TWR-75738
ECS SS10969

SPACE SHUTTLE PROGRAM
Space Shuttle Projects Office (MSFC)
NASA Marshall Space Flight Center, Huntsville, Alabama

Reusable Solid Rocket Motor
STS-104 Flight Readiness Review/CoFR

Motor Set RSRM-80

28 June 2001

Presented by Stan Graves

THIOKOL PROPULSION

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Agenda

Flight Readiness Review/CoFR

1.0 Previous Flight Assessment—STS-100

2.0 Certification Status—**No Constraints**

3.0 Changes Since Previous Flight

4.0 Configuration Inspection

- 4.1 As-Built Versus As-Designed, Hardware, and Closeout Photo Review Status—**No Issues**
- 4.2 Hardware Changeouts Since ET/SRB Mate Review—**None**

5.0 SMRB Nonconformances—**None**

6.0 Technical Issues/Special Topics

7.0 Readiness Assessment

Backup LCC and Contingency Temperatures for STS-104

Previous Flight Assessment—STS-100

Disassembly Evaluation Summary—Status of Disassembly Activity

KSC Operations		LH RSRM	RH RSRM	Remarks
Initial LH/RH SRB viewing	*	Complete	Complete	
SRB/RSRM walkaround assessment	*	Complete	Complete	
Demate/evaluate aft exit cone (AEC)	*	Complete	Complete	
Remove/evaluate S&A and OPTs	*	Complete	Complete	
Remove/evaluate nozzle	*	Complete	Complete	Thru Gas Path in LH Nozzle-to-Case Joint Polysulfide With Wiper O-ring Erosion (in-family)
Remove/evaluate stiffener rings/stubs		Complete	Complete	
Remove/evaluate igniter	*	Complete	Complete	
Demate/evaluate field joints/evaluate insulation	*	Complete	Complete	
Utah Operations				
Disassemble/evaluate nozzle (joint No. 4 and 5)	*	Complete	Complete	
Disassemble/evaluate nozzle (joint No. 2 and 3)	*	Complete	Complete	
Disassemble/evaluate S&A	*	Complete	Complete	
Washout nozzle phenolics		Complete	Complete	
Washout nozzle AEC phenolics		Complete	Complete	
Measure/evaluate aft dome and RH segment insulation		04 Dec 2001	04 Dec 2001	
Measure/evaluate igniter insulation		04 Dec 2001	04 Dec 2001	

* RSRM Project committed to complete prior to next launch

- **No constraints to STS-104 flight**

Previous Flight Assessment—FSM-9

Disassembly Evaluation Summary—Status of Disassembly Activity

Test Operations	FSM-9	Remarks
Evaluate nozzle (quick-look)	Complete	PFAR FSM09-01, Unusual Erosion Area on Aft Exit Cone
FSM-9 walkaround assessment	Complete	
Remove/evaluate S&A and OPTs	Complete	
Demate/evaluate aft exit cone (AEC)	Complete	PFAR FSM09-02, Pocket/Wash Erosion on The Throat and Forward Exit Cone
Ship AEC	Complete	
Remove aft skirt	Complete	
Ship aft segment to Clearfield	Complete	
Demate/evaluate field joints/evaluate insulation	Complete	
Ship forward segment to Clearfield	Complete	
Clearfield Operations		
Receive AEC	Complete	
Washout nozzle AEC phenolics	02 Jul 2001	
Receive aft segment	Complete	
Remove nozzle	Complete	
Disassemble/evaluate S&A	Complete	
Disassemble/evaluate nozzle (joint No. 4 and 5)	Complete	
Disassemble/evaluate nozzle (joint No. 2 and 3)	Complete	
Receive remaining segments	Complete	
Remove/evaluate igniter	Complete	
Washout nozzle phenolics	12 Jul 2001	
Measure/evaluate igniter insulation	12 Jul 2001	
Measure/evaluate aft dome and segment insulation	Jul-Sep 2001	

- No constraints to STS-104 flight

Changes Since Previous Flight—Approved

Class I Engineering and LCC

ECP SRM-3555, RSRM Certification to Block II SSME Loads Environments (with exception)
LCN 01067, Generic Maximum Allowable Ground Winds
Criticality: 1
Status: CR S071759 approved at PRCB 12 Apr 2001, LCN 01067 approved at PRCB 17 May 2001

Change Description

Decrease RSRM prelaunch ground wind requirement in the region from 101 to 150 deg

- CR S071759: Implement an exception to NSTS-07700, Vol. X, Book 1, ground wind requirements for RSRMs paired with Block II SSMEs
- LCN 01067: Update the LCC to reflect the new maximum allowable wind velocities between 101 and 150 deg

Reason for Change

Implementation of these requirements will allow the RSRM to be generically certified to the Level II prelaunch ground wind requirements for the SSME Block II engine loads

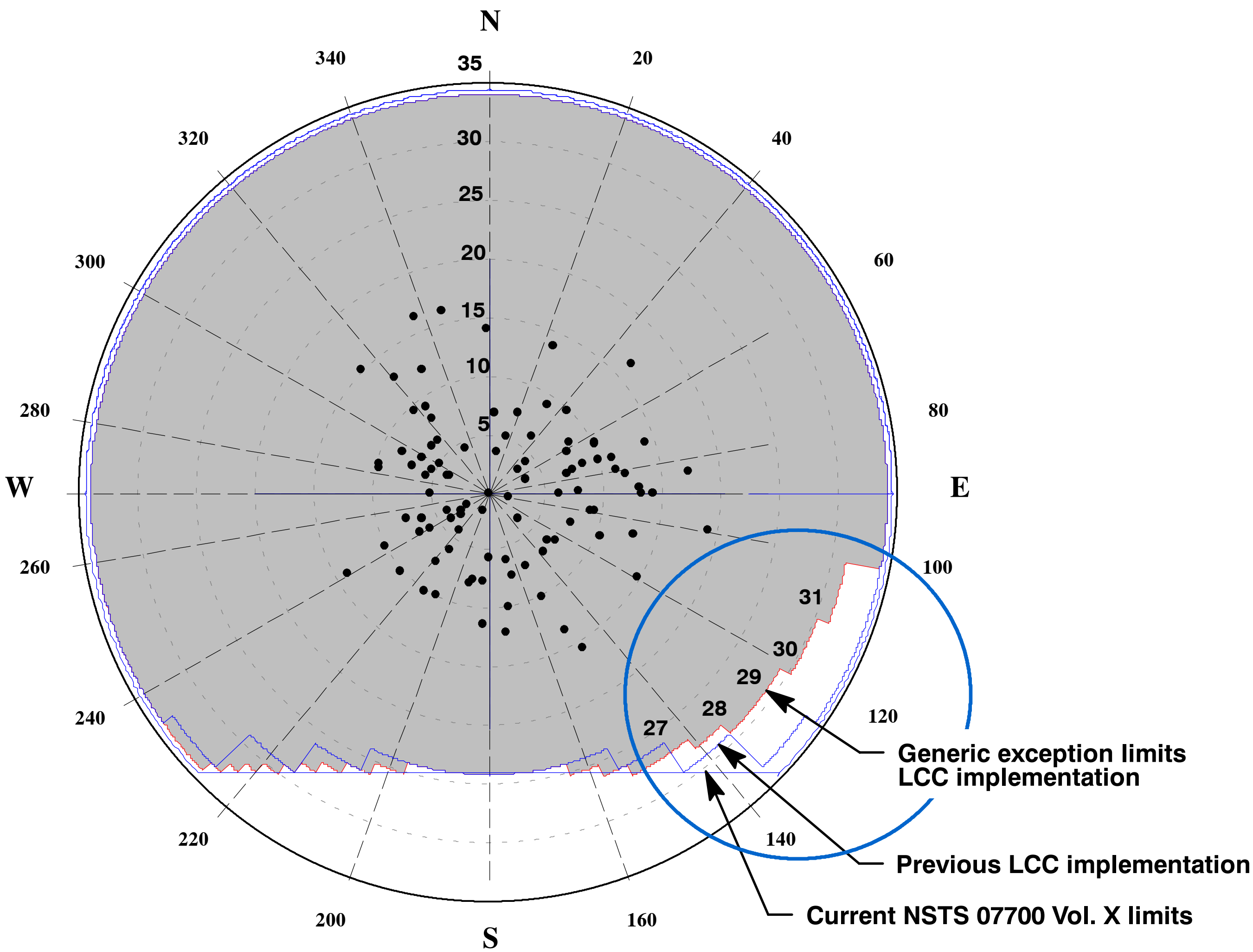
Basis of Verification

Analysis: Buckling certification analysis verifies that the RSRM generically meets the system prelaunch ground wind requirements, as modified with the reduced wind requirements from 101 to 150 deg, with a 1.4 factor of safety

STS-104 and subsequent are safe to fly

Changes Since Previous Flight—Approved

Class I Engineering ECP SRM-3555, and LCC LCN 01067 (Cont)



Changes Since Previous Flight—Approved

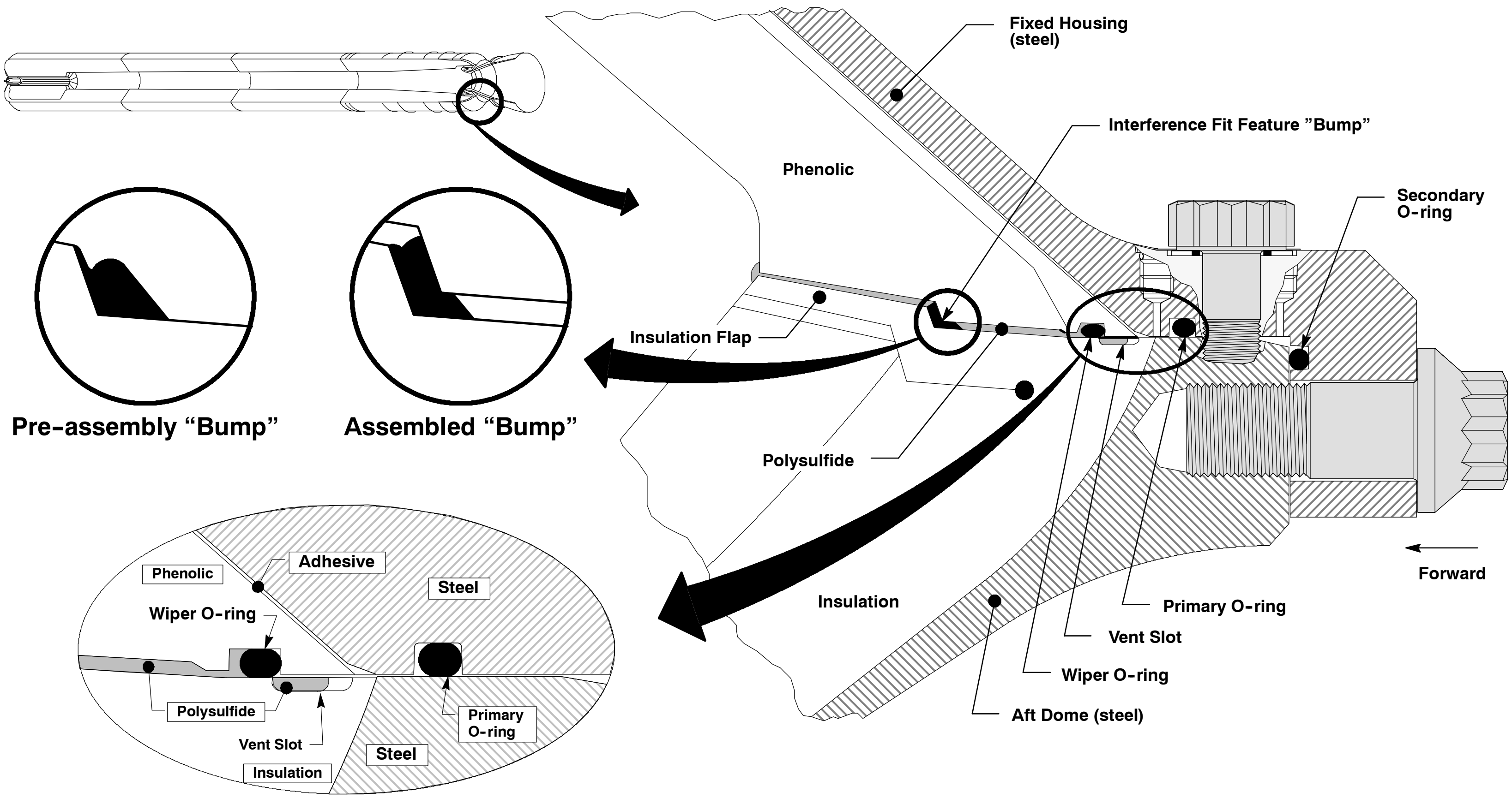
Process

OCRs 0200470 and 0200641, Nozzle-to-Case Joint Assembly Process Enhancements
Status: CR S074812A approved by PRCB on 21 Jan 1999

Change Description	Reason for Change	Basis of Verification
Nozzle to case joint interference fit feature "bump" Narrow vent slots Slower assembly rate Power screed application of acreage polysulfide to reduce air voids Index acreage screed from aft dome boss Forward vent slots in polysulfide Laser measurement on acreage polysulfide profile Mass flow meter to monitor venting during assembly	Process enhancements on the nozzle-to-case joint assembly significantly reduce potential for polysulfide gas path formation and polysulfide extrusion to the primary O-ring during joint assembly	Test: Extensive subscale and full-scale development tests defined enhancements to the assembly process and demonstrated the desired improvements (151 assembly tests conducted) Demonstration: Seven full-scale normal hardware variation tests (includes four NJADs, FSM-6, -7, and -8) with no thru gas paths or excessive extrusion Inspection: Process limits and laser tool for flap and polysulfide profile dimensional inspection Analysis: All previous RSRM nozzle-to-case joint structural and thermal analysis, flaw testing, and flight performance history remains applicable STS-104 and subsequent are safe to fly

Changes Since Previous Flight—Approved

Critical Process, OCRs 0200470 and 0200641 (Cont)



Technical Issues/Special Topics

Suspect Rubber Pattern Labels in RSRM Internal Insulation

Observation

- A pattern identification label was found embedded in the clevis insulation of the STS-105 LH aft segment during processing at KSC
  - The label-caused void was cut open, most of the label removed, the rubber bonded back in place, and the repair blended to the surrounding contour
  - STS-105 LH aft segment repair has been fully evaluated and meets all requirements

Concern

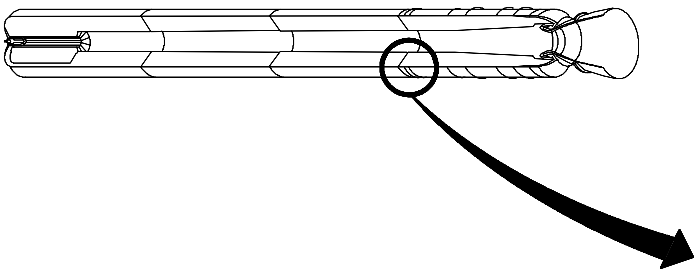
- Consequence of a label incorporated anywhere within the insulation on any segment relative to thermal, structural, or sealing requirements
  - Label could create a small unbond or void (1.75 in. x 2.5 in.)

Background

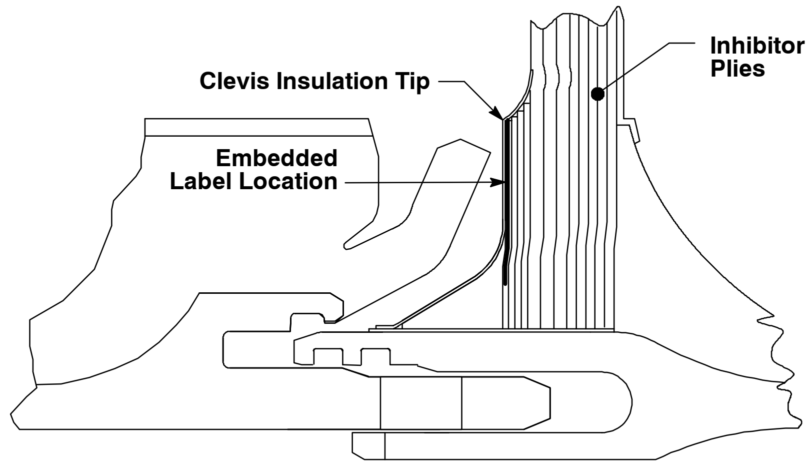
- Cause of the out-of-place label is understood
  - Missing or misaligned polyethylene film cover resulted in label adhering to the back of a green rubber ply in the pre-cut ply kit
  - Cause determined to be a rare and isolated event
- A joint Thiokol and MSFC team conducted a comprehensive evaluation of the insulation layup process and design to understand the probability and criticality of labels in the insulation

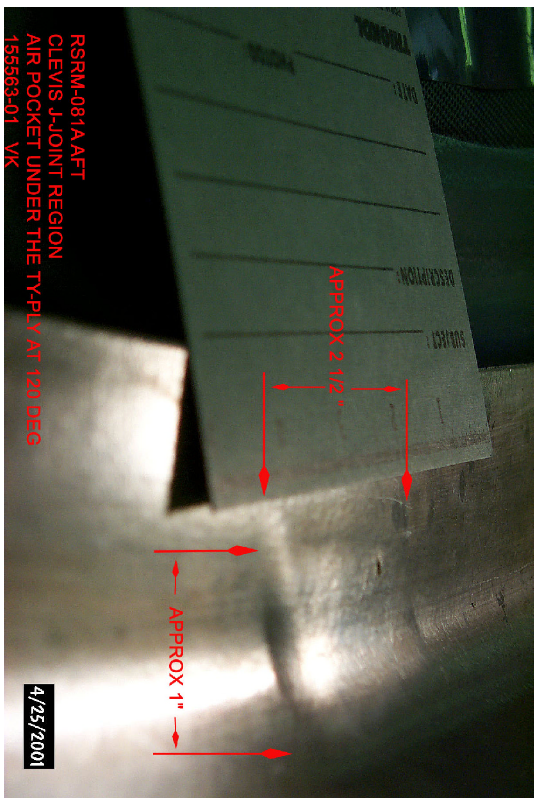
Technical Issues/Special Topics

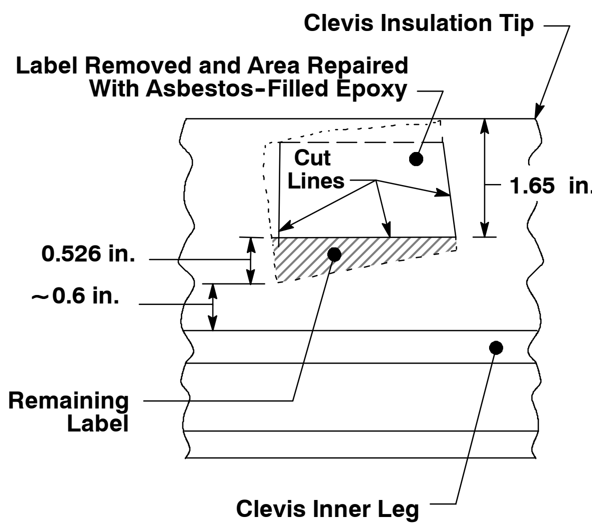
Suspect Rubber Pattern Labels in RSRM Internal Insulation (Cont)

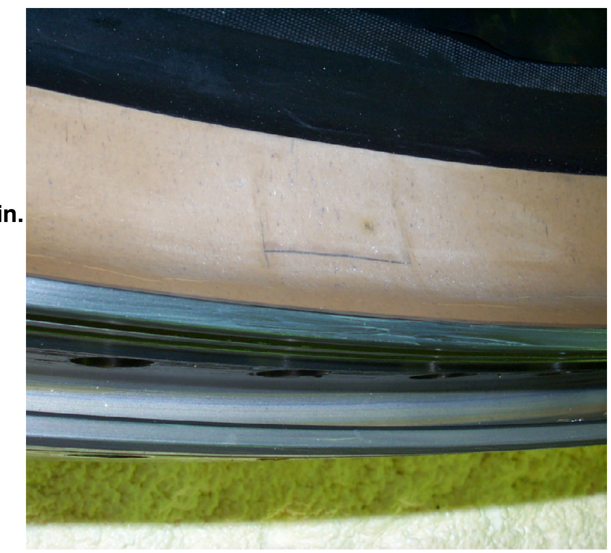


STS-105 (RSRM-81) LH Aft Condition









Technical Issues/Special Topics

Suspect Rubber Pattern Labels in RSRM Internal Insulation (Cont)

Discussion

- The investigation team concluded the following
  - Extensive controls are in place to preclude foreign materials being introduced into the insulation layup process
    - Controls to ensure areas are clean and free of foreign material
    - Restrictions for transient personnel and unapproved items
    - Tools and in-process materials are accounted for during and after layup
    - In-process inspections, process design, training and experience
  - The vast acreage of the motor is tolerant of label-sized inclusions
    - Large voids (greater than 5 in. axial by 20 in. circumferential) are allowed by engineering and do not affect thermal or structural margins
    - Numerous motors have flown with voids much larger than label size with no adverse effects
  - Thermal margins of safety are unaffected at all locations due to the small size and small volumes associated with label-induced voids
  - Structurally critical areas of the motor were assessed as safe to fly in one of the following ways:
    1. No credible mechanism to get a label in that location, or
    2. Analyses show that all structural requirements are met

Technical Issues/Special Topics

Suspect Rubber Pattern Labels in RSRM Internal Insulation (Cont)

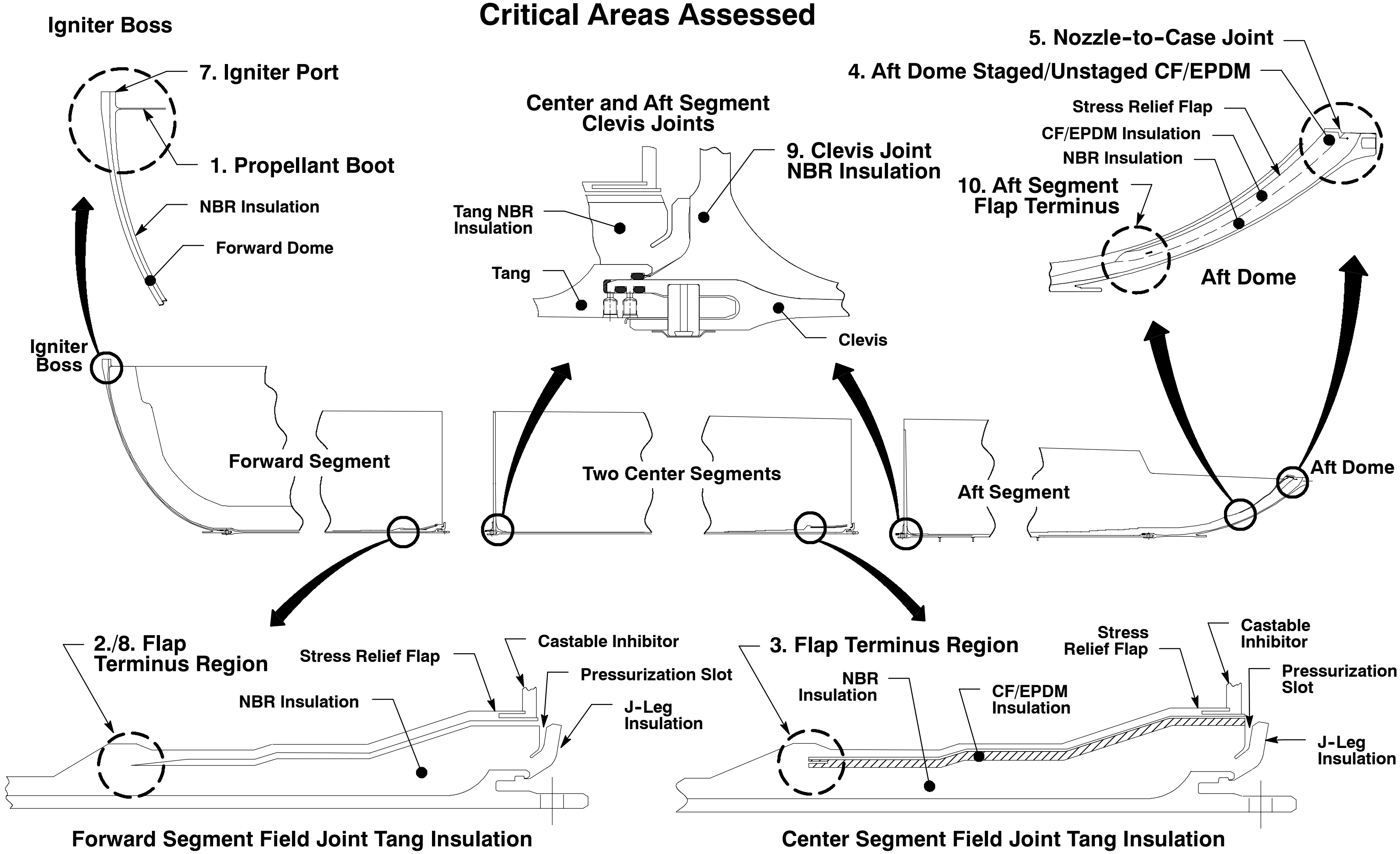
Discussion (Cont)

- The following structurally critical areas (see figure) were found to have no credible mechanism for getting a label in that location (no labels used in the process, for example)
  1. Propellant boot
  2. Forward segment flap terminus
  3. Center segment flap terminus
  4. Aft dome staged/unstaged CF/EPDM
  5. Nozzle-to-case joint
  6. Igniter chamber and adapter
- While unlikely, labels could occur sometime in the life of the program in the following critical areas, but all have adequate structural margins even if a label were present
  7. Forward dome igniter port (2.04 factor of safety, 2.0 required)
  8. Forward segment flap terminus (1.5 factor of safety, 1.4 required)
  9. Clevis joint (2.0 factor of safety, 2.0 required)
  10. Aft segment flap terminus (2.8 factor of safety, 2.0 required)
- All analyses assumed label was in worst possible location, with worst possible orientation, under worst-case loads and environments

Technical Issues/Special Topics

Suspect Rubber Pattern Labels in RSRM Internal Insulation (Cont)

Critical Areas Assessed



Technical Issues/Special Topics

Suspect Rubber Pattern Labels in RSRM Internal Insulation (Cont)

Flight Rationale

- No changes to the insulation layup process have been identified
    - Future insulation flight performance predicted to be within family of past performance
- Low probability of having a label in future motors based on extensive process controls and inspections
    - STS-105 observation determined to be a rare and isolated event
- All areas of the insulation subject to potential label inclusion are structurally and thermally tolerant of a label-size void
- Field joint and igniter J-joints are subject to stringent inspections for surface irregularities, and are fault tolerant as demonstrated by full-scale flaw testing and analysis
- STS-104 and subsequent motors are safe to fly

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and Forward Exit Cone

Observation

- **The aft region of the FSM-9 throat ring experienced pocketing erosion**
  - **72 pockets were observed with depths up to 0.38 in.**
    - **Erosion factor of safety 1.9 (-0.04 margin with 2.0 safety factor)**
    - **Substantial remaining virgin material (0.88 in.)**
    - **Remaining burn time = 175 seconds beyond the nominal 123-second motor burn time**
- **Similar in appearance to STS-79 RH, STS-80 LH and RH, and STS-85 RH**

Concern

- **Adequate nozzle thermal protection**

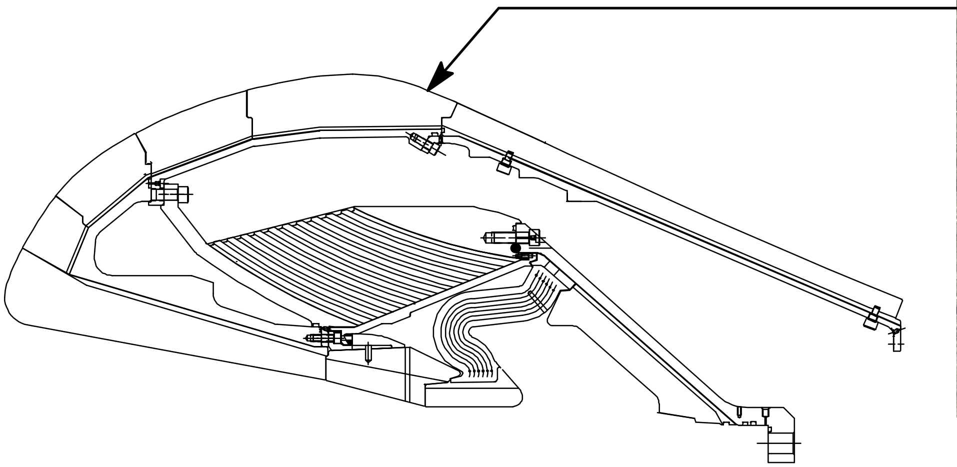
Background

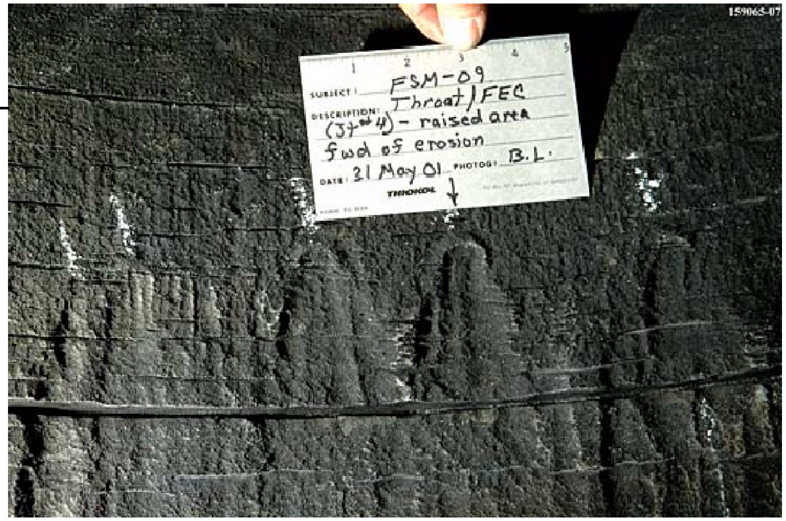
- **Major investigative effort was completed following pocketing in STS-79 and STS-80 in 1996/1997 timeframe**
- **STS-79 RH, STS-80 LH and RH, and STS-85 RH nozzle throat pocketing attributed to near flame surface ply distortions in combination with a high-propensity-to-pocket material**

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

FSM-9 Throat Ring Pocketing





Throat Ring Performance Summary			
Nozzle	Maximum Erosion (in.)	Virgin Remaining (in.)	Burn Time Remaining (beyond nominal 123 seconds)
STS-42 RH (worst nonpocketed nozzle)	0.60	0.87	173 seconds
STS-79 RH (worst pocketed nozzle)	0.80	0.80	175 seconds
FSM-9	0.82	0.88	175 seconds

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

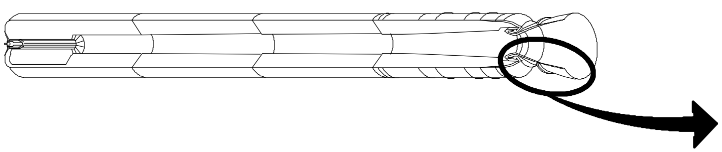
Background (Cont)

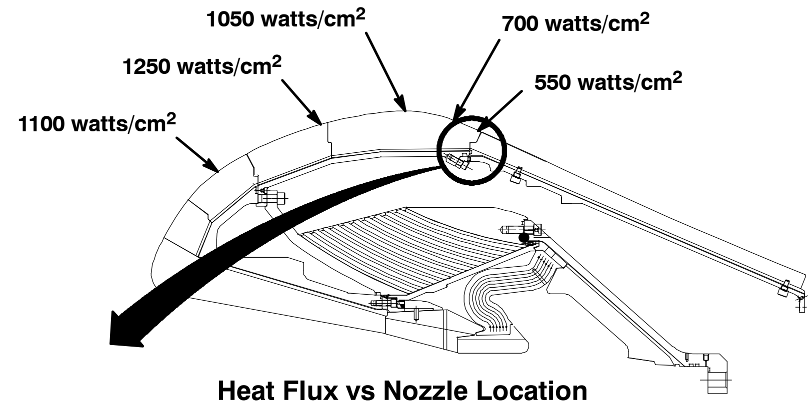
- Investigation showed that nozzle pocketing occurs when pyrolysis gas pressures exceed the carbon-fiber strength in the hot char material
  - Key factors include
    - High heating rate
    - High ply angle relative to flame side gas flow
    - Low carbon fiber tensile strength at 2000 to 3000°F
- Investigation results are based on a high fidelity test bed which has been developed to explore nozzle material response to very high heat rates under controlled conditions
- Test bed uses the high-powered laser at the Laser Hardening Materials Evaluation Laboratory (LHMEL) at Wright-Patterson
  - Laser intensity set to match RSRM motor heat flux
  - Highly instrumented samples measure in-depth temperatures, pore pressures, char density, etc.
  - Tests explore material response to ply angle, heat rate, and environmental exposure

Technical Issues/Special Topics

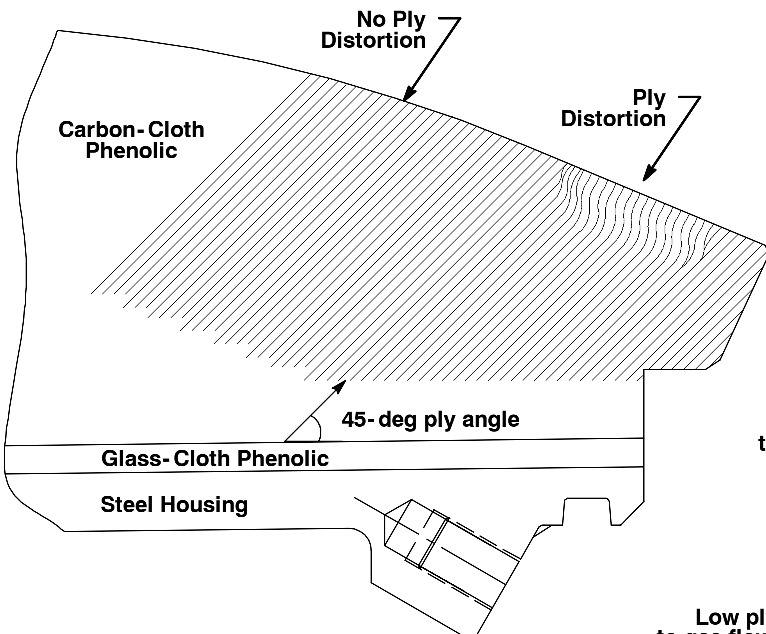
Pocket/Wash Erosion on Throat and FEC (Cont)

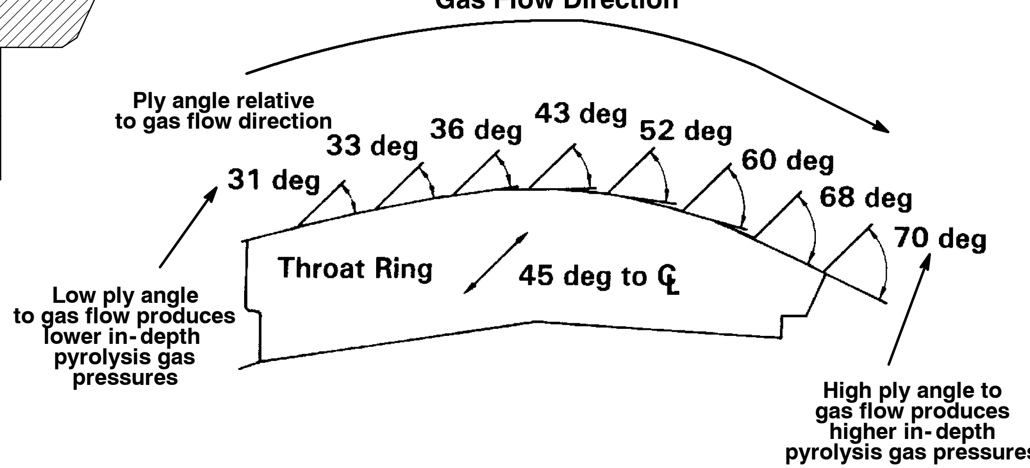
Carbon-Cloth Phenolic Ply Angle Relative to Combustion Gas Flow





Heat Flux vs Nozzle Location





Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

Background (Cont)

- Flight rationale established following STS-79 RH
  - Total heat-affected depth only slightly deeper than nonpocketing case—remaining capability substantial
  - Worst-case bounding assessments show acceptable remaining carbon thickness
  - Pocketing erosion on subsequent flights is possible, bounded, and safe
- Pocketing determined to be self-limiting due to distorted plies eroding away, decreased heat transfer due to decreasing motor pressure and growth of char layer which limits heating rate
- Flight safety established based on self-limiting rationale and substantial remaining margins
- Deviation against CEI specification based on statistical assessment of occurrence lowered erosion safety factor
  - From 2.0 to 1.6 for throat
  - From 1.7 to 1.6 for forward exit cone
  - Char safety factor remained at 1.25
- New mandrel implemented on STS-106 expected to eliminate ply distortions, and eliminate pocketing
  - Five flight sets flown with no pocketing STS-106, -92, -98, -102, and -100
  - Two previous static tests with no pocketing on FSM-7 and FSM-8

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

FSM-9 Investigation Results

- **Joint Thiokol and MSFC anomaly investigation team used a comprehensive fault-tree analysis method to conclude that FSM-9 resulted from a combination of "in-family" events**

FSM-9 Pocket/Wash Erosion Investigation

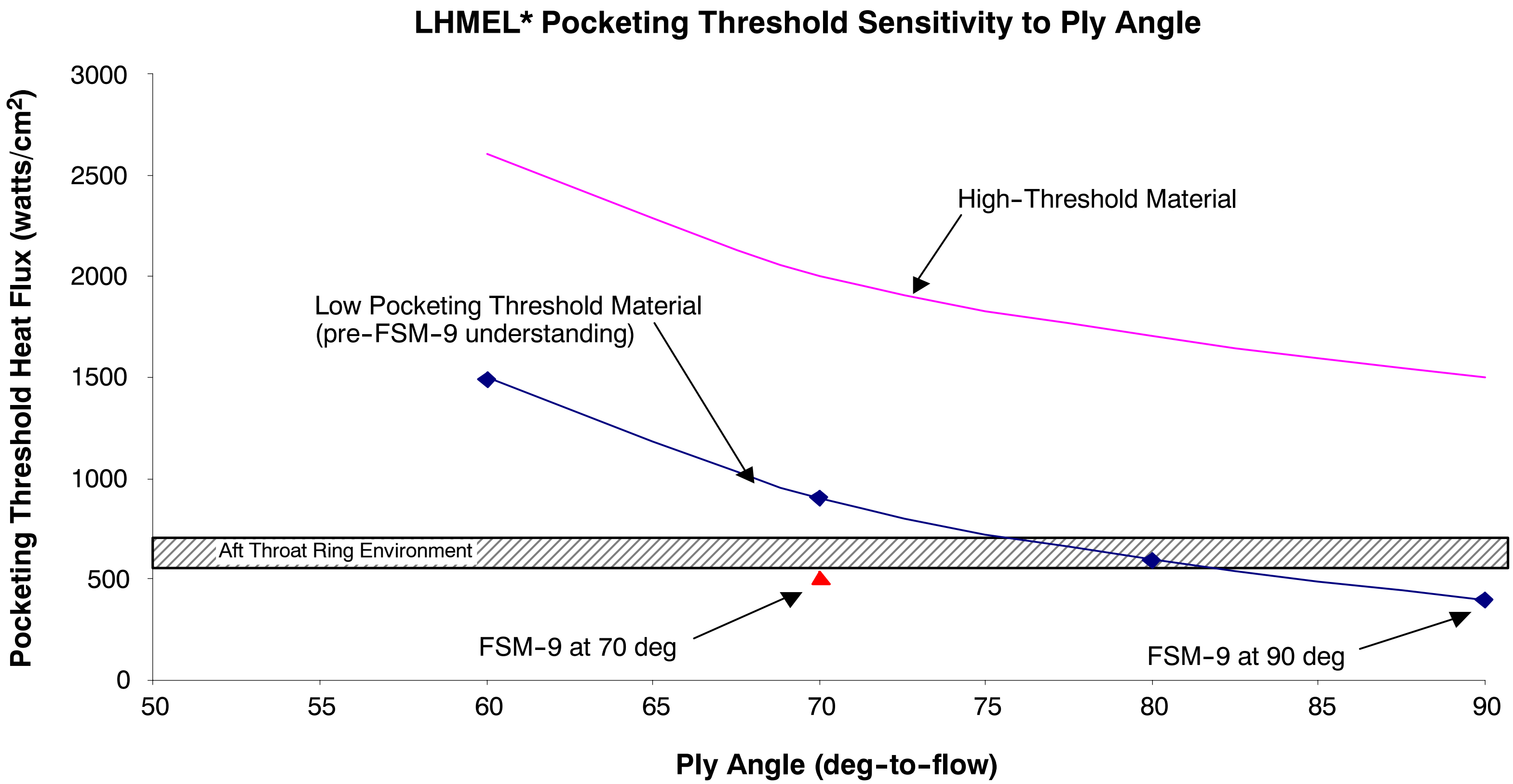
- **Materials Assessment**
  - All raw materials show in-family characteristics
  - Material samples show high propensity to pocket similar to STS-79 (400 watts/cm^2 @ 90-deg ply angle)
  - Material samples pocketed when subjected to motor heat flux at design ply angle (500 watts/cm^2 @ 70-deg ply angle)
- **Processing Assessment**
  - In-family processing
  - No evidence of severe ply angle distortion (angle ranged between 63 to 73 deg)
- **Motor Environment Re-Assessment**
  - Previous assessments of heat flux in pocketing region 550 watts/cm^2
  - Current assessment varies heating range from 550 watts/cm^2 to 700 watts/cm^2

- **FSM-9 cause summary**
  - **FSM-9 had a high (70-deg) ply angle unique to aft end of throat ring, and a high, in-family propensity-to-pocket material**
  - **No unique or special causes are necessary to explain FSM-9—validity of basic pocketing hypotheses not challenged**

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

FSM-9 Investigation Results (Cont)



*LHMEL = Laser Hardening Material Evaluation Laboratory at Wright-Patterson

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

Latest Understanding Based on FSM-9 Investigation

	Previous	New
1.	Heat rate in pocketing region (at joint No. 4) 550 watts/cm^2	Heat rate in pocketing region (3 in. forward of joint No. 4) 700 watts/cm^2
2.	Ply distortions required for pocketing	Ply distortions not required for pocketing
3.	800 watts/cm^2 needed to pocket at 70-deg ply angle with low end material	500 watts/cm^2 needed to pocket at 70-deg ply angle with low end material
4.	Self-limiting due to distorted plies eroded away, plus self-limiting due to drop in heat rate in first 20 seconds	Self-limiting due to drop in heat rate in first 20 seconds

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

Pocketing Erosion—Self-Limiting Assessment

Analysis	Subscale Tests	Materials	Nozzle History
• Mechanism—Pyrolysis gas pressure buildup exceeds tensile capability • Bounding analyses of pocket depths based on nozzle history and LHMEL tests • Pocketing stops because heat flux in pocket drops below 400 watts/cm^2 within 20 seconds	• 5000+ LHMEL test database at worst-case 90-deg ply angle, always self-limiting at conservative heat flux conditions • 30+ FPC motors with pockets were all self-limiting at worst-case ply angles and conservative heat flux levels	• Extensive statistical design of experiment studies have shown FSM-9 represents worst material expected with production baseline • FSM-9 had roll of low-threshold material in worst-case location	• 6 of 236 HPM/RSRM nozzles have pocketed • Minor affect on virgin material remaining • 100+ seconds of burn time capability

- Analysis capability is strong, mechanism not challenged by FSM-9 erosion
- Variety of subscale tests have shown pocketing is self-limiting
- Nozzle throat pocketing history has shown consistent worst-case depths and margins

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

Bounding Case Margin Assessment

- LHMEL tests run for 20 or more seconds. All pocketing stopped within 17 seconds. Most stopped by 10 seconds

Heat Flux watts/cm^2	Total History (90 deg)*		FSM-9 (90 deg)		FSM-9 (70 deg)	
	Number of Tests	Maximum Depth (in.)	Number of Tests	Maximum Depth (in.)	Number of Tests	Maximum Depth (in.)
400	113	0.239	3	0.189		
500	303	0.467	2	0.241	2	0.28
600	167	0.517			2	0.29
700	58	0.632	4	0.405		
800					4	0.40

- Thermal model was used to assess the effects of a bounding case pocket depth (0.65 in.) using worst ply angle, material, heat flux
  - 0.53 in. of virgin material remaining
  - Erosion factor of safety = 1.39
  - Remaining burn time = 105 seconds beyond the nominal 123-second motor burn time
- Thermal model matches FSM-9 char and erosion with a 0.2-in.-deep pocket
- RSRM motors have substantial margin even with worst-case ply angles and highest propensity-to-pocket materials

* History includes material “outside the box” with very high propensity to pocket

Technical Issues/Special Topics

Pocket/Wash Erosion on Throat and FEC (Cont)

Flight Rationale

- Pocketing on flight nozzles assessed to be a possibility
    - Pocketing erosion is limited to shallow, early-in-burn events
    - Statistical assessment of pocketed nozzles shows a high probability of future nozzles meeting a 1.6 safety factor
    - The pocketing process is self-limiting
    - Process controls limit lower threshold materials to in-family condition
    - Remaining margins are substantial
- STS-104 and subsequent materials and processes are in-family and in-family performance is expected
- STS-104 and subsequent are safe to fly

THIOKOL
PROPULSION

STS – 104 Readiness Assessment

Pending satisfactory completion of normal operations flow (per OMRSD), the RSRM hardware is ready to support flight for mission

STS – 104

28 June 2001

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/s/ M. U. Rudolphi

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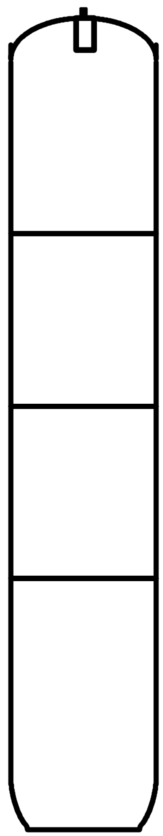
Current Flight Predictions

LCC and Contingency Temperatures for STS-104



Heater Location	LCC	Minimum Allowable Sensor Temperature*	
		LH	RH
Igniter	74°F	72°F	72°F
Forward Field Joint	80°F	66°F	68°F
Center Field Joint	80°F	70°F	70°F
Aft Field Joint	80°F	69°F	64°F
Nozzle-to-Case Joint	75°F	70°F	74°F

***Launch commit criteria (LCC) contingency temperature in the event of heater failure**

Note: Calculation includes all standard repair conditions