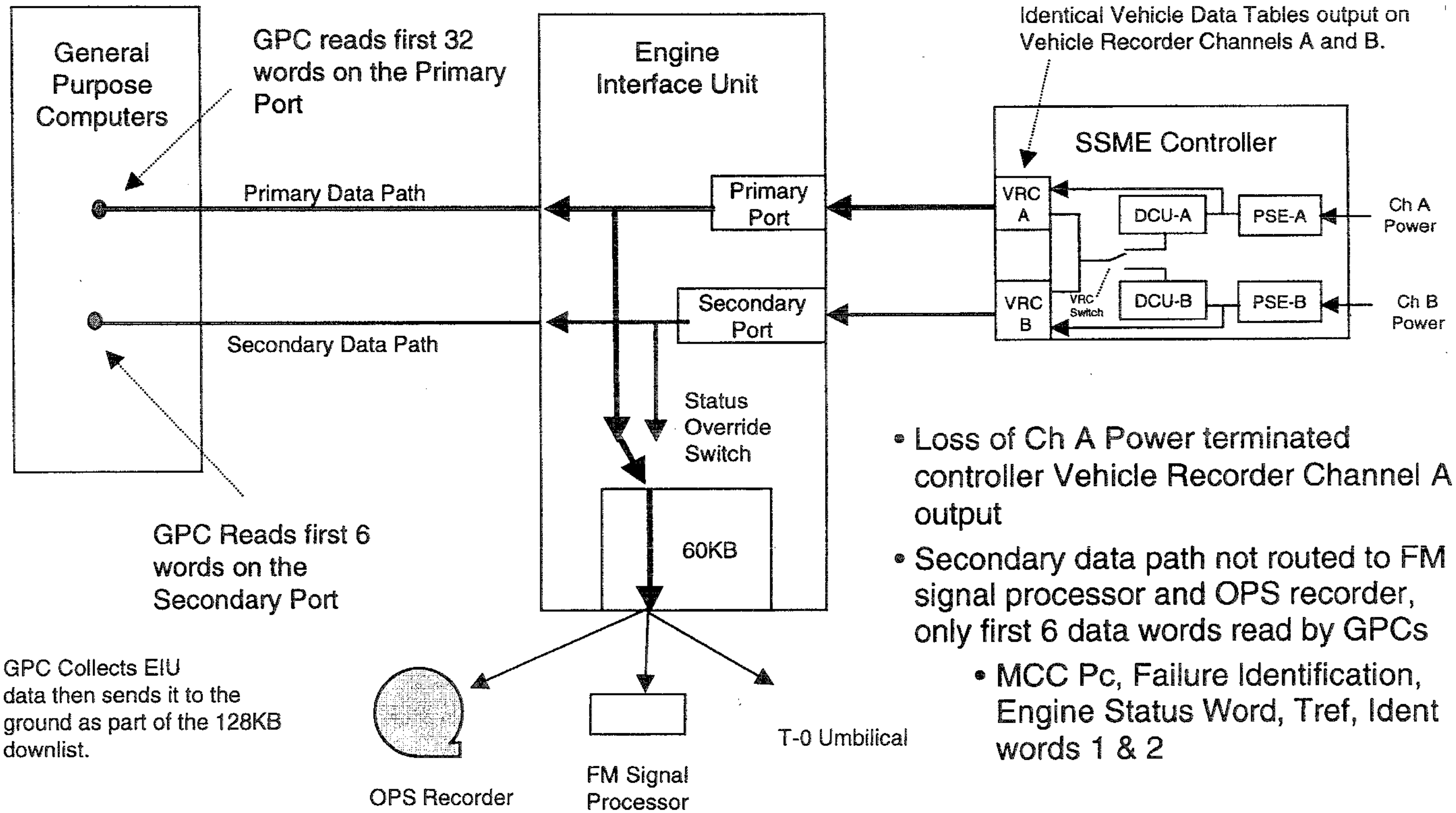
STS-93 AC Power Anomaly

ME-1 & ME-3 AC Voltage



STS-93 AC Power Anomaly

ME-1 Data Loss



- Loss of Ch A Power terminated controller Vehicle Recorder Channel A output
- Secondary data path not routed to FM signal processor and OPS recorder, only first 6 data words read by GPCs
  - MCC Pc, Failure Identification, Engine Status Word, Tref, Ident words 1 & 2

STS-93 AC Power Anomaly

ME-1 Data Assessment

- **Complete data available up to engine start +11.34 seconds**
  - Review complete - no anomalies
- **Alternate data available from +11.34 seconds through shutdown**
  - Vehicle interface data indicates nominal performance
  - No data anomalies (FIDs) posted during flight
  - Nominal MCC chamber pressure
  - Dynamic data evaluation reveals no anomalies
  - Post flight hardware inspections complete with no concerns
- **Subsequent hot-fire confidence test of E2012 at SSC verified no anomalies in the engine system**

STS-93 AC Power Anomaly

Summary / Conclusions

- **STS-93 demonstrated SSME control system redundancy**
  - Power failure caused ME-1 and ME-3 to operate on single computer channel
    - Control system maintained mixture ratio and commanded thrust as designed
    - Control system not hampered by loss of sensors
  - Control system responded to ME-3 nozzle leak as designed
    - Thrust and control maintained throughout flight
    - Adequate redline and structural margins maintained
- **Engine Control System Provided for Safe Operation as Designed**
  - No Flight Constraints

STS-93 AC Power Anomaly

SSME Harness Inspection Summary

- **Actions Taken**
  - Comprehensive review and evaluation of SSME harness design, fabrication, functional testing and operational history completed
  - PRCB briefed on 9/16/99 (SR1119) - No additional SSME action required
    - Robust Hardware design
    - Existing Comprehensive Inspections
    - Fleet Leader management and high time hardware evaluations
- **Corrective Action**
  - Maintain existing harness processing procedures
  - No additional actions required
- **Pre-Program FRR briefed 11/2/99 - Rationale for Flight Accepted**

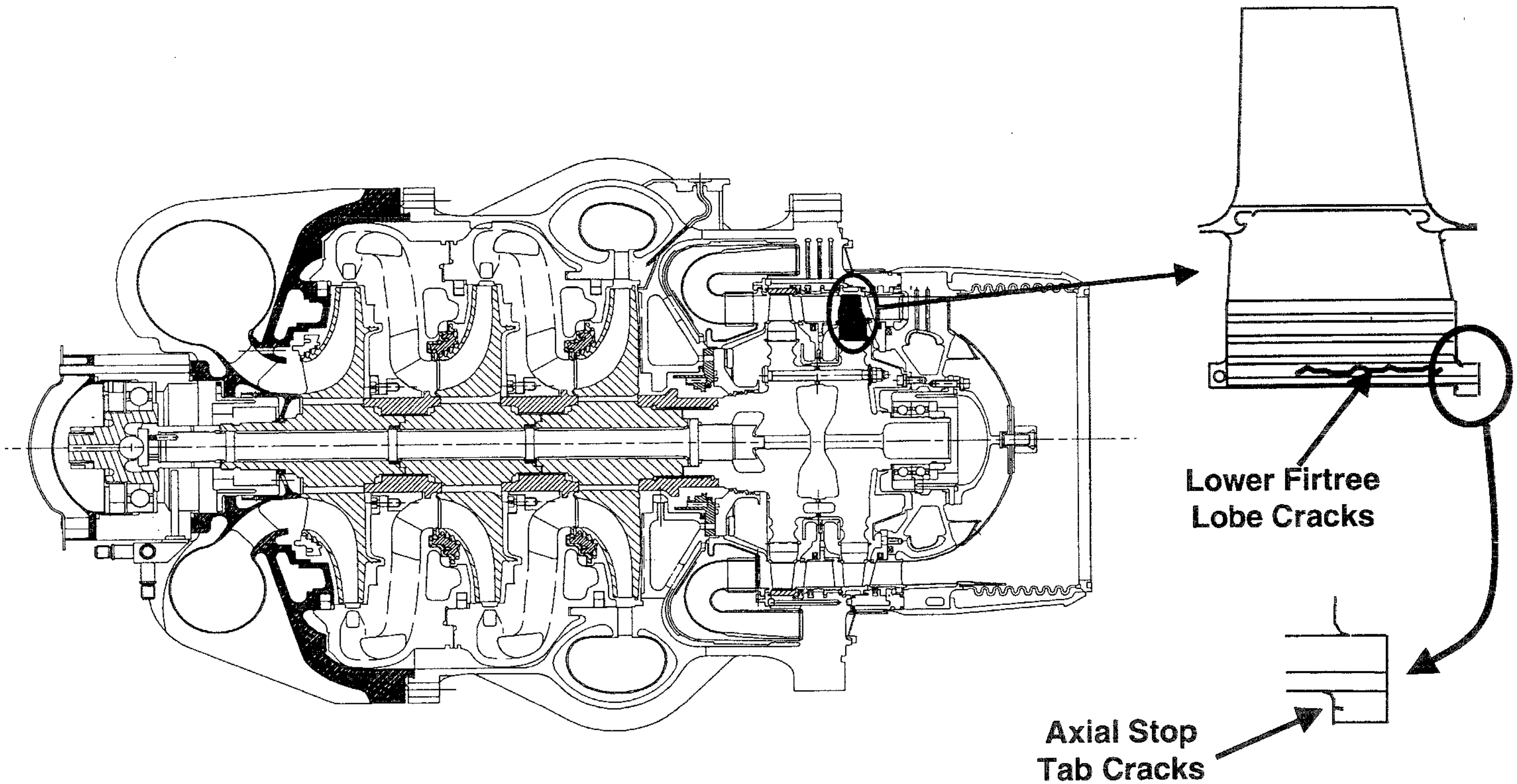
HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe and Stop Tab Cracks

- **Issue**
  - Reoccurrence of cracks in 1st stage blade lower firtree lobe and in axial stop tab
- **Background**
  - HPFTP 2128R2 recently returned from field for disassembly and recycle (7 starts and 3396 seconds on build)
    - Pump initially assembled in 1994
  - Cracks found during normal disassembly visual inspections (confirmed with dye penetrant inspection)
    - 10 blades with lower firtree lobe cracks
    - 11 blades with axial stop tab cracks
      - 3 blades with both types of cracks
  - Investigation Team formed - actions in work
    - No change to existing flight rationale anticipated

HPFTP 1st Stage Turbine Blade

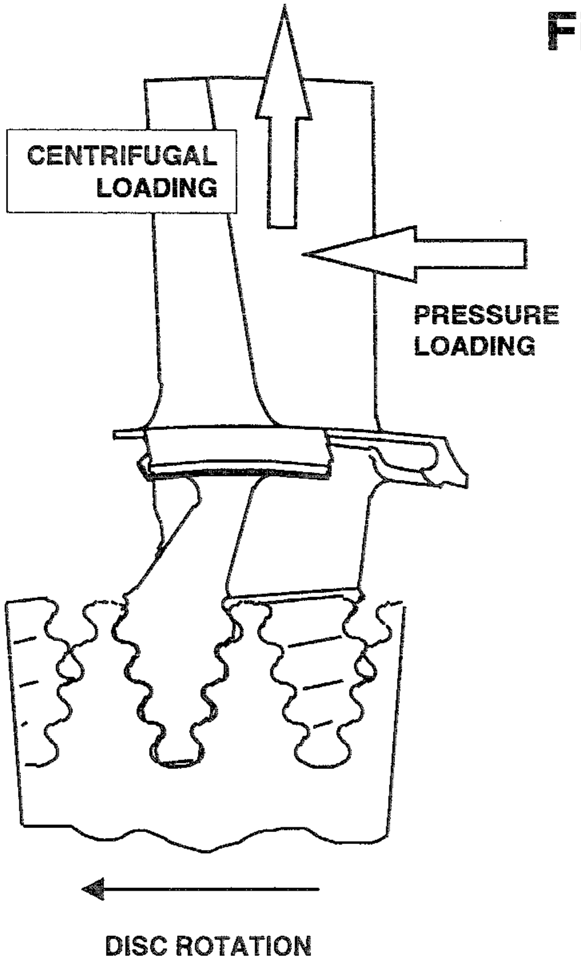
Lower Firtree Lobe and Stop Tab Cracks

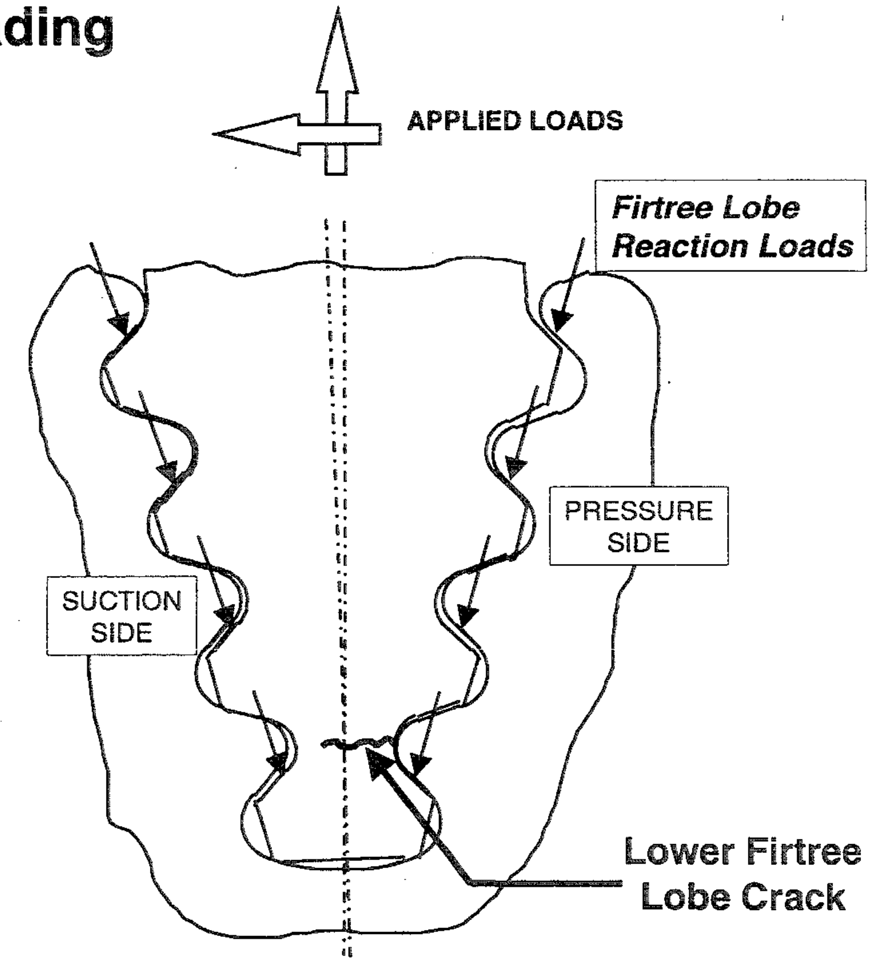


HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe Cracks

Firtree Loading





G. HOPSON
19 November 1999

103PROG.PPT

HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe Crack History

- **Prior to HPFTP 2128R2**
  - Previously identified condition
    - 34 blades prior to "Return to Flight" (0.83% occurrence rate)
      - 11 of 65 blades sets (max of 15 blades cracked in one set)
      - 4 blades with cracks in 2nd lobe
    - 4 "Return to Flight" configuration blades (0.09% occurrence rate)
      - 3 of 72 blade sets (max of 2 blades cracked in one set)
      - No occurrences of cracks in 2nd lobe
  - Reduced occurrence rate since "Return to Flight"
    - Process modifications incorporated in 1986
      - Improved load sharing between firtree lobes (process change)
      - Improved blade material capability (shot peening)

HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe Crack Occurrences

- **Lower firtree lobe cracks since 1986 "Return to Flight" Improvements**

HPFTP	Starts	Seconds	No. Cracked Blades	Axial Length
2423R1	20	9826	1	0.84
4016R1	10	3927	2	0.60/0.70
4112R4	8	4176	1	0.30
2128R2	7	3396	10	0.94

HPFTP 1st Stage Turbine Blade

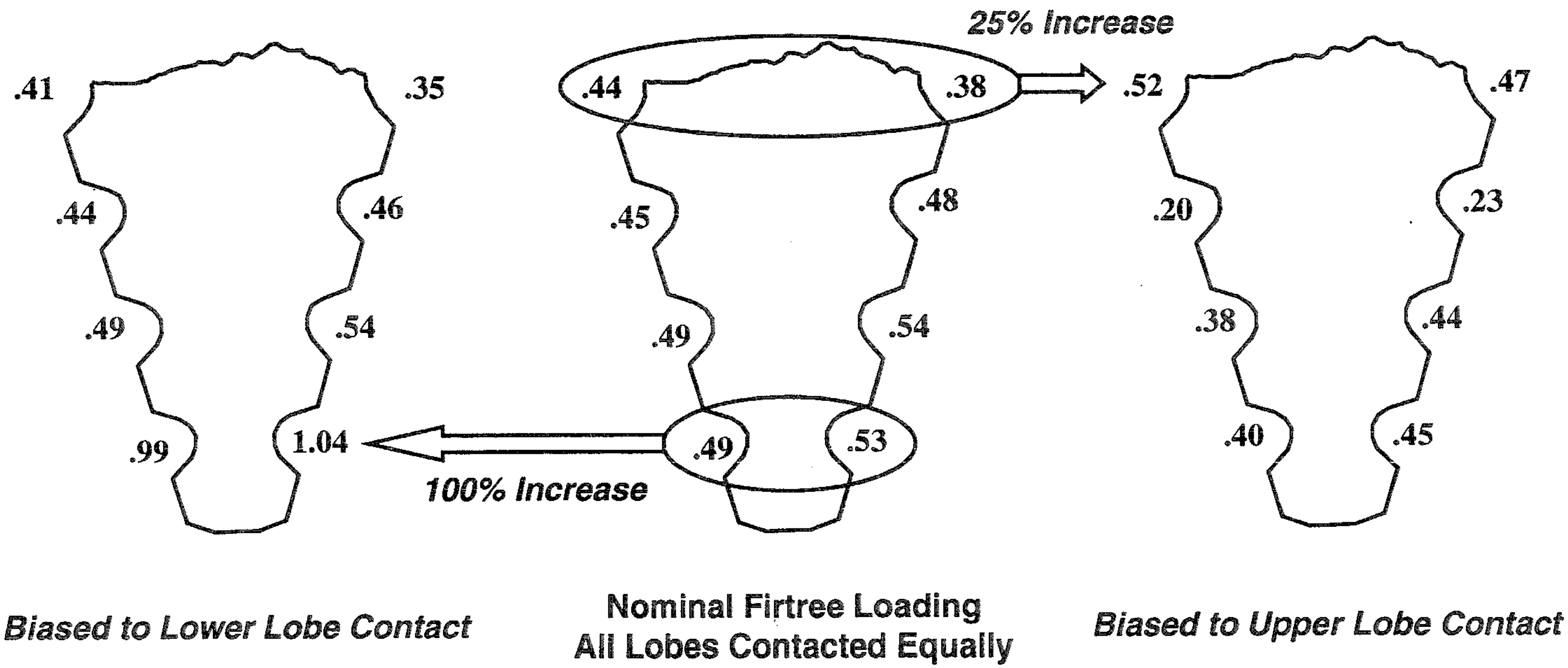
Cracking Mechanism

- **Hydrogen Assisted, Sustained Load Cracking**
  - Crack initiates in 1st or 2nd test
  - Multiple, pressure side, midspan initiation sites (typically at carbides)
  - Growth continues through firtree to suction side
  - No history of complete separation of lower lobe
    - Loads redistribute to upper lobes, self limiting
- **Most Probable Cause**
  - Tight fit of blade into disc firtree slots
  - Lower lobe neck is most sensitive to tolerance and fit variations between lobes
    - Largest increase in strains and largest peak strains
    - Supported by detailed finite element analyses

HPFTP 1st Stage Turbine Blade

Lobe to Lobe Dimensional Tolerance Sensitivity

Operating Strains in Firtree Necks, %



HPFTP 1st Stage Turbine Blade

Demonstrated Tolerance to Lower Firtree Lobe Cracks

- **Safety factor maintained with bottom lobe crack**
  - Demonstrated 1.64 safety factor at 104.5% operating conditions
    - Analysis anchored to laboratory spin tests and material shear tests
- **Successful fleet experience**
  - 210 blade sets (13,200 blades)
    - 778,000 seconds
    - 47 blade sets > 4300 second flight limit
  - 6 individual blades successfully hot fired with lobe cracks > flight limit
  - Fleet leader - 46 starts and 22,241 seconds
- **No loss of material ever experienced**
  - Upper firtree lobes provide redundant load paths and redistribute loads as crack forms and propagates

HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe Cracks

- **Assembly Process Variability Further Reduced in 1997**
  - Refinements in firtree load sharing
    - Same disc broach now used on 1st stage as used on 2nd stage ("looser fit", more movement)
      - No history of cracking on 2nd stage blades
    - Increased minimum required assembly tangential blade movement
      - Was .002"-.023", now .010"-.023"
    - Eliminated use of "broaching blades" during assembly process
  - Enhanced computed tomography inspections for casting porosity in firtree
- **Improvements incorporated with all pumps assembled as of July 1997**
  - HPFTP 2128R2 assembled in 1994

HPFTP 1st Stage Turbine Blade

Stop Tab Crack History

HPFTP	Starts	Seconds	No. Cracked Blades	Loss of Tab?
12108R3	46	22,241	61	No
4007R3	9	3510	2	Yes (1)
4016R1	10	3927	1	No
4110R2	10	6308	6	Yes (1)
2128R2	7	3396	11	No

- **Failure Mechanism**
  - Hydrogen assisted, sustained load flaw growth
    - Crack initiates in radius and propagates radially through stop tab
    - Final ligament failure due to overload

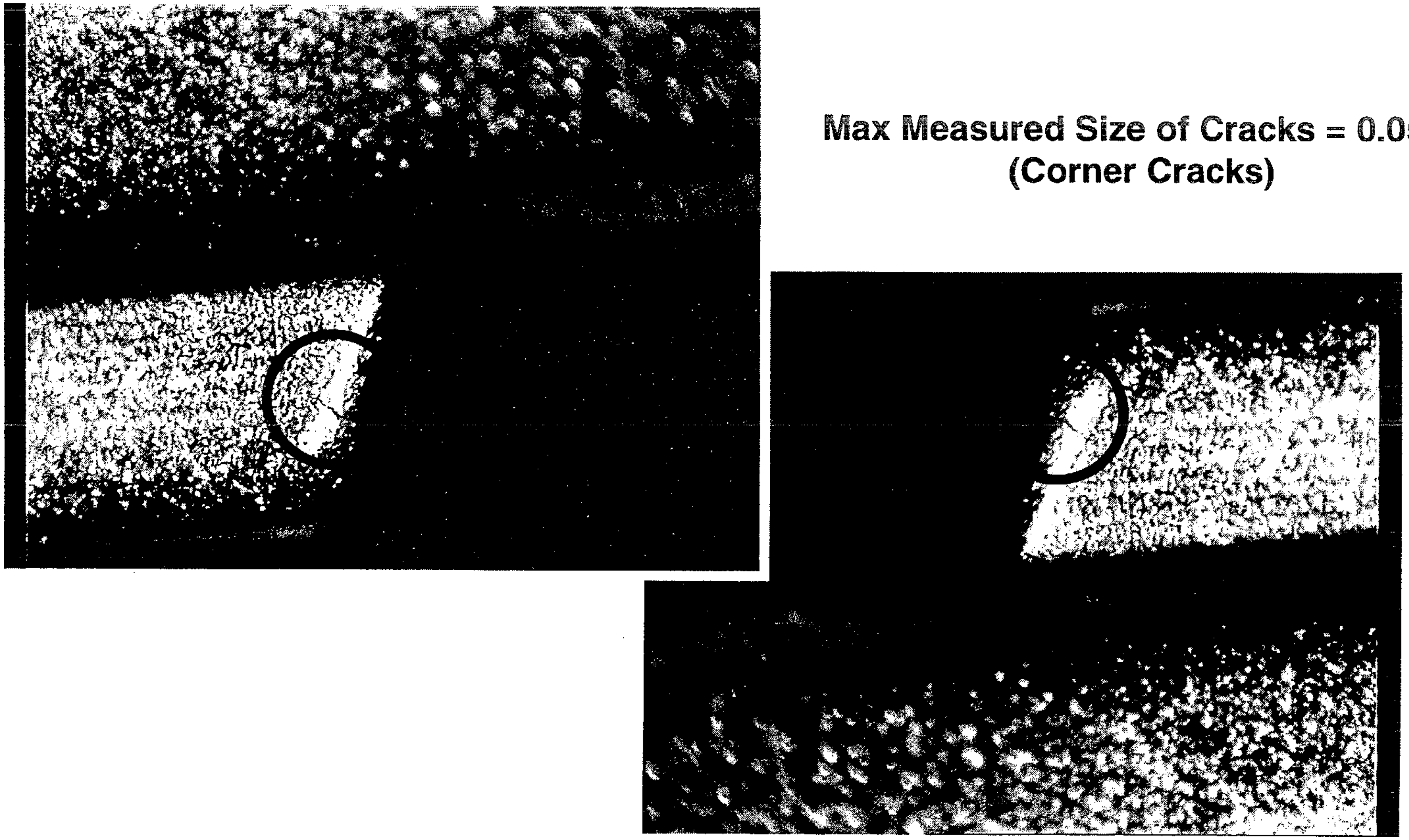
HPFTP 1st Stage Turbine Blade

Stop Tab Cracking Scenario

- **Assembly operations generate residual stresses in blade stop radius**
  - Blades typically installed in disc 3 - 8 times during assembly
- **Tight firtree fit requires repeated tapping with nylon tools**
  - Can result in plastic strain and residual stresses in stop radius
  - Blade stop deformation simulated by assembly procedures in lab and confirmed by residual stress measurements
- **Combined operating conditions make blade stop area susceptible to hydrogen**
  - Residual stresses from assembly + operating stresses
  - Ambient, high pressure hydrogen environment
  - Plastic strain enhances hydrogen diffusion which reduces material strength and ductility

HPFTP 1st Stage Turbine Blade

HPFTP 2128R2 Stop Tab Cracking



Max Measured Size of Cracks = 0.050"
(Corner Cracks)

HPFTP 1st Stage Turbine Blade

Assembly Procedure Changes

- **Assembly procedures modified in November 1991 to eliminate occurrences of stop tab cracks**
  - Utilized scrap blades with varying firtree sizes to hand broach disc slots
    - Eliminated in 1997 as part of process improvements to eliminate lower firtree lobe cracks
      - Use of "wider" 2nd stage broach eliminates need to hand broach slots
  - Restricted / controlled the use of polymer head hammer and nylon drift during assembly
  - Prior occurrences of stop tab cracks were with pumps assembled prior to use of new procedures
  - HPFTP 2128R2 assembled in 1994 after new procedure in place
    - Combined occurrence of lower lobe and stop tab cracks suggests "tight fit" of blades into disc
      - Supported with documented use of broaching blades

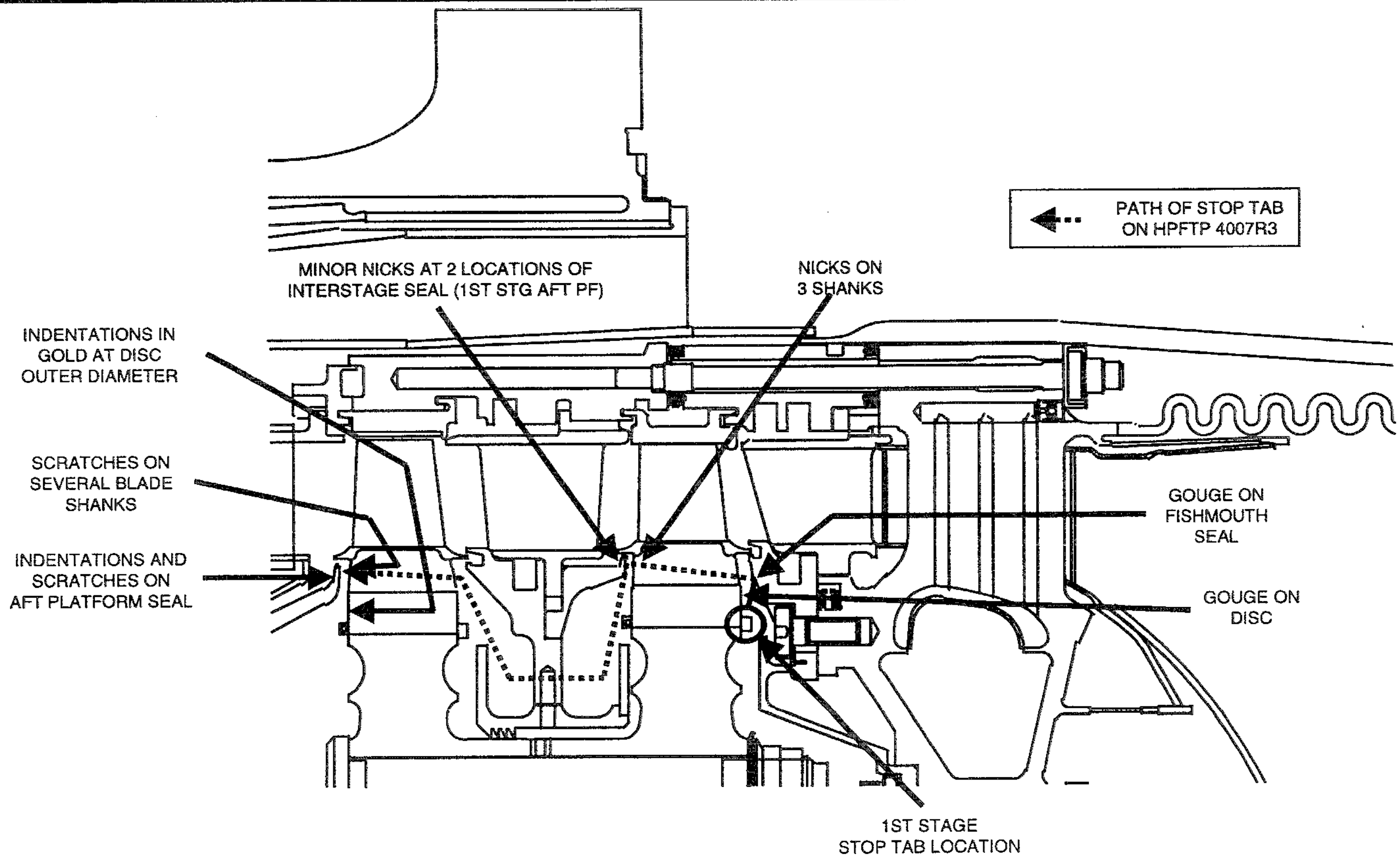
HPFTP 1st Stage Turbine Blade

Demonstrated Tolerance to Loss of Stop Tab

- **Negligible effect on blade retention and damping**
  - No evidence of movement of blade on either HPFTP 4007R3 or 4110R2
  - Blade movement precluded by high firtree frictional forces
- **No effect on engine start from dislodged fragment**
  - Breakaway torque up to 1000 in-lbs has no effect on start
    - HPFTP 4007R3 required 660 in-lbs to rotate with fragment fully lodged between 2nd stage disc and aft platform seal
- **Fragment of insufficient mass to cause damage**
  - Results in minor scratches and nicks on blade shanks, discs, fishmouth and platform seals
  - Stop tab remains below blade platforms and cannot enter flowstream in one piece
    - Only 36% of tab fragment mass (0.06 grams) could enter hot gas flow stream with worst case tolerances

HPFTP 1st Stage Turbine Blade

Loss of Stop Tab - HPFTP 4007R3 Particle Path



HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe and Stop Tab Cracks

- **Investigation Team Open Actions**
  - Continue fault tree and work actions as required
    - Complete review of all fabrication and assembly records for HPFTP 2128R2 blades and disc
    - Complete materials analyses and fractography of sectioned blades
      - Confirm cracking mechanism / compare to prior history
    - Provide explanation for apparent "out of family" number of lower lobe cracks
  - Assess flight readiness of STS-103 HPFTPs based on results of investigation

HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe and Stop Tab Cracks

- **Flight Rationale - Lower Firtree Lobe Cracks**
  - Safety factor maintained with bottom lobe cracked
    - Demonstrated 1.64 safety factor at 104.5% operating conditions
  - Successful fleet experience
    - 210 blade sets (13,200 blades)
      - 778,000 seconds
      - 47 blade sets > 4300 second flight limit
    - 6 individual blades hot fired with lobe cracks > flight limit
    - Fleet leader - 46 starts and 22,241 seconds
  - STS-103 blades < flight limit, post RTLS abort

ME-1	HPFTP 6017	2 Starts / 1274 Seconds
ME-2	HPFTP 6014	6 Starts / 2437 Seconds
ME-3	HPFTP 6110	7 Starts / 3684 Seconds

HPFTP 1st Stage Turbine Blade

Lower Firtree Lobe and Stop Tab Cracks

- **Flight Rationale - Stop Tab Cracks**
  - Stop tab loss has negligible effect on blade retention or damping
    - No evidence of blade movement in cases with complete loss of tab
  - Potential increased torque due to dislodged fragment has no effect on engine start
  - Stop tab has insufficient mass to cause downstream damage
    - Too large to enter flowstream in one piece
    - Fragment well within demonstrated capability for FOD
    - Only superficial damage noted on components

HPOTP/AT ECI Master Calibration

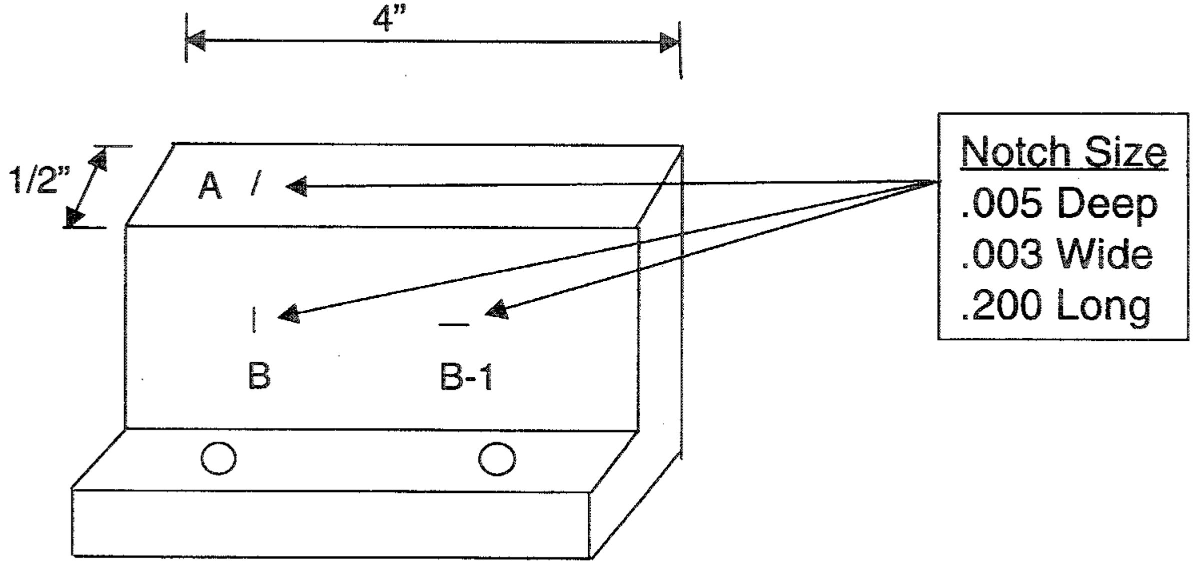
- **Issue**
  - Critical Initial Surface Flaws may not be detected due to improperly calibrated eddy current inspection (ECI) equipment
- **Background**
  - ECI used in concert with other NDT to ensure flaws in parts are less than the Critical Initial Flaw sizes (CIFS)
    - Also used to supplement penetrant inspections when surface etch not performed
    - All finished parts are penetrant inspected for surface flaws
  - Prior to inspection, ECI equipment is calibrated using a standard with a defect of known size and shape
  - Three eddy current machine types used for inspections
    - RECHII, CESIS, and Anorad

HPOTP/AT ECI Master Calibration

- **Background (Continued)**
  - Calibration of Anorad machine has been performed using one standard for all crack orientations and probe types
    - Discovered in Air Force audit at P&W Middletown, CT
  - Result is inspection errors for certain setups for parts - splines, slots, small fillets, ID bores, etc
  - P&W machining process controls have history of producing defect-free parts
    - No evidence of machining induced flaws in the AT program history

HPOTP/AT ECI Master Calibration

ECI Anorad Calibration Block Illustration



- Notch orientations B and B-1 have incorrect calibration
- Calibration for notch orientation A is correct

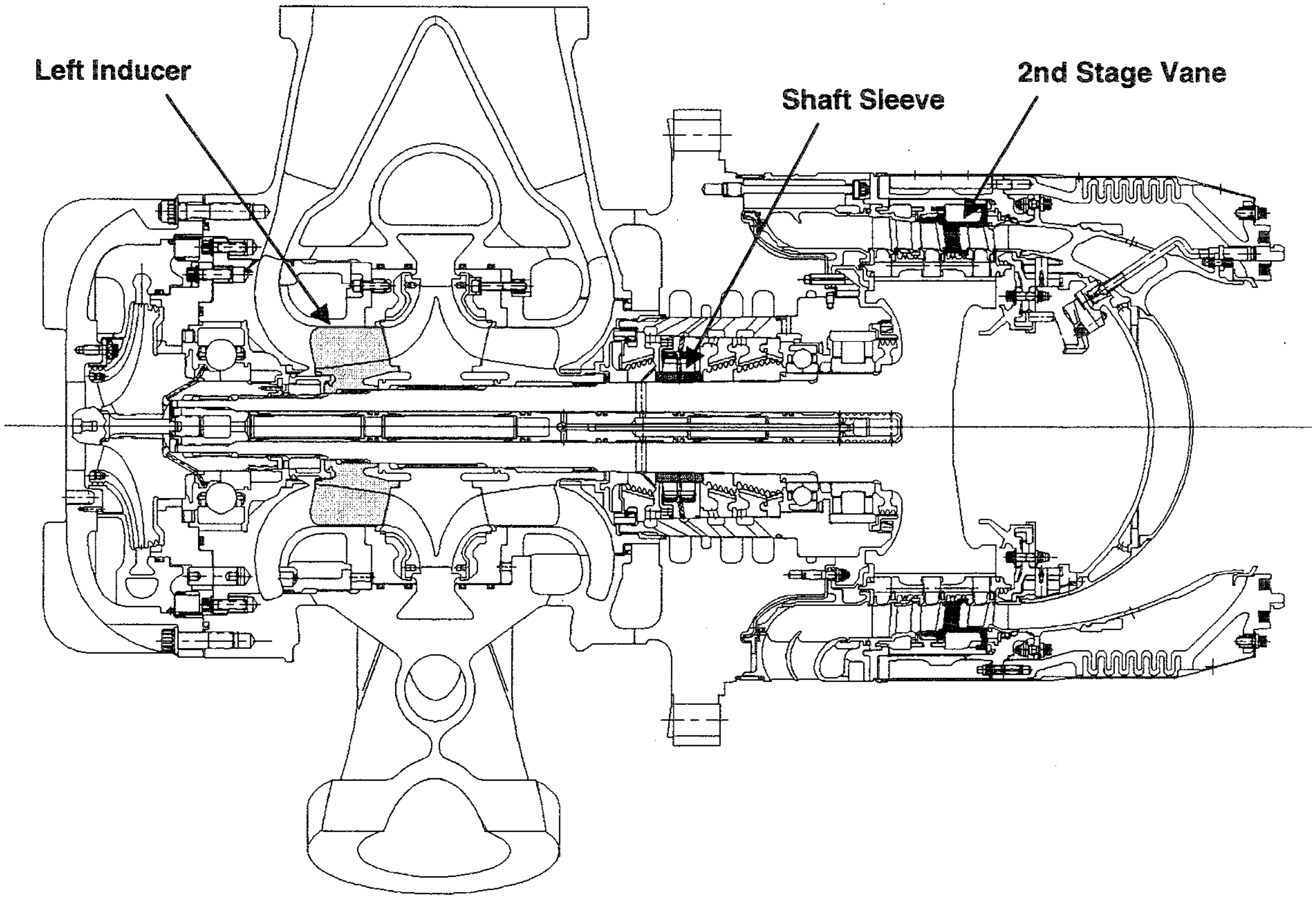
HPOTP/AT ECI Master Calibration

Analysis

- **Diagnostic testing performed to quantify inspection error**
  - Inspection error found to be 47%
- **Assessment of flight hardware for STS-103 is complete**
  - Screen of 25% of target signal amplitude used
  - ECI trace review for 21 components per pump which use Anorad machine in B and B-1 orientations
    - 44 parts on STS-103 exceed 25% screen
    - 5 parts on STS-103 had corrected indications in excess of reject signal amplitude
  - Fracture life analysis performed on components which exceeded the reject level
    - Included correction for signal error
    - Assessed as known defects
    - All parts on STS-103 meet CEI life requirements

HPOTP/AT ECI Master Calibration

STS-103 Parts Exceeding ECI Reject Amplitude



G. HOPSON
19 November 1999

HPOTP/AT ECI Master Calibration

- **STS-103 Flight Rationale**
  - All components installed on STS-103 meet CEI life requirements
    - Fracture analysis performed assuming indications are known defects
  - All finished parts penetrant inspected for surface flaws and found acceptable

Discovery STS-103
SSME CoFR

- **Flight Readiness Review CoFR Exceptions:**
  - HPFTP 1st Stage Turbine Blade Cracks
    - Pending Failure Team investigation results
    - Defer / close UCRs
      - A034268: Lower firtree lobe cracks
      - A034269: Axial stop tab cracks
  - HPFTP Main Housing Backplate Casting - Potential Undersized Wall Thickness
    - Generic MR 1238688
- **Closure at STS-103 Mission Management Team Review**

Discovery STS-103

SSME Readiness Statement

- **The Discovery Main Engines are in a ready condition for STS-103 pending completion of open issues.**

G.D. Hopson
Manager
SSME Project

J. B. Plowden
Vice President and Program Manager
Space Shuttle Main Engine

LPOTP SPEED SENSOR
PUMP MOUNTING